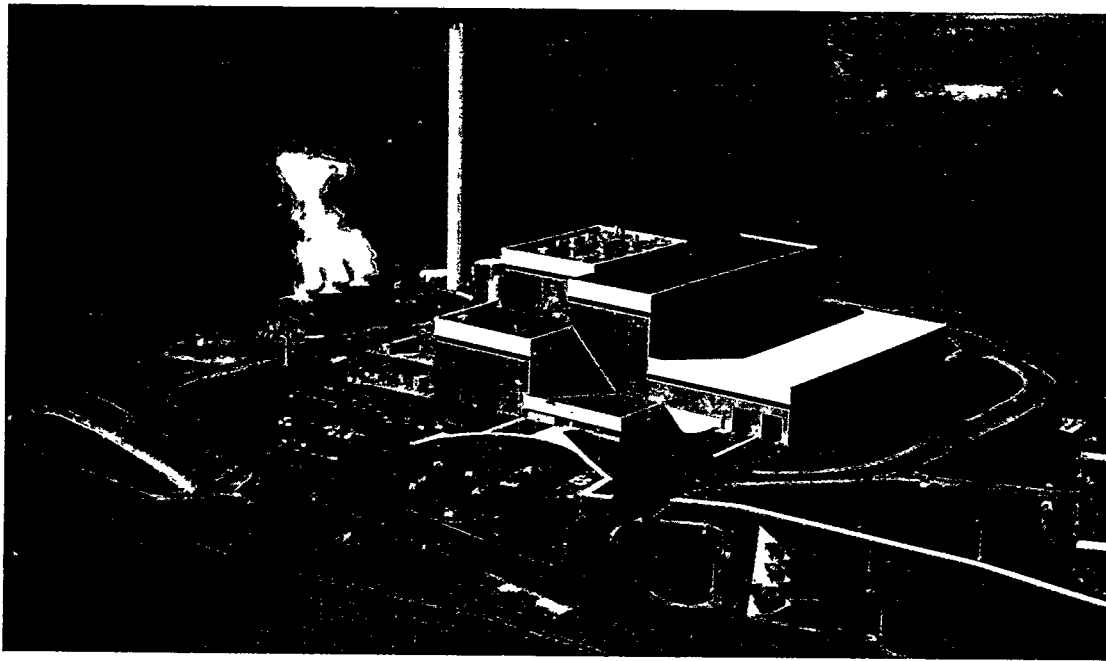


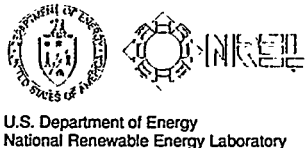
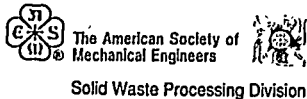
PROCEEDINGS OF

Fifth Annual North American Waste-to-Energy Conference

Research Triangle Park, North Carolina
April 22-25, 1997



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**Fifth Annual North American
Waste-to-Energy
Conference**

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The Solid Waste Association of North America
(SWANA)
1100 Wayne Avenue, Suite 700
Silver Spring, MD 20910
Phone: (301) 585-2898
Fax: (301) 589-7068

Air & Waste Management Association
(A&WMA)
One Gateway Center, Third Floor
Pittsburgh, PA 15222
Phone: (412) 232-3444
Fax: (412) 232-3450

Integrated Waste Services Association (IWSA)
1401 H Street NW, Suite 220
Washington DC 20005
Phone: (202) 467-6240
Fax: (202) 467-6225

U.S. Department of Energy (DoE/NREL)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401
Phone: (303) 275-2915
Fax: (303) 275-2905

American Society of Mechanical Engineers
(ASME) Solid Waste Processing Division
Licata Energy & Environmental Consultants
Inc.
345 Concord Road
Yonkers, NY 10710
Phone: (914) 779-3451
Fax: (914) 779-4234

U.S. Environmental Protection Agency (EPA)
Air Pollution Prevention & Control
Air Pollution Technology Branch
Research Triangle Park, NC 27711
Phone: (919) 541-2854
Fax: (919) 541-0554

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FOREWORD

The NAWTEC Program Committee is pleased to present the Proceedings from its Fifth Annual North American Waste-to-Energy Conference (NAWTEC V). The Proceedings consist of manuscripts as prepared by the Conference Technical Session presenters. They represent a broad range of topics of interest to professionals in the waste-to-energy sector of the municipal solid waste management field.

We would like to acknowledge and thank the presenters who prepared manuscripts for this year's Proceedings. These individuals spend a significant amount of time preparing both their presentations and papers. We would also like to thank and acknowledge the following individuals and groups for contributing to this year's technical program:

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The NAWTEC Program Committee prides itself on offering timely and pertinent information in its technical programs and proceedings. We trust that these Proceedings will serve as a valuable resource to the reader.

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OPENING PLENARY SESSION

THE EVOLUTION OF WTE UTILIZATION
A GLOBAL LOOK

The Evolution of WTE Utilization - The European Perspective

Håkan Rylander

President, International Solid Waste Association/ISWA

**Managing Director, The Southwest Scania Solid Waste Company/SYSAV,
Sweden**

The ECO-Society

Everyone involved in the protection and proper use of raw materials, natural resources and the environment and in the daily operation of solid waste management aims to reach the "Eco Cycle Society". That means that each of us, in our present and future handling of raw materials, products, residues and waste will minimize the use of terminable resources and bring back as much as possible of them in the closed cycle after being used. The idea of the "Eco Cycle Society" is showed in graph nr 1.

The Producer's Responsibility

To reach the "Eco Cycle Society" it is necessary to reduce the amount of waste and to significantly increase the reuse and recycling of different materials and products. It is important to understand that wastes are simply discarded products and the design of a product can have a very significant impact on the nature of the waste that is produced. Recycling and reuse can be enhanced by designing products so that components and materials can be easily separated, by eliminating contaminating materials that inhibit recycling, and by using more recycled materials in the original products. Eliminating certain materials from products can also reduce the release of toxic materials to the environment during waste treatment.

We are beginning to see the implementation of the concept of the "Producer's Responsibility" in laws that are being passed in various European countries requiring manufacturers to take back discarded products and packagings for reuse or recycling. In Sweden the Swedish Government in 1993 decided about guiding principles for packagings and some other products in order to reach the "Eco Cycle Society". The "Producer's Responsibility" means both physical and economical responsibilities. The same principle will step by step be introduced for more products. The "Producers" have been given the economical and physical responsibility for the collection, recovery and recycling of used packagings. Requirements and goals have been settled for the recovery and recycling of these packagings. For news-papers, journals and old tyres there is also a "Producer's Responsibility" from the 1st of July 1994 in Sweden.

The consequences of the "Producer's Responsibility" for the future handling of waste will most probably be decreased amounts of Municipal Solid Waste/MSW to be treated as compared with today. For example the amounts of MSW being incinerated in Waste-to-Energy plants will decrease but it opens at the same time up the possibilities for an increased amount of burnable industrial waste being incinerated with energy recovery instead. Besides, there is or being planned a ban or very strong restrictions of landfilling organic and burnable MSW in many European countries, which will increase the need for incineration.

Establishment of Environmentally Sound Treatment and Disposal Facilities - A Combination of Methods.

Even with maximum feasible rates of waste reduction and recycling, there will still be a need for waste treatment. The state of the art of waste treatment has advanced rapidly in recent years. Today, technologies are available to effectively treat wastes in an environmentally sound manner. For example, standards for solid waste incineration units incorporate emissions monitoring and highly efficient air pollution control systems to control organic emissions, metals, acid gases and other pollutants. Today's state-of-the-art landfills meet with similar tough stan-

dards, most of them are equipped with leachate collection systems, groundwater monitoring, systems for control of landfill gas and recovery of its energy content, and closure and post-closure care. The objective is to ensure that landfilling, when used, is performed in a manner that greatly reduces the chance of environmental degradation and also ensure that any release that does occur is quickly detected and remedied.

Solid waste management in practice must be based on **integrated systems with a combination of many different methods**. There should not be any contradiction between the different methods, on the contrary they should be regarded as complement to each other:

- Recovery of materials in households and industries, involving direct action by residents and industries in cooperation with those given the responsibility for the collection, recovery and recycling of different materials and products.
- Increased utilization of the material and energy resources in industrial waste. The conservation of resources should mainly take place within the industry, by the use of low-waste technology, and by internal recovery of the residues and the waste.
- Thermal treatment of waste, with energy recovery.
- Utilization of the easy biodegradable part of the organic waste for the production of biogas and compost
- Landfilling, which always will be needed regardless of other methods utilized, for non-recyclable materials, and for residues from other waste treatment.

Results and experiences today from different countries and different used systems for solid waste management clearly shows the need of attacking the waste problem with an integrated waste system. In order to fulfill this concept the scheme as shown in **graph nr 2** is already used or will soon be used in most municipalities in Sweden, in order to recover material- and energy resources and to get cleaner products for recycling, cleaner compost and less emissions from different treatment plants as a result of a cleaner input.

In most European countries the following list of Priority is recommended in order to solve the waste problem:

- 1 Waste Reduction and Minimization
- 2 Reuse
- 3 Recycling
- 4 Energy Recovery
- Landfilling

Municipal Solid Waste Treatment in Europe

In Europe there is a total population of approximately 360 million people, producing a total amount of Municipal Solid Waste/MSW of about 140 million tons per year (1991). Per capita this is an amount of about 400 kg per year. The total amount of MSW produced in each country is presented in **graph nr 3** as well as the production per capita. Also the composition of the MSW per country is listed. An average composition for the whole of Europe is given as a reference.

In Europe Municipal Solid Waste/MSW is disposed of in mainly four different ways: Recycling, Composting, Incineration and Landfilling. In **graph nr 4** is shown the treatment of MSW per country in Europe. All figures in the graph are in % of the total MSW per country. The figures are from 1991 and some changes have taken place since then, the recycled amount has increased and the landfilled amount has decreased in many countries. However, it is very difficult to find up-to-date figures covering all the changes that are taking place for the moment.

The effects of the introduction of the Producer's Responsibility, the increased source recovery in households and industries and the very heavy restrictions on landfilling in many countries will most certainly dramatically change the use of different methods for treating MSW in a few years. For example, in France it will be prohibited after the year 2002 to landfill other waste than residues from other treatment, in Germany it will only be allowed after 2005 to landfill waste with a very low content of organic materials, in Sweden there is currently a proposal to prohibit landfilling of burnable waste from the year 2000 and waste with an organic content from the year 2005, in Switzerland and The Netherlands there are very heavy restrictions on landfilling, similar to those restrictions mentioned above. This means that there will be an increase in recycling, biological treatment and incineration of waste just within a few years in Europe. In many countries there are plans and measures taken to meet with this new situation.

Energy from Waste

Waste incineration is an old and established method for treating MSW in Europe. The first plant was built already during the 1890'ies. By that time waste incineration was used for hygienic aspects, not least to solve the enormous problems with cholera in the densely populated cities of Europe. Still being a method to tackle the hygienic problems it also during the 1900'ies became a method for reducing the increasing volumes of waste being generated. Incineration was not associated with any form of recovery. An objective like that is relevant for a society with linear material flows where raw materials are provided from virgin materials and the waste dumped without any recycling. This is not in accordance with a society of sustainable development. Today we are aiming at a cyclic flow. There is only one objective for waste incineration that is relevant in the eco cyclic society and that is energy recovery. Volume reduction is no more an objective but still an important parameter when comparing environmental impact. Furthermore incineration is only justified when the method is at least as favourable as other recycling or recovery alternatives. In many European countries you will not even get a permission today to build a new waste incineration plant without recovering the produced energy. Besides, the operation costs in a modern plant with advanced flue gas cleaning and a strict handling of the residues will be too high without any incomes from energy recovery.

The situation in Europe when coming to waste incineration is today actually a little bit difficult to overlook. In some countries there are a number of old, small incineration plants not meeting the EU-directives on waste incineration. Of course they have to be closed down, probably replaced with new, larger plants, but there is an uncertainty about the future amounts of waste to be incinerated due the effects of the increased recycling activities, the effects of the producer's responsibility and of the ban or restrictions on landfilling of organic and burnable waste. Will the amounts for incineration increase, decrease or remain at today's level? At some larger plants in Europe there is to-day an overcapacity, due the increased amounts of waste being recycled or composted. The restrictions on landfilling will probably change this situation into the opposite and there will probably soon be a demand for increased incineration capacity in many European countries.

Number of plants and capacity

In Europe there are between 450-500 MSW incineration plants with a total nominal capacity of more than 6000 tons per hour. All together there is an annual capacity of about 45 million tons, based upon 7000 hours of operation. **Graph nr 5** shows in which countries the incineration plants are located and how much of the total amount of MSW is incinerated in these plants. As already mentioned there have probably already been some changes in the figures presented in the graph and there will be even more changes in the future - less small plants, more larger plants with an increased incineration capacity and equipped with advanced flue gas cleaning systems.

In graph 5 it can be seen that France has the most incineration plants by far. However, these 225 incineration plants are relatively small as they represent 46,4% of the number of incineration plants in Europe but only incinerate 26,1% of the total amount of MSW in Europe. On the contrary the installations in Germany and in The Netherlands are relatively large: 10,1% (Ger-

many) and 2,1% (The Netherlands) of the incineration plants incinerate respectively 27, 9% and 7,3% of the European MSW.

Energy Recovery

In Europe there is some kind of energy recovery from most of the incineration plants (56% by number representing 82% of the MSW incineration capacity in 1993, probably even more today). **Graph 6** gives an overview of the energy recovery per country. In general the Scandinavian countries use a high percentage of the recovered energy to produce hot water for district heating whereas the other countries mainly produce steam for electricity production, mostly without usage of the remaining energy which has to be cooled off. However, there is a change towards better use of the produced heat outside the Scandinavian countries as well as there is a very significant tendency in the Scandinavian countries of more and more combined production and use of as well heat as electricity.

Emission Guidelines and Flue Gas Cleaning Systems

Almost every country in Europe has its own legislation concerning emissions from MSW incineration. These regulations, however, differ a lot from country to country, not only in emission limits, but also in the number of pollutants for which there are limits. Some regulations only set limits to the emission of dust, HCl, HF and CO, whereas others also include SO₂, NO_x, total organic carbon (TOC), heavy metals, PCDD/F as well as certain performance demands, other than emissions.

Graph 7 gives an overview of the emission limits according to the different regulations existing in Europe. For comparison the latest EU directives on Hazardous Waste Incineration (HWC) have been included. The values in the table are related to an oxygen concentration in the flue gases of 11vol% (dry, at standard temperature and pressure: 273 K, 101,3 kPa), except for Norway (10vol% O₂) and Sweden (10vol% CO₂). An oxygen concentration of 11vol% is corresponding with a CO₂ concentration of 9 vol%.

Most of the regulations also require certain conditions to be met for the flue gases after the last air injection. For example the German regulation requires that the flue gases, after the last injection of air remain at a temperature of at least 850 degrees centigrade and a concentration of 6 vol% O₂ for at least 2 seconds. This is done to guarantee the destruction of combustible matters in the flue gases. Besides the limit values it is very important to specify the time period during which the measurements have to be averaged to meet the limit values. For example a limit value as a half hour average is more difficult to meet with as the same value over a longer period of time (time to even out peaks).

Member countries of the European Union have to comply with the EU-directives at minimum, but can have stricter limits. This is the case for example for Germany and The Netherlands, see **graph 8**. In this graph the EU Draft Directives for incineration of waste are also shown. However, it is still a draft. In **graph 9** the needed removal efficiency to reach the Dutch guidelines is shown, in relation to the raw flue gas concentration.

To reach the EU guidelines and most national guidelines advanced fluegas cleaning systems have to be installed. In **graph 10** all the different steps that could be included in such a system is shown. Of course all the steps in the graph can be used, or combinations of the different steps, to reach the different guidelines. The strictest emission guidelines (Germany, Austria, Netherlands) can be reached by using state-of-the-art cleaning techniques, but not without considerable effort. In newly designed flue gas cleaning systems the following sequence of equipment is in principle often used:

- Electrostatic Precipitators
- Multi-staged wet scrubber with waste water evaporation
- Active cokes/lime injection with fabric filter
- SCR-DeNO_x.

Residue treatment

Of the residues in general only the bottom-ash (slag) can be reused for the moment. Before reuse the bottom-ash can be crushed and/or sieved and iron scrap is removed and in many cases recycled. Several processes are under development to improve the bottom-ash quality to ensure disposal of the bottom-ash when the regulations are toughened. The bottom-ash which is not reused is landfilled, but because of the large amounts of bottom-ash which are produced from waste incineration there is a pressure to reuse as much of the bottom-ash as possible. In some countries the "gravel" fraction of the bottom-ash is used in road constructions.

Fly-ash reuse is in fact not possible for the time being: it is landfilled in a secure way - stacked in big bags, stabilized with cement or binders or in some other way safely land-filled.

As the emissions to the air to a large extent are controlled, the research is more and more focusing on the safe handling and better use of the residues.

Costs of MSW Incineration

In a TNO Environmental and Energy Research Report from 1993 the costs (the investment cost and the cost per ton) are calculated for an incineration plant which basically has the following equipment:

- moving grates
- boilers in which steam is produced
- a turbine and electricity generator
- a flue gas cleaning system which consists of: an ESP, a 2-staged wet scrubber and an entrained flow adsorber (reactor with subsequent fabric filter) with active cokes addition.
- a waste water treatment system which neutralizes the waste water and precipitates a gypsum sludge and heavy metals.

The costs are given with and without evaporation of the waste water. The latter is done because it is not certain whether discharge of waste water will be allowed. For the moment at most locations which are close to the sea or to a river, discharge of waste water is allowed. Both options are considered. Waste water evaporation results in a solid salts residue which has to be land-filled. The evaporated waste water is condensed and used again in the first step of the wet scrubber.

The investment and operating costs were determined for different capacities in a range from 9 tons per hour to 115 tons per hour. With an availability of the facility of 80% this is equal to an annual capacity from 63 000 tons to 806 000 tons. Each plant is calculated for a minimum of 2 separate units. The investment costs are shown in **graph 11**.

Besides investments costs also the costs per ton of MSW processed are important. These are calculated with the following assumptions:

- the availability of the plant is 80%
- the depreciation period for a new MSW incineration plant is 25 years and the interest is 10%
- maintenance of the building/construction part is 1% of the investment for this part, maintenance for the electro/mechanical part is 5% of the investment for this part.
- personnel costs 40 000 ECU per year per person.
- insurance 1% of the total investment

Besides there are of course costs for chemicals and utilities. It is assumed that the bottom-ash can be reused and that the cost for disposal of the bottom-ash equals zero. Disposal of the other residues (fly-ash, sludge, salts, used active coal mixture) is assumed to cost 182 ECU/ton. The costs per ton are shown in **graph 12**.

The net cost will of course vary very much due to the price for the produced electricity and, as in the Scandinavian countries, if the produced heat can be sold and not cooled off.

The Swedish Example

Modern waste incineration with energy recovery got its break through in Sweden during the sixties and seventies, not only because of hygienic aspects and volume reduction, but also because the energy content could be utilized for district heating purposes. Waste incineration is still a very important method for handling the waste problem and for energy recovery and will remain so in the future handling of waste in Sweden. Today about 1,8 million tons of waste are being incinerated in 21 Waste-to-Energy plants, with in all 38 furnaces - including about 1,4 million tons of MSW (of a total amount of about 3,3 million tons before a material recovery of about 0,7 million tons) and about 0,4 million tons of industrial waste. 18 of the plants produce heat and 3 of the plants are combined heat and power facilities. There will most probably be an increased production of power in the future.

Waste contains mostly materials of biological origin, only 10% have fossile origin. The waste do contain materials which should be separated from the waste before incineration. By efforts to eliminate hazardous waste from the market (for example Mercury-batteries) and by separation at the source in accordance with the scheme in graph nr 2, the remaining waste becomes cleaner and also the emissions.

During the last ten years the waste incineration system has gone through a considerable technical development. Originally the Swedish waste incineration plants were only equipped with cyclones or electrostatic precipitators for the reduction of emissions, especially dust. Nowadays all Waste-to-Energy plants in Sweden have installed advanced flue gas cleaning systems to meet with the more stringent emission standards set up by EU and the Swedish Environmental Protection Agency. From an environmental point of view, waste incineration in Sweden with advanced flue gas cleaning is a very clean way to produce energy.

Swedish Plants - capacities, type of furnaces, flue gas cleaning equipment

Plant	Capacity (tons /year)	Grate/FB	Flue gas cleaning
Avesta	45 000	Grate	ESP, Dry+Wet,FF
Bollmora	13 000	Grate	FF
Bollnäs	20 000	FB	FF
Borlänge	26 000	Grate	ESP, Wet
Eksjö	8 000	FB	FF
Göteborg	400 000	Grate	ESP, Wet
Halmstad	90 000	Grate	ESP, Wet
Karlskoga	35 000	Grate	ESP, Dry, FF
Karlstad	50 000	Grate	ESP, Dry, FF
Kiruna	18 000	Grate	FF
Köping	33 000	Grate	ESP, Dry, FF
Lands- krona	5 000	FB	Dry, FF
Lidköping	65 000	FB	Dry, FF
Linköping	230 000	Grate	ESP, Dry, FF
Malmö	220 000	Grate	Dry, FF
Mora	20 000	Grate	Dry, FF
Stock- holm	300 000	Grate	Dry, FF
Sundsvall	17 000	FB	ESP, Dry, FF
Umeå	120 000	Grate	Dry, FF
Uppsala	250 000	Grate	ESP, Wet+Dry, FF
Västervik	30 000	FB	Dry, FF

FB=Fluidized Bed
Wet=Wet cleaning

ESP=Electrostatic Precipitator
Dry=Dry cleaning.

FF=Fabric Filter

At twelve of the twentyone plants steps have been taken to reduce the emissions of NO_x .

The annual emissions from the the Swedish Waste-to-Energy plants have been reduced as follows from 1985:

Substances	Unit	1985	Today	Reduction
Dust	tons/year	420	40	90%
HCl	tons/year	8400	290	96%
SO_x	tons/year	3400	820	76%
NO_x	tons/year	3400	1600	53%
Hg	kg/year	3300	100	97%
Cd	kg/year	400	15	96%
Pb	kg/year	25000	300	99%
Dioxins	g/year	90	1,7	98%

In all 5 TWh of energy are produced from waste incineration in Sweden. All energy is used and delivered to the district heating systems and the power systems in the cities concerned. The produced energy covers almost the heating of 250 000 apartments or 15% of the district heating in Sweden every year, corresponding to the saving of 500 000 tons of oil annually. In some cities the waste incineration stands for 30-40% of the district heating. Due to the development of the incineration technology, the high energy value of the waste and due to a very professional staff at the incineration plants, the energy efficiency in average is as high as 85%.

The incinerated amount of waste has been more than doubled since 1980. During the same period the production of energy from the Swedish Waste-to-Energy plants have been almost quadrupled. This is due to the fact that the energy content of the waste has increased but most of all because the introduction and use of a more efficient technique for energy recovery. Less energy has been cooled off since 1980. In 1986 about 1,5 million tons of waste were incinerated with an energy production of 3, 4 TWh. Today about 1,8 million tons are incinerated with an energy production of 5 TWh.

While the incinerated amount has increased with 20% since 1986, the energy production has increased with 47%, and different emissions have decreased between 54% to 99%.

After energy recovery the waste incineration treatment costs in the Swedish Waste-to-Energy plants vary somewhere between 200-400 Swedish Crowns/ton, depending upon age, size and equipment of each plant. Without energy recovery the cost would have been doubled.

Waste incineration with energy recovery will even in the future be one of the more important methods in Sweden to reduce the waste amount, to protect the environment and to take care of energy resources.

Conclusion

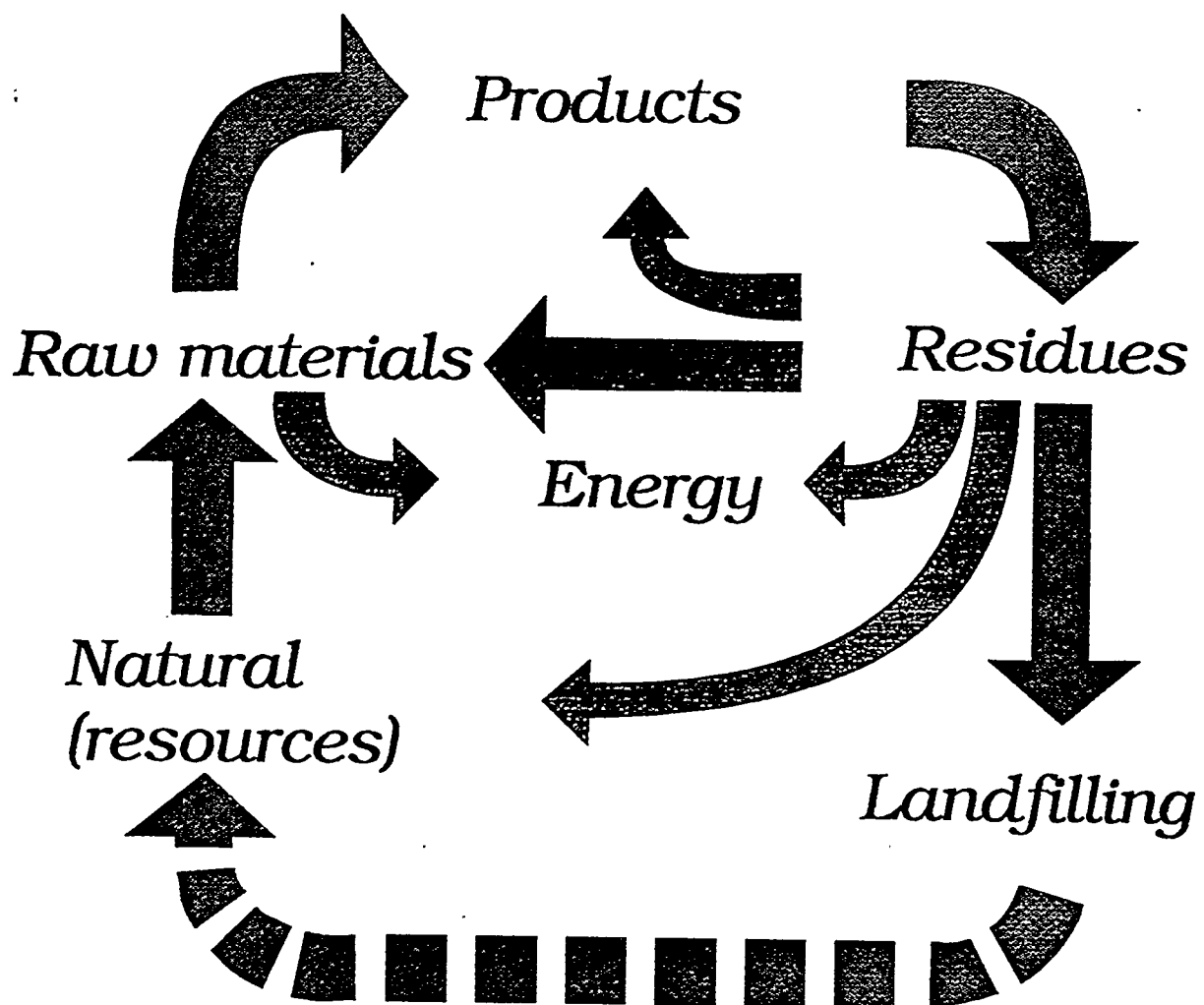
Waste-to-Energy is an established and well functioning method for waste treatment and energy recovery and the most effective way of taking care of the energy content of waste. Waste is to a very large extent to be considered as a bio-fuel and the incineration of waste decreases the need of fossil fuels to be burned, resulting in a decrease of the emissions of green-house gases. Due to far-reaching restrictions on landfilling of MSW in Europe there will most probably be an increased need for waste incineration with energy recovery, as a complement to recycling and biological treatment of waste. New plants will be equipped for using the produced energy for heating purposes as well as for electricity production. The strict emission guidelines already implemented in for example Germany and The Netherlands will most probably, at least to some extent, be introduced in the other EU-countries, resulting in the installation of very advanced flue gas cleaning systems.

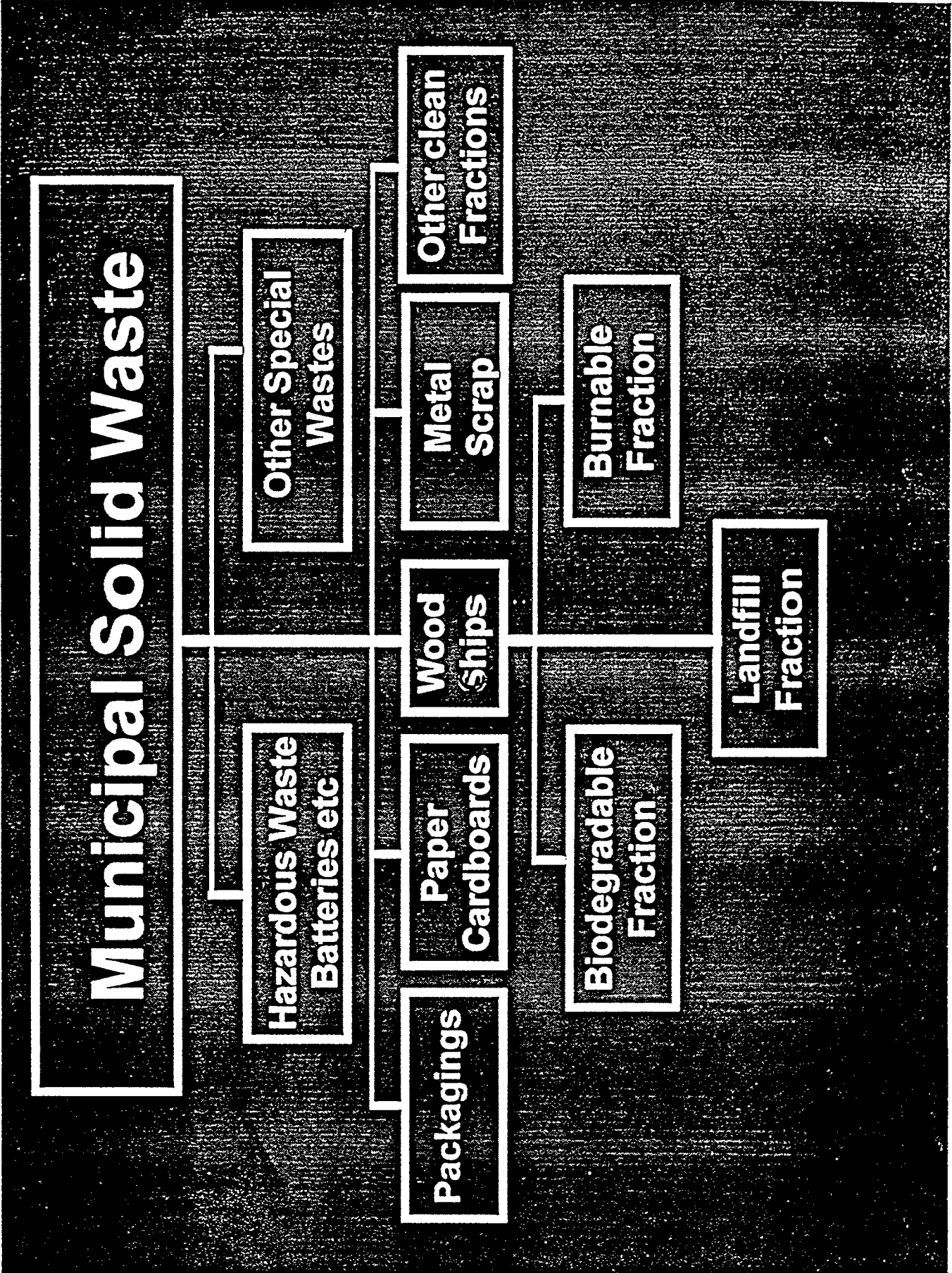
There is only one objective for waste incineration that is relevant in the eco cyclic society and that is energy recovery. Volume reduction is no more an objective but still an important parameter when comparing environmental impact. Furthermore incineration is only justified when the method is at least as favourable as other recycling or recovery alternatives. □

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- | | |
|--|---|
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” Closed Cycle Society”





Graph 3

Composition of Municipal Solid Waste per country in Europe
All figures consider total MSW per country

Country	Amount of MSW		Putrescibles/ fines Wt%	Paper Wt%	Plastic Wt%	Glass Wt%	Metals Wt%	Miscell (textiles Incl.) Wt%
	k tonnes /yr	kg/capita						
A	2,800	370	30	30	9	10	4	17
B	3,500	350	47	28	7	7	4	7
CH	3,700	550	30	31	13	7	6	13
D	25,000	410	44	24	7	9	6	10
DK	2,600	510	40	35	5	4	5	11
E	13,300	340	49	20	7	8	4	12
F	20,000	360	25	30	6	12	5	22
GR	3,150	310	53	18	7	3	4	15
I	17,500	300	40	22	7	8	3	20
IRL	1,100	310	55	20	10	3	3	9
L	180	480	47	28	7	7	4	7
N	2,000	470	25	32	7	4	4	28
NL	7,700	520	38	35	7	7	5	8
P	2,650	260	60	22	4	3	4	7
S	3,200	380	30	40	9	7	3	11
SF	2,500	500	30	40	6	4	3	17
UK	30,000	520	42	28	7	8	9	6
Europe min-max ¹⁾	140,880	395	40	27	7	8	6	13
		260-550	25-60	18-40	4-13	3-12	3-9	6-28

Treatment of Municipal Solid Waste per country in Europe

Country	Amount ktonnes/yr	Incineration	Landfill	Composting	Recycling
A	2,800	11	65	18	6
B	3,500	54	43	0	3
CH	3,700	59	12	7	22
D	25,000	36	46	2	16
DK	2,600	48	29	4	19
E	13,300	6	65	17	13
F	20,000	42	45	10	3
GR	3,150	0	100	0	0
I	17,500	16	74	7	3
IRL	1,100	0	97	0	3
L	180	75	22	1	2
N	2,000	22	67	5	7
NL	7,700	35	45	5	16
P	2,650	0	85	15	0
S	3,200	47	34	3	16
SF	2,500	2	83	0	15
UK	30,000	8	90	0	2
Europe	140,880	24	63	6	8

MSW Incinerators in Europe

Country	Number of incinerators per country	% of total number of incinerators in Europe (%)	Incineration capacity per country (ktonnes/yr)	% of total incineration capacity in Europe (%)
A	2	0.4	340	0.8
B	24	4.9	2.240	5.2
CH	30	6.2	2.840	6.6
D	49	10.1	12.020	27.9
DK	30	6.2	2.310	5.4
E	15	3.1	740	1.7
F	225	46.4	11.330	26.1
I	28	5.8	1.900	4.4
L	1	0.2	170	0.4
N	18	3.7	500	1.2
NL	10	2.1	3.150	7.3
S	21	4.3	1.860	4.3
SF	1	0.2	70	0.2
UK	31	6.4	3.670	8.5
Europe	485	100.0	43.140	100.0
EU	413	85.2	37.530	87.0

Level of energy recovery in the different countries in Europe

Country	Number of incinerators per country	% of total number with energy recovery (%)	Incineration capacity per country (ktonnes/yr)	% of total capacity with energy recovery (%)
A	2	100	340	100
B	24	46	2,240	64
CH	30	80	2,840	90
D	49	100	12,020	100
DK	30	100	2,310	100
E	15	27	740	73
F	225	42	11,330	70
I	28	64	1,900	76
L	1	100	170	100
N	18	28 ¹⁾	500	83
NL	10	90	3,150	97
S	21	100	1,860	100
SF	1	100	70	100
UK	31	16	3,670	32
Europe	485	56	43,140	82
EU	413	54	37,530	80

1) On 13 small incinerators it is assumed that no heat is recovered

Graph 7

Emission guidelines for Municipal Solid Waste combustion in Europe (see text for explanation)

Component	A 1989	B 1982	CH 1991	D 1990	DK 1991	I	N	NL 1989	S	UK 1992	EC 1989 MSW	EC Haz. waste	Component
Dust	15	100	10	10	30	30	10	5	20	30	30	5	Dust
HCl	10	100	20	10	50	50	100	10	100	30	50	5	HCl
HF	0.7	5	2	1	2	2	-	1	1	2	2	1	HF
SO ₂	50	-	50	50	300	300	300	40	200	300	300	25	SO ₂
CO	50	1000	50	50	100	100	100	50	100	100	100	50	CO
NO _x (as NO ₂)	100	-	80	200	-	-	-	70	400	350	-	-	NO _x (as NO ₂)
TOC (as C)	20	-	20	10	20	20	-	10	-	20	20	5	TOC (as C)
Heavy metals													Heavy metals
Hg	0.05	-	0.1	0.05	-	-	0.1	0.05	0.03	0.1	0.2	0.05	Hg
Cd	0.05	-	0.1	-	-	-	-	0.05	-	0.1	0.2	-	Cd
Hg+Cd	-	-	0.1	-	0.2	0.2	-	-	-	-	-	-	Hg+Cd
Cd+Tl	-	-	-	0.05	-	-	-	-	-	-	-	0.05	Cd+Tl
Pb	-	-	1	-	1	-	-	-	-	-	-	-	Pb
Zn	-	-	1	-	-	-	-	-	-	-	-	-	Zn
Pb+Zn+Cr	2	-	-	-	-	-	-	-	-	-	-	-	Pb+Zn+Cr
Pb+Cr+Cu+Mn	-	-	-	-	5	5	-	-	-	-	5	-	Pb+Cr+Cu+Mn
As+Ni	-	-	-	-	1	-	-	-	-	-	1	-	As+Ni
As+Co+Ni	0.5	-	-	-	-	-	-	-	-	-	-	-	As+Co+Ni
Tot.rest	-	-	-	0.5	-	-	-	1	-	1	-	0.5	Tot.rest
PCDD/F	0.1	-	-	0.1	-	4000 1)	2	0.1	0.1	1	-	0.1	PCDD/F
Conditions	11% O ₂	11% O ₂	11% O ₂	11% O ₂	11% O ₂	11% O ₂	10% O ₂	11% O ₂	10% CO ₂	11% O ₂	11% O ₂	11% O ₂	Conditions
Temperature		800		850	850	950	800	850		850	850	850	Temperature
Residence time		1		2	2	2	1.5	2		2	2	2	Residence time
Oxygen conc.		6		6	6	6	-	6		6	6	6	Oxygen conc.

Emission levels for waste incineration plants in Europe

Pollutants	Germany 17.BImSchV	Netherlands, BLA (1 hour average)	EU *
mg/nm ³			
Hydrogen chloride	10	10	10 (60)
Hydrogen fluoride	1	1	1 (4)
Sulfur oxides	50	40	50 (200)
Nitrogen oxides	200	70	200 (400)
PCDD/PCDF (ng/m ³ TEQ)	0.1	0,1	0.1 ng/m ³ (6-16 hours)
Dust	10	5	10 (30)
Cd + Hg	0.05 + 0.05	0.05 + 0.05	0.05+0.05
Heavy metals (remainings)	0.5	1	0.5
CO	50	50	50 (daily average)

*) Draft Directive Incineration of Waste, 20.08.94, GH016
daily average values for new plants: > 3 ton/hour
between (): half-hourly average values.

All values are related to 11% O₂ and dry flue gas

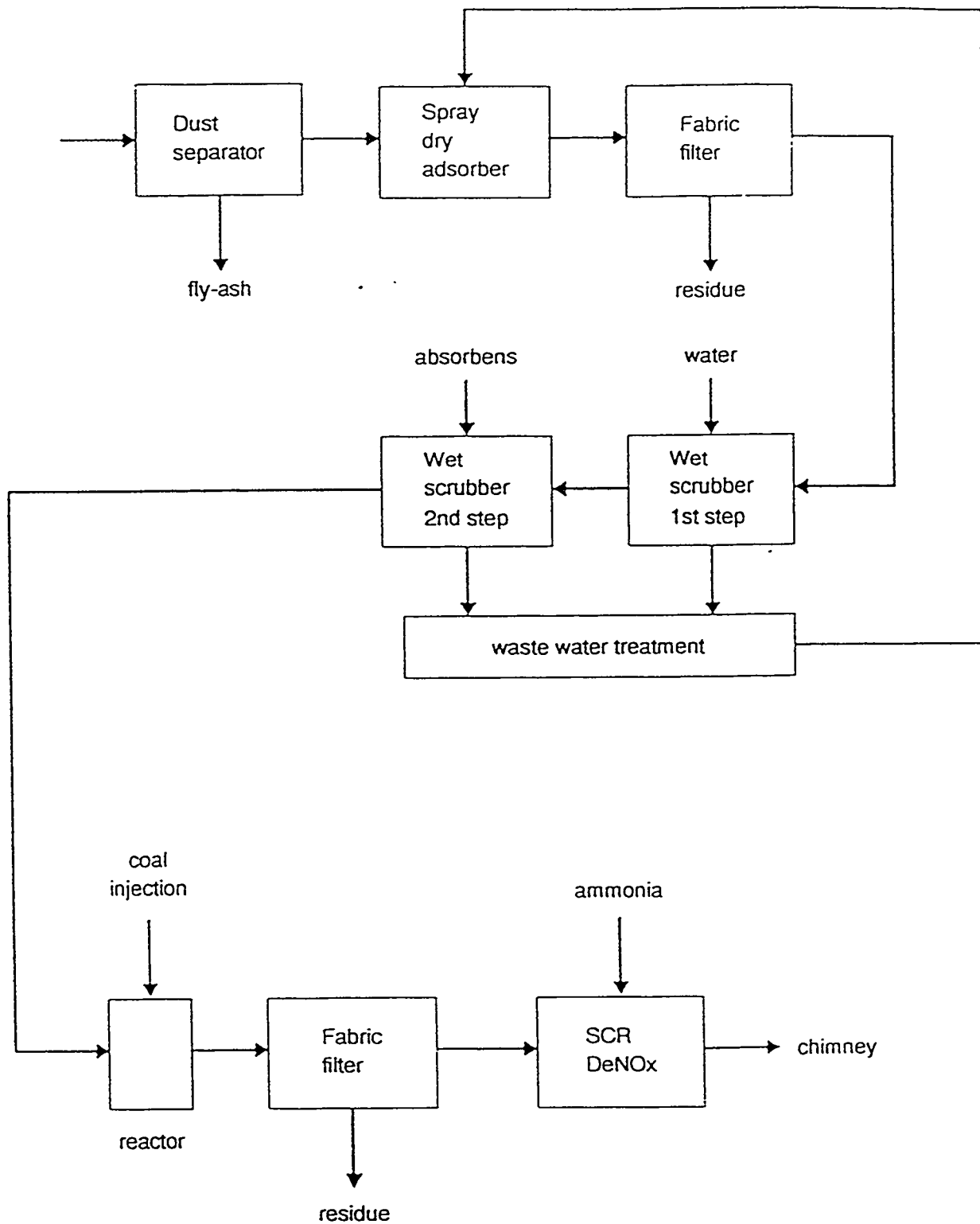
Component	Raw flue gas concentration		Dutch guideline	Removal ¹⁾ efficiency (%)
	minimum	maximum		
Dust	2 000	5 000	5	99,9
HCl	800	3 000	10	99,7
HF	10	100	1	99,0
SOx (as SO ₂)	200	1 500	40	97,3
NOx (as NO ₂)	200	500	70	86
CO	10	50	50	²⁾
TOC (as C)	1	20	10	50 ²⁾
Heavy metals:				
- Hg	0.1	1	0.05	95
- Cd	0.1	0.5	0.05	90
- others	1	5	1	80
PCDD/F (ng TEQ/m ³) ³⁾	1	10	0.1	99

¹⁾ The removal efficiency required to comply the maximum value with the Dutch guideline 'Richtlijn Verbranden 1989'

²⁾ Not taken care of in flue gas cleaning system

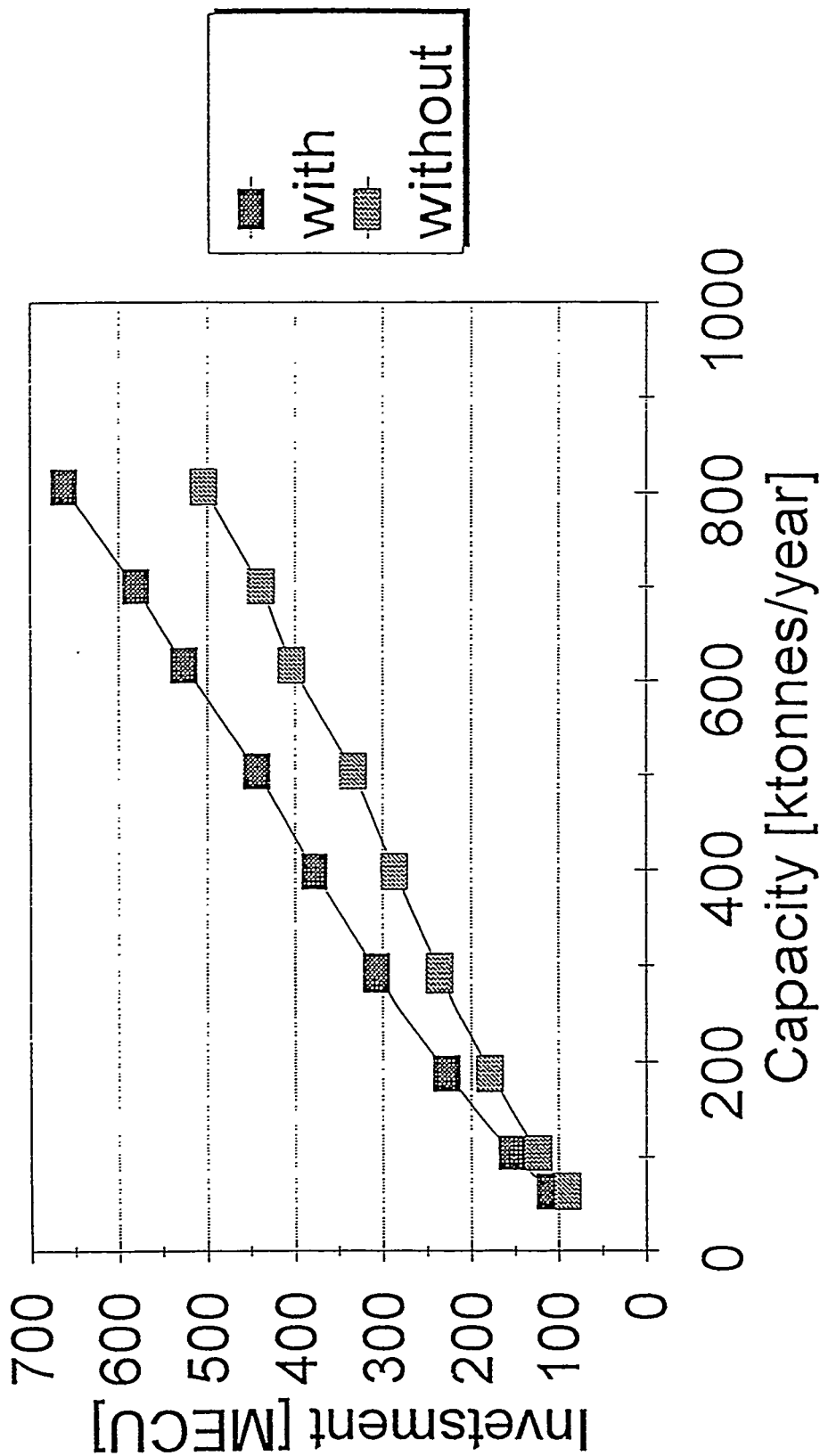
³⁾ TEQ = Toxicity Equivalent Quantity (related to 1,2,7, 8-TCDD)

Graph 10



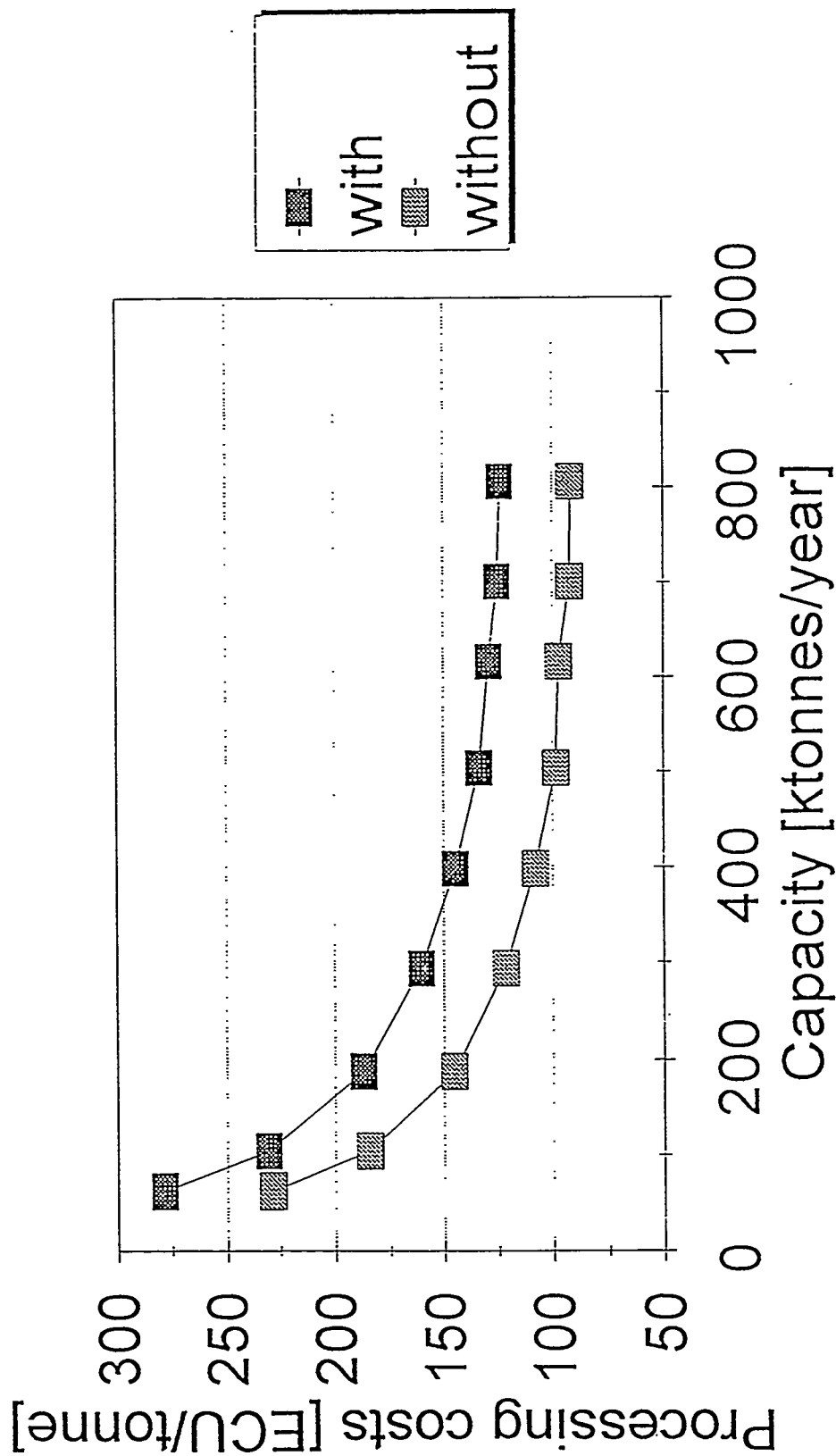
Investment cost new MSWC facility

With/without waste water evaporation



Costs per tonne new MSWC facility

With/without waste water evaporation



The Evolution of WTE Utilization - A Global Look
Asian Perspective - Waste Incineration and It's Value in Japan

Masaru Tanaka
The National Institute of Public Health
6-1 Shirokanedai 4-chome
Minato-ku, Tokyo, 108
Japan

INTRODUCTION

Incineration carries significant weight in waste disposal in general. Seventy-five percent of the total quantity of municipal solid waste is incinerated. In the year 1994, there were a total of 1,854 incineration plants in Japan. Waste heat from MSW incineration is utilized for a power generation at most large-scale incineration plants.

In 1994, a total of 3,376 industrial waste incineration plants existed in Japan. They have been contributing much toward waste volume reduction, improvement of the quality of landfill materials through conversion of organic substances into inorganic substances which are more beneficial for landfill purposes, and conservation of resources by energy recovery.

But air pollution by exhaust substances -- especially dioxin -- from incineration plants pose a problem. This may place a big hurdle before future incineration plant projects. Small batch-type incineration furnaces are slowly dying out. Some municipalities will jointly construct a large incineration plant among themselves while others will consider introducing RDF producing plant, which is getting popular. More efforts will be made to melt and solidify the incineration residue, reduce the environmental load imposed by pollutants in the exhaust gas from now on.

GENERATION OF WASTE

Good health and comfortable life call for various foods, clothes and a house. All these essential items, however, are reduced to waste ultimately. Industrial waste is generated in a manufacturing process and in the distribution stage for a product. Waste is closely related to our health. In actuality, promotion and maintenance of health give rise to municipal solid waste and industrial waste.

Generated waste, if left as it is, gives out a bad odor and results in the breeding of noxious insects, which leads to a public hygiene problem highly detrimental to the human body. Thus presence of waste involves a risk to health. Waste is treated so as to make it into a state less harmful to the human body. Thus its disposal can contribute toward the enhancement of public hygiene and the preservation of the living environment. If it is improperly treated or disposed of, however, the waste or the treatment facility affects the environment with resultant physical harm and risk. Some measure to reduce this risk is therefore demanded. Thus health and waste are in complicated interrelation with each other.

The correlation between health and waste and that between waste disposal and physical risk are shown in Fig. 1. Probably dioxin is arousing the greatest concern now as a very dangerous byproduct of waste treatment. An exhaust gas is generated from incineration or some other intermediate process in a waste disposal system. Hazardous substances in such an exhaust gas are diffused into the air in large quantities, and they deteriorate the environment and adversely affect the human health -- that is, they are a serious threat to the human health. A leachate from a landfill site for incineration ash or the like contains hazardous chemical substances, which pollute underground water and surface water. These substances are taken into the bodies of various living things and condensed and may then be taken into human bodies also.

Breaking this circulation chain threatening human health is absolutely essential. Air pollution is controlled under the Air Pollution Control Law now, and water pollution under the Water Pollution Control Law. Soot, dust, nitrogen oxides, sulfur oxides and hydrogen chloride from waste incineration plants are under statutory control, but dioxin is still exempted from the regulation. Aside from dioxin, cadmium, mercury and some other possibly dangerous heavy metals are not under statutory control in Japan. But they are regulated under a law in some other countries.

WASTE DISPOSAL AND BASIC PRINCIPLE

The basic principle underlying waste disposal is shown in Fig. 2. Generation of waste is controlled at source by households and business enterprises, in which the waste originates. Recyclable components of such waste are separately discharged to facilitate recycling.

Municipalities and waste disposal agents, who dispose of waste, sort out useful components from the collected waste and put them in a recycling route. If recycling is not an appropriate action because of the technical difficulty involved in it, the environmental load, etc., volume reduction by incineration with every effort to take appropriate environment preservation action, and use of the energy derived from the incineration should be promoted. The ultimate residue is subjected to the proper final disposal.

The municipal waste disposal by municipalities and regional governments in Japan was initiated upon the promulgation of the "Dirt Removal Law" in 1990. Infectious diseases were rampant in Japan at that time, and it was therefore an important task to take effective measures against the generation of infectious insects and unsanitary water channels. Attention was directed to waste disposal from the standpoint of public hygiene action.

In 1954, after the end of World War II, the "Public Cleansing Law" was introduced to secure a hygienically sound living environment, followed by the "Waste Disposal and Public Cleansing Law" in 1970. These two constitute the main framework of the present waste management legislation. The "Waste Disposal and Public Cleansing Law" had a widened regulatory coverage extended from municipal solid wastes to "industrial wastes" generated from industrial activities. Thus a complete legislative framework for environment conservation was established.

In the 20 years from the enactment of the original "Waste Disposal and Public Cleansing Law", the Japanese people's life style and economic structure have undergone drastic changes with their economic affluence in the background, with resultant quantitative growth and diversity in nature of wastes. Mass-production and mass-consumption in the human society have resulted in the depletion of forests, mineral resources, etc., the warming of the earth, acid rain, destruction of the ozone layer, sea pollution and other global environment problems. It has been realized that waste management holds the key to "sustainable growth".

Under the circumstances, the "Law for Promotion of Resource Recycling and Reuse" and the new "Waste Disposal and Public Cleansing Law" were enacted in Japan as basic statutory regulations regarding waste disposal and recycling in 1991. The "Law for Promotion of Resource Recycling and Reuse" aims at promoting recycling at the production, distribution, and consumption stages, having resources effectively used, suppressing generation of wastes and conserving environment.

Measures for waste reduction through waste discharge control, promotion of recycling, etc. were incorporated into the revised Waste Disposal and Public Cleansing Law. Furthermore, the Law for Promotion of Separate Collection and Recycling of Packaging Waste was enacted in June, 1995 and put into force in April, 1997.

As shown in Table 1, the earliest actions related to waste disposal were public hygiene measures including those for preventing contagious diseases. A shift was subsequently effected to environment hygiene measures to maintain urban functions and preserve living environment. Today waste disposal is quite significant for the purpose of global environment preservation.

WASTE DISPOSAL AT PRESENT

Disposal of Municipal Solid Waste

Japan is quite densely populated in comparison with other countries of the world, and its industries and population concentrate in cities. In its populous cities, waste generation density is high, but space resources are scarce. The difficulty in acquiring suitable land in such a city for a waste treatment or disposal site has been increasing every year. Pronounced difficulty in its acquisition is encountered in the case of a final disposal site which demands a very large space. In Japan, extra efforts have therefore been made to reduce generated waste by various intermediate treatments. Incineration, a process which can sharply reduce the volume of waste and is hygienic, is extensively adopted. In 1993, 74.3% of the total quantity of waste discharged in that year was directly incinerated, 9.4% was separated and crushed, put in a high-speed composting process or otherwise treated, and 1.9% was processed in some other ways. Thus 85.6% of the discharged waste was subjected to some form of intermediate processing. The

quantity buried at landfill sites was reduced by the promotion of such intermediate processing from 15.3 million tons in 1992 to 14.96 million tons in 1993.

Fig. 3 is a diagram showing the entire disposal flow of a municipal waste. Besides domestic waste collected by the municipal authorities, bulky refuse is also discharged from house holds. In addition, some ordinary business waste from small businesses such as food left-over from restaurants in a town and twigs cut off by gardeners is brought directly to facilities run by the municipal authorities.

According to the results of the Ministry of Health and Welfare's survey in 1991, the quantities of waste disposed of at the municipal facilities throughout Japan add up to approx. 50 million tons. That is, approx. 1 kg of waste is generated per capita per day in Japan. Some waste from households or elsewhere, although it a very slight portion of the aggregate quantity, is subjected to "backyard disposal" - kitchen refuse of a farmer's house used as a fertilizer in his field, combustible waste burnt at a backyard and so on.

Another part of the generated waste is retrieved through a private route such as one provided by a self-governing organ of a local community, as a substance of value instead of being discharged as unwanted stuff for collection by a municipality. This is called "group collection". Various unwanted items in a substantial quantity including old paper, cloth, metal and a glass bottle are retrieved in this way. While 2.2 million tons of waste collected by municipalities were recycled in 1993, 1.9 million tons were picked up by citizens' group collection. Thus a quantity virtually equal to that recycled by municipalities was collected through private-sector routes. The above group collection figure was based on municipalities' statistics, and a substantial additional quantity was presumably collected by resource retrieval agents and others. The voluntary private-sector activities contribute significantly to resource recovery. To encourage such voluntary recycling activities, some municipalities grant a subsidy based on the collected quantity, lend or furnish the tools and others necessary for the recovery activities, provide information for collection agents, made publicity effort directed to residents of the community and perform other actions.

To prolong the service lives of landfill sites, many municipalities incinerate the entire quantity of combustible waste in principle. The rest of the waste is separated into non-combustibles and waste which, if incinerated, may have an evil consequence and is therefore directly buried at a landfill site. Organic waste such as garbage is composted or fed to animals on trial. Composters used at households, a major source of garbage, play an important part in waste reduction. Waste paper, glass, metal, etc. are collected as recyclable items or separated waste. Part of such waste is further screened and recycled at recycling facilities, and bulky waste containing paper, glass, metal, etc. (large-size waste articles such as home electric appliances or furniture) is crushed, and different substances of value are sorted out and retrieved. A typical waste disposal system for minimization of the final-disposal quantity is illustrated in a diagram in Fig. 4 below.

Disposal of Industrial Waste

The industrial waste discharged is divided into three groups for recycling, intermediate treatment and final disposal, as shown in Fig. 5. Of approx. 403 million tons of industrial waste discharged, approx. 250 million tons (62%) were given an intermediate treatment, approx. 92 million tons (23%) were recycled, and approx. 61 million tons (15%) were sent directly to final disposal sites.

The approx. 250 million tons of industrial waste subjected to an intermediate treatment were dissipated to approx. 97 million tons, out of which approx. 69 million tons were recycled and 28 million tons were finally disposed of. Approx. 89 million tons (22% of that total quantity) were finally disposed of.

The ways of industrial waste disposal differ with waste categories, states at the time of discharge, etc. Most of ashes and the like is directly brought to final disposal sites. Items which cannot be recycled finally disposed of or are unsuitable for recycling or final disposal directly in the state in which they are discharged, are given some intermediate treatment. Waste oil, waste acid, waste alkali and other items in liquid state are given treatments such as separation of oil and water or neutralization, etc. Sludge (which is left after treatment of a waste liquid) is put through a dehydration or drying process or the like to reduce its moisture content. Waste oil, waste plastics and other organic industrial waste are incinerated or treated otherwise. Such intermediate treatments turn some industrial waste into dehydrated sludge, incineration residue or the like, reducing the weight or volume.

In April 1992, there are a total of 12,970 facilities for intermediate treatment and final disposal of industrial waste throughout Japan. (That figure, however, is the total number of facilities of stipulated scale or larger scale, in respect of which an official notification is required under Article 15 of the government law. There are supposedly many small facilities free of that obligation to notify.) Of these intermediate treatment and final disposal facilities, 10,440 are operated for intermediate treatment, and 2,530 for final disposal; thus intermediate treatment facilities account for 80% of the total number. The number of incineration plants is 3,376 as indicated in Table 2.

CONCLUSION

Most putrefactive (organic) substances in waste are turned into water and carbon dioxide by incineration and then diffused into the air, and non-putrefactive ash is left. It does not rot and is therefore sanitary. Its weight is only 1/6 of the weight of the original garbage, and its volume is 1/10 to 1/20 of the volume of the original garbage. Waste Disposal methods other than landfill are valued highly in Japan where a landfill site is extremely difficult to acquire. According to an estimate, the utility of a landfill site increases even tenfold to twentyfold if garbage is not directly buried there. Hence incineration is the primary waste disposal method in Japan now. Seventy-five percent of the municipal solid waste discharged throughout the country is incinerated. This is at a very high level as compared with the similar percentages in other countries of the world, and Japan leads the world in incineration technology. Japan's success in neutralizing the biohazard and organic toxicity accomplished by incineration and in reducing the volume is highly evaluated.

A combustion exhaust gas is generated from a waste incineration process. As waste contains a variety of substances, the exhaust gas contains hydrogen chloride and other hazardous gases. Accordingly, an emission standard was established in respect of soot and dust, sulfur oxides, nitrogen oxides and hydrogen chloride under the Air Pollution Control Law. Various pollution preventive means were installed in waste incineration plants throughout Japan to reduce the adverse effect on the environment to meet the specified emission requirements. Many large-scale facilities and many facilities in an urban area adopted a very strict self-imposed standard higher than the emission standard under the Air Pollution Control Law since the operation of such plants may seriously affect the environment and residents.

The purposes of introduction of an incineration plant include the reduction of the waste volume to prolong the service lives of final disposal sites, the conversion of organic substances into inorganic substances for stabilization into a state fit for final disposal and the recovery of energy by utilizing the characteristics of the waste in its original state. The order of priority for these purposes and their relative weight may differ according to the place and the plant operating organization. Many of the municipality officials in charge, however, say that the prolongation of the incineration plant service life is the primary purpose.

The followings are some of the findings and conclusions.

- 1) The available practicable solutions to the waste problem are waste reduction at source, promotion of recycling, volume reduction by intermediate treatment and its proper final disposal.
- 2) Landfilling is an essential way of waste disposal, but it is extremely difficult to acquire the land for a landfill disposal site because of space availability and the concern about the environmental risk involved in such disposal.
- 3) Incineration is valued highly as a beneficial method of reducing the waste volume, stabilizing the substances to be buried and recovering energy.
- 4) Desirable municipal waste management in the future should feature the following:
 - Waste dischargers' best possible waste reduction efforts.
 - Recovery of newspapers, magazines, etc. by group retrieval or through other volunteer activity.

- Municipalities' recovery and recycling of recyclable items such as glass and metal. Crushing of bulky waste and recovery and recycling of metal. Incineration of the rest and combustible waste. Landfill disposal of the other items. In fact, the amount to be disposed of at landfill disposal sites can be minimized by this combination of processes.

5) Waste is composed of various substances, and reduction of the environmental risk from treatment and disposal facilities to zero in a strict sense would be impossible. Hence it is important to take safety ensuring measures with the locations of those facilities, waste inflow control, the seepage control function, the monitoring system, etc. all taken into consideration.

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Table 1. History of waste-related legislation

Year	Purpose	Law
1900	Public hygiene measure	Dirt Removal Law
1954	Living environment preservation	Public Cleansing Law
1970	Domestic environment preservation	Waste Disposal and Public Cleansing Law
1991	Global environment preservation	Revision of the Waste Disposal and Public Cleansing Law Law for Promotion of Resource Recycling and Rence
1995	Global environment preservation (Promotion of recycling of packaging waste)	Law for Promotion of Separate Collection and Recycling of Packaging Waste

Table 2. Numbers of incineration plants (in April, 1994).

	number
Plants for incinerating sludge	514
Plants for incinerating waste oil	522
Plants for incinerating waste plastics	2,122
Industrial waste incineration plants (excluding those mentioned above)	218
Total	3,376

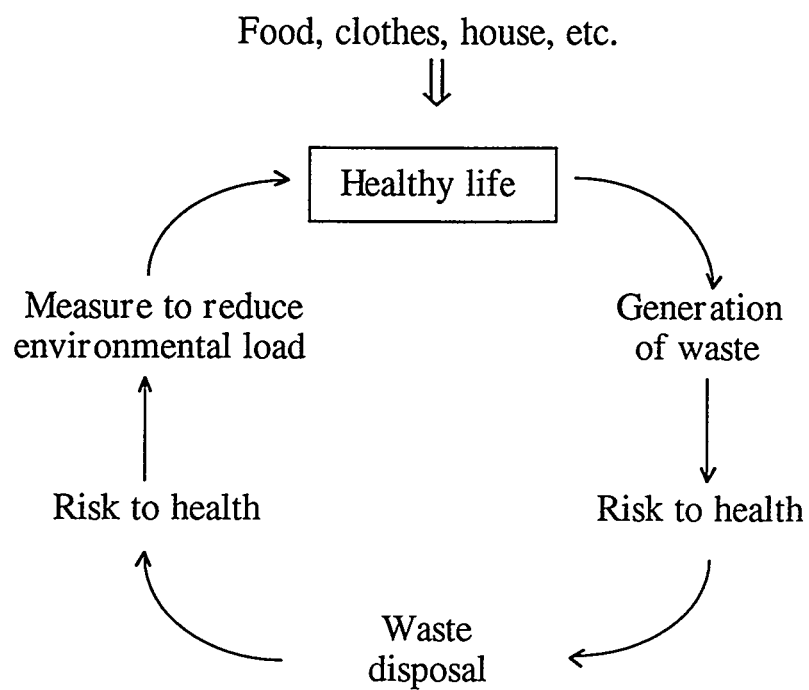


Figure 1. Interrelation Between Health and Waste and Interrelation Between Waste Disposal and Health.

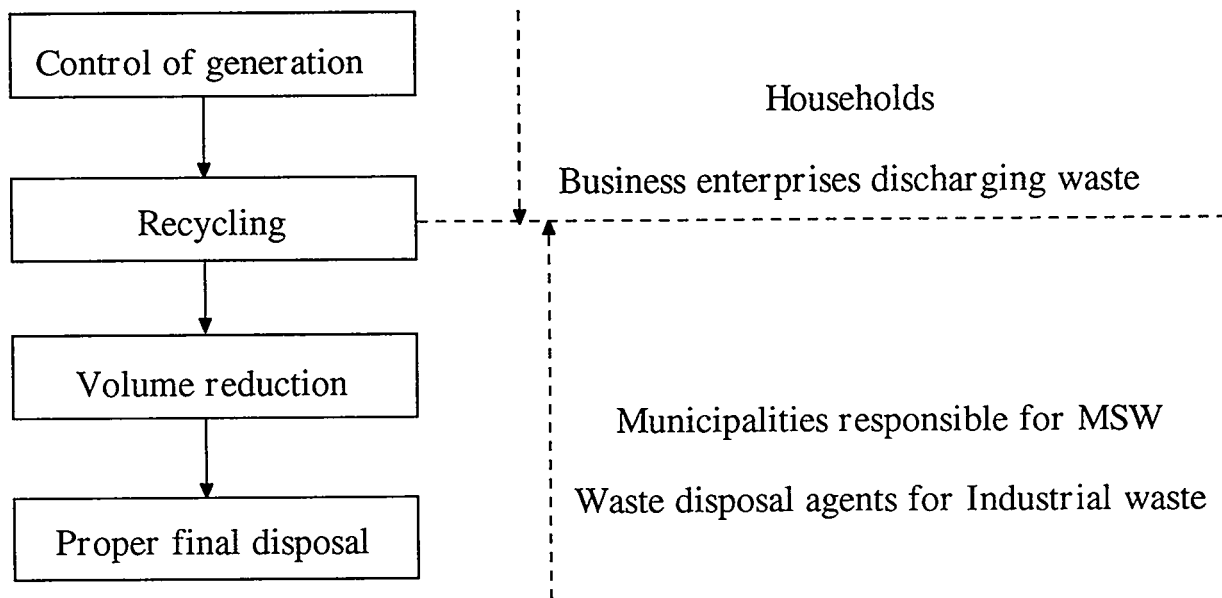


Figure 2. Basic Principle Underlying Waste Disposal.

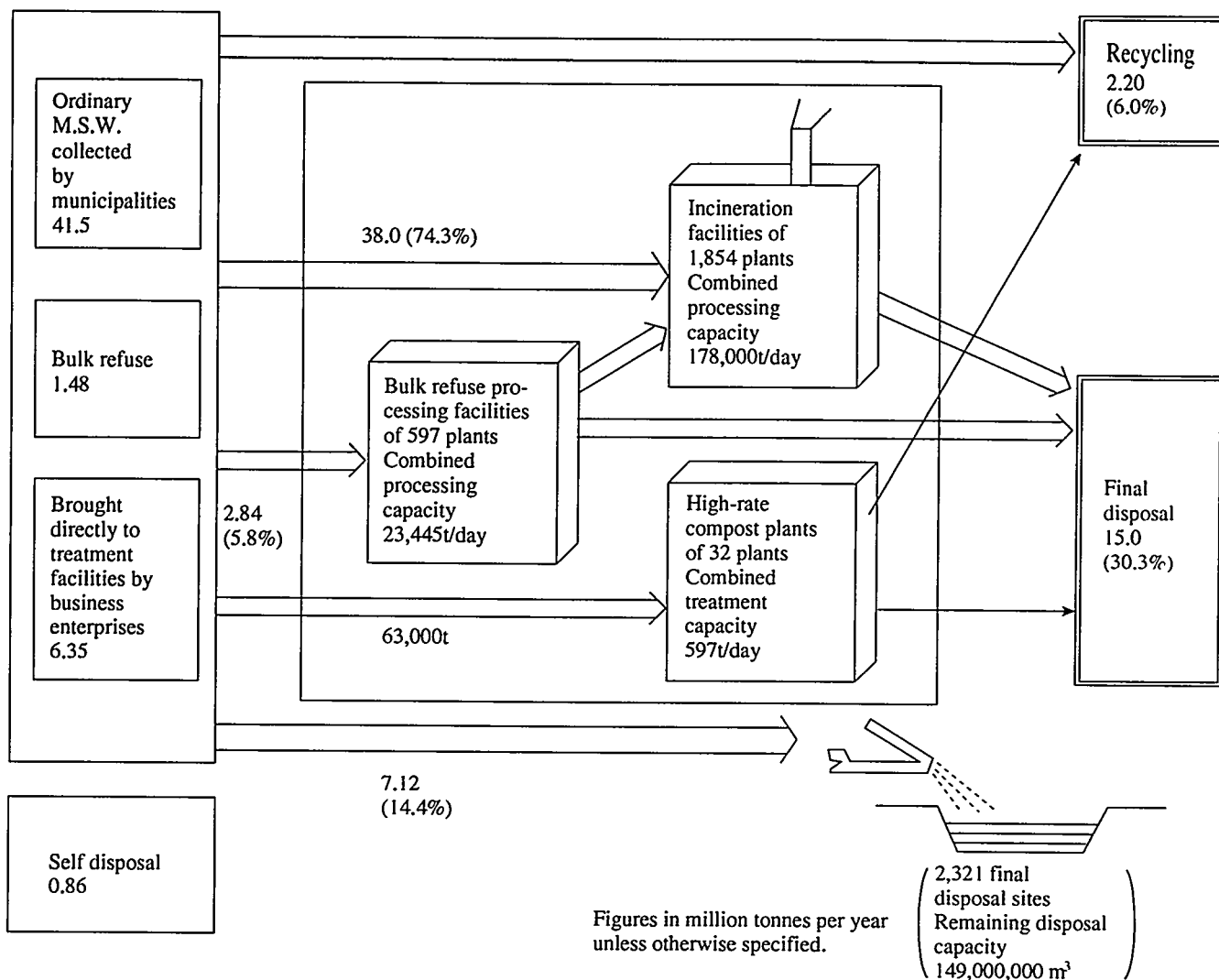


Figure 3. Waste Disposal Flow Diagram (1993).
 Since: "Survey of Waste Disposal" by the Water Supply and Environmental Sanitation
 Department of the Ministry of Health and Welfare Japan.

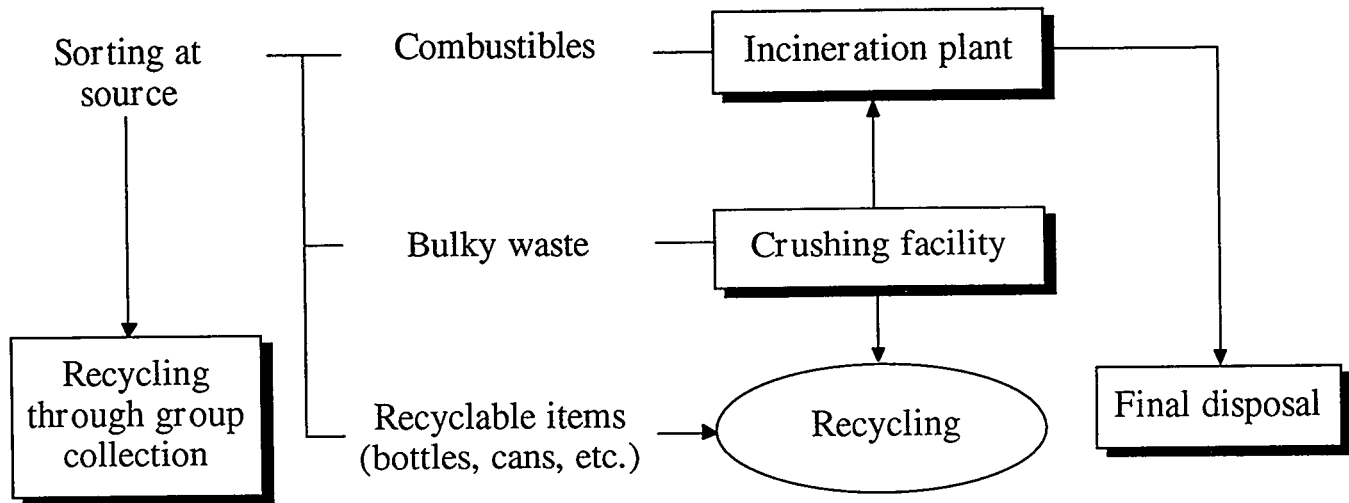


Figure 4. Waste Disposal System for Minimization of Final-disposal Quantity.

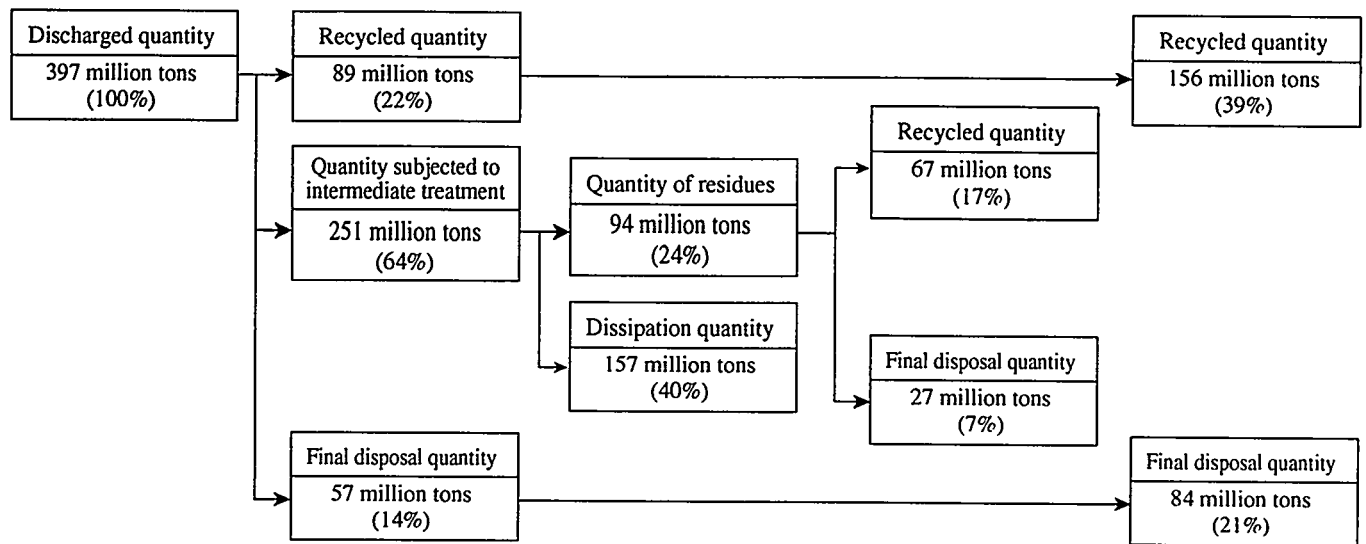


Fig. 5 Industrial Waste Disposal Flow (1993)

Bridging the Information Gap

**Kit Strange
World Resource Foundation
Bridge House
High Street
Tonbridge
Kent TN9 1DP
UK**

INTRODUCTION

Waste management facilities of every type are unpopular for a wide variety of reasons. Waste-to-Energy (WTE) plants, commonly described dismissively as 'burners' or 'incinerators' are the least popular. Yet any technical, informed and objective review of the facts show that the recovery of energy from material which has reached the end of its useful life has a valid role to play in society. The challenge for society is to ensure that WTE achieves its rightful role within a menu of waste management options, in a balanced, integrated and sustainable strategy. In many parts of the world, sophisticated arguments are presented to sceptical, doubtful and often hostile groups of stake-holders. These arguments explain why and how waste should be managed, and although the technical cases are well-rehearsed, proposals are often rejected by potential host communities, who opt instead for an often inferior solution.

This paper reviews the factors that shape public responses to planned developments which they perceive as unwelcome. The conflict between technically excellent arguments and perception-driven hostility is explored, and a tool-box of responses given by way of advice to waste planners and developers.

WTE - CONFUSED OBJECTIVES

Energy recovery is the most controversial of the waste management options. Everyone agrees that waste prevention is the supreme aspiration, and that there should be a reduced dependency on landfill disposal. Voices of dissent are raised when considering whether energy recovery is a valid adjunct to materials recovery and composting, or merely a waste-hungry prelude to disposal. There are sound reasons for recognising that both opinions have a basis in fact. In many countries waste management strategies are developed around just this confused ambiguity. A brief review of the European Union's waste strategy provides useful illustrations of this situation.

Approximately 60 per cent of municipal solid waste (MSW) in Europe fetches up with no prior treatment in landfills of variable quality. Martin¹ reports that landfill leachate pollutes aquifers at an annual rate of 120 km². One of the most significant pressures towards improving landfill operation is aimed at the putrescible fraction of landfilled waste. Composting bio-waste is mandatory in Austria, the Netherlands, several German regions and parts of Belgium. Thirty million Europeans now enjoy selective collection systems for bio-waste. France will introduce a ban on landfilling untreated waste within the next few years. The imminent draft EU landfill directive is set to ban organic wasteprogressively from landfills. Future policy will make pre-treatment of wastes a requirement of landfill. Under the German law, only waste which cannot be recycled may be landfilled. Organic content must not be greater than three or five per cent (depending on the landfill type). It is inevitable that some form of thermal processing will be required for the bulk of German MSW currently landfilled. Here, WTE is regarded as a waste pre-treatment technique.

Renewable energy resources currently provide Europe around 63 million tonnes of oil equivalent (Mtoe) each year, nearly five per cent of primary energy needs. The European Commission's Action Plan for Renewable Energy Sources in Europe was contained in the Madrid Declaration², and set a goal of delivering 15 per cent of Europe's primary energy demand from renewables (including biomass and waste) by 2010. Also relevant to renewable energy is the EU Altener programme, which aims:

- to reduce dependence on imported energy
- to protect the environment by limiting emissions of greenhouse gases

Under Altener, the annual contribution of biomass and waste is set to rise across the EU to 20 terawatt-hours per year (TWhpa) by 2005 (up from 6.3 TWhpa in 1991). This resource will comprise 10.4 per cent of all EU renewables by 2005, and will deliver 0.8 per cent of the Union's primary energy demand by that time. One of Altener's targets is for 7.8 per cent of the Union's primary energy demand to come from renewables, compared to 3.7 per cent in 1991. Here, WTE is viewed as a real contribution to renewable energy, with global environmental benefits.

EU policy and the Framework Waste Directive

Council Directive 75/442/EEC established (in 1975) the basis for a system to co-ordinate waste management in the European Community, to limit arisings. This was later amended by the 1991 Waste Framework Directive. A number of subsequent instruments helped implement these principles,

particularly the 1989 Waste Management Strategy³ and the 1991 Waste Framework Directive⁴. The latter document established the familiar hierarchy:

- prevention and minimisation
- recycling, recovery and re-use
- optimisation of final disposal

The use of waste 'principally as a fuel or other means to generate energy' is considered as a form of recovery.

EU waste strategy review

In July, 1996, the European Commission published a controversial proposal for a review of the EU waste management strategy³ and a draft Council Resolution⁵, which set out the Commission's views on the original strategy. In this review, the Commission adhered to the 1989 hierarchy of prevention, recovery and safe final disposal. However, elaboration in the Review showed a clear preference for materials recycling over energy recovery, making the following points:

- recovery is at the core of any sustainable waste management policy
- material recovery implies separation of wastes at the source
- end-users and consumers should carry out source-separation
- energy strategies relying on waste supplies should not be detrimental to the principles of prevention and material recovery

The review states that "....preference should be given, where environmentally sound, to the recovery of material over energy recovery operations. This general rule is based on the fact that material recovery has a greater effect on waste prevention than energy recovery". The author of the review⁶ confirmed that, as a general rule, "material recycling should be favoured above incineration with energy recovery". This view is broadly shared by Ken Collins MEP, chairman of the European Parliament's environment committee. He expressed the view⁷ that "....where possible it is better to recover materials than energy, because the world's resources are clearly finite". Here, we see a grudging acknowledgement that WTE provides a second-best resource conservation option.

Finally there are intriguing reports⁸ that the European Commission's environment directorate plans to classify incineration with energy recovery as a disposal option under EU law. This apparently comes in response to pressure from some Member States anxious to ban trans-frontier shipments of waste for energy recovery. Re-defining this activity as a disposal operation would allow such bans. This does not seem to be due to an aversion to incineration. The Danish government is reportedly embarrassed by the flow of MSW imports arriving from Germany for incineration. Denmark seems concerned that these imports will consume the capacity needed for its own MSW. In Germany, a shortage of waste for installed plants is seen as the reason why two regions have blocked exports of wastes that the Belgian and French cement industries want for fuel. Here, WTE becomes a strategic economic policy tool.

This quick tour shows a certain schizophrenic approach to WTE as a waste management tool. It is seen by some policy-makers as a means to an end, although the end might be diversion of waste from landfill, it might be pre-treatment of organic wastes prior to landfill, and it might be as a source of renewable or alternative energy displacing fossil fuel consumption. If waste strategists cannot decide whether WTE is really a form of resource recovery or a disposal option, one might sympathise with a concerned member of the public in a community faced with hosting a new WTE facility.

There are encouraging signs that once entrenched positions on the 'matter vs. energy' debate are giving way to a more balanced search for the real goal of sustainable waste management - the best practicable environmental option for all waste streams. The UK National Recycling Forum is part way through its own policy wrangles in this area. The Recycling Council of Ontario has also explored this route, approving a new policy towards incineration⁹. The Recycling Council of Ontario believes that energy from waste, fuel substitution and incineration should be considered on a case-by-case basis only if:

- It is clearly demonstrated that reduction, re-use and recycling initiatives are maximised
- Any technique used to handle remaining residual materials is of net benefit to the environment and economically sound

- Energy from waste or fuel substitution initiatives meet or exceed stringently enforced environmental performance standards
- Incineration of solid non-hazardous waste includes energy recovery

This review was at least partly provoked by the decision of the incoming Ontarian Progressive Conservative government to repeal the ban on any new energy from waste incinerators.

The real dilemma will lie not in relative positions or fractions of the waste stream, but in absolute tonnage routed one way or another. The competition will be for tonnes of recyclables or fuel, not for percentage points. Project scale will be the most important issue to resolve, managing the trade-offs between economies of scale and available material. The social dimension, i.e. public attitudes towards waste management alternatives, is likely to become increasingly important.

There are several alternatives to conventional MSW combustion being explored around the world. Although public acceptability is not the main driver, there can be little doubt that any incidental increment in popular support will be a welcome benefit. In the Netherlands¹⁰, work is underway to develop co-combustion systems for a range of waste streams in coal-fired power stations. Wood waste, sewage sludge and refuse-derived fuel (RDF) are promising options. Integrating waste management facilities, but leading with the materials recovery option¹¹ has been successful in Britain. In Japan, the Toyohashi plant¹² blends waste incineration, with sewage treatment and a composting plant, producing electricity, hot water and steam. German packaging waste recovery policy has shifted to allow combustible packaging to be converted to gas which is permitted to be burned. Plastic packaging can be added to steel furnaces, where it serves as a reducing agent, in a material sense rather than simply as a source of energy. In Thailand¹³ a \$US70 million WTE plant is being built to burn MSW and lignite, generating 20 MW of electricity.

PUBLIC PERCEPTION

If given a choice, people tend to prefer things as they used to be (or seemed to be) than they are now. They also tend to prefer things as they are now, rather than risk something worse in future. The nature of the environmental problems are complex and far from understood. Public perceptions of these issues are sometimes clouded and communication processes often imperfect. The public are now bombarded, and confused, with information and opinions that often conflict. As a result they lose confidence and withdraw the trust that they once placed in the hands of the experts and decision-makers. This leads to a breakdown in communication and Not In My Back Yard (NIMBY) reactions become almost inevitable. However, because the issues are complex, the public may lack the expertise to endorse decisions themselves, becoming increasingly dependent upon views of experts. Given this dilemma, and a lack of confidence in establishment-based experts, groups claiming to represent the public interest take a more active role, demanding more information, more communication and involvement in decisions.

The public receives information from many sources, which frequently conflict with one another. All of these elements play a role in shaping our perception of reality (see figure 1). It is hardly surprising when pollster Robert Worcester¹⁴ claims that "[the public] tell us that they are sceptical of politicians and journalists. Industry's and the government's scientists are little more believed than are business leaders and senior civil servants and their ministers. The public don't know whom to trust".

Perception and trust

Gaskell¹⁵ observes that "to have trust in someone is to anticipate the future, to behave as if the future were certain. Trust gives us confidence to make choices in an increasingly complex world, without it we are condemned to anxiety and inaction". Loss of trust triggers a switch from passive to active (see figure 2), the sceptical view is no longer acceptable and a search is initiated to alleviate uncertainty by the public themselves. Studies in more than twenty countries show that Green Activism is growing¹⁶. Loss of trust and increased activism create a demand for better communication to disseminate information and public participation to rebuild trust. However, mis-trust and activism are by no means universal. It is understandable that there are communication problems when raising awareness of global concerns given

the fact that experts themselves can rarely reach agreement. Locally, however, where there is greater scope for data acquisition and understanding, this is less of an excuse, and problems of distrust and NIMBY reactions here are the result of a breakdown in communication between the general public and the experts upon whom they rely.

The need for openness

The British Royal Commission on Environmental Pollution reported on its detailed investigation into waste incineration¹⁷. One of the areas it investigated was that of public concern, finding that "relations between the plant operator and the community are also important in explaining differences in the level of concern". The Royal Commission recommended that the "waste management industry should adopt a policy of openness in providing information to the public". A key section of the Royal Commission's report notes that "Before the public will accept a large incineration plan, whether existing or proposed, the site operator will have to earn their trust and establish his credibility as a source of accurate and impartial information". The UK Government replied formally to the Royal Commission, observing that "Openness by the waste management industry may well lead to improvements in the public perception of waste disposal". The apparent view that industry should shoulder the burden of persuading the public that energy recovery was a fine waste management option was modified somewhat in the UK national waste strategy¹⁸, when the Government set out a target for overall recovery - including energy. This obliged the policy-makers themselves to help deliver the policy.

MAKING COMMUNICATION EFFECTIVE

Petts¹⁹ has identified four areas where the communication process is beset by problems:

- Message Problems: e.g. deficiencies in knowledge and scientific understanding; large uncertainties in risk estimation; highly technical language.
- Source Problems: e.g. disagreements between experts; resource limitations which prevent reduction of uncertainty; use of technical legalistic language leading to a lack of trust and credibility in experts; limited understanding of the interest, concerns, and preferences of different communities.
- Channel Problems: e.g. biased media reporting; premature disclosure of information; inaccuracies in interpretation of information, one-way information flows; over simplifications, distortions, inaccuracies in technical information.
- Receiver Problems: e.g. lack of interest; inaccurate perceptions; unrealistic expectations about the effectiveness of regulatory action; reluctance to make trade-offs between risks and costs; difficulties in dealing with probabilistic information; suspicions of industry's motives.

So how can communication be improved, to improve public perceptions and rebuild trust? Furnham²⁰ recommends four actions for dealing with the general public:

- Acknowledge that there is a risk of pollution, accidents etc.
- Explain the preventative action being taken, and any plans to cope with outcome of any problems or disasters.
- Stress that perfection is unrealistic and that a process of improvement is a more important and practical way forward.
- Build trust.

Likewise, Gaskell¹⁵ suggests six points for cultivating a reputation:

- Technical competence is crucial, don't deny the risks, because few will believe it is risk-free.
- Acknowledgement - admit mistakes of the past, respond to crises quickly and effectively.
- Disclosure - be more forthcoming about who you are and what you stand for.
- Accountability - articulate areas of responsibility.
- Take on the wider responsibilities and obligations reflecting the concerns of society.

These represent only one side of the communication process. It should be remembered that communication is a two-way process. This is highlighted by Petts¹⁹ in the first of five ways forward for risk communication:

- Risk communication must be a two-way process: a process of bargaining. Statutory authorities, industry and the public must expect to learn and be prepared to change views.

- Risk communication which is perceived as simply risk education is unlikely to be effective, because it will almost certainly fail to address the main concerns of the public and information requirements of decision-makers
- Risk communication is an ongoing process; it is not simply a specific assessment in response to questions on a specific planning application.
- Quantified risk assessment is becoming an essential element of siting decisions where risk is a dominant factor or is perceived by the public to be a dominant factor. Subjective discussion of 'small', 'low', 'insignificant' etc. risks is no longer acceptable.
- Risk acceptability is location and time dependent. Risk communicators must understand the specific concerns for specific siting decisions.

It is clear that communication is a process of participation in a debate in which both sides learn from one another, and as a result shift to some common ground. It is clear that this participation must be with the specific local community that is likely to be affected by any decisions made.

The experience of the German Federal Environment Agency in this respect has been summarised by Johnke²¹ as follows:

- In projects involving public participation, the climate in which discussions are held needs to be improved. Proponents and opponents must take each other's arguments seriously
- The data on which technical proposals are based should be disclosed at an early stage
- The fact that the situation will worsen for affected residents must be acknowledged and compensation granted if at all possible
- Decentralised solutions should be preferred; burdens must be distributed evenly within the region concerned
- Ecologically committed groups must be involved in the planning and try to accommodate opposing views
- Pollution levels must be compared and considered in relative terms. For example, waste incinerators are able to comply today with dioxin emission levels that are ten times lower than the value applicable for the open burning of wood. If the waste-related emission limits applied to wood, it would have to be shipped to an incinerator for combustion!
- The relative environmental burdens should be demonstrated in greater detail.

Public Participation

A 'ladder of participation' (see figure 3) has been widely adopted and used in the design and consideration of the public participation programmes. Described by Petts¹⁹, "This ladder commences at the bottom with the primarily 'manipulative' methods of the public relations exercise, and with steps up the ladder of informing, consulting, placating, forming a partnership, and finally (at the top) delegating powers to the public for both decisions and implementation. In the USA, Kiser et al²² indicate that "communities are involving citizens in the decision-making process regarding WTE projects in their communities. This public role frequently includes more than one mechanism for gathering input from citizens, and often includes formation of a citizens advisory group".

Paradoxically perhaps, public participation can slow the pace of change. Lanny Hickman²³, formerly CEO of the Solid Waste Association of North America reports that no new WTE facility has been developed in America for a number of years, primarily due to public resistance. Hickman notes that developments by industry, for example of transfer stations and material recovery facilities, are more likely to succeed than municipal initiatives, because industry has less onerous duties for public consultation. He compares discreet, innocuous municipally-owned local transfer stations which are strongly resisted, with private sector 'megafills' taking 5,000 tonnes per day for landfill disposal which may receive consent without difficulty. Hickman adds that the concept of Host Community Fees can deliver locally negotiated revenue that exceeds local tax income.

Kiser et al²² present evidence of success explaining that "citizens who are involved say the majority of people served by modern WTE operations in the US consider the facilities to be good neighbours, based on satisfactory operation and the benefits these facilities provide to their communities". The authors conclude that "the favourable reaction to WTE plants should give other community leaders the confidence to consider integrated waste management systems of their own that include WTE".

Similar groups to those in the USA are evolving in Britain, as Lisney²⁴ reports on the development of community advisory forums for debating the waste management strategy for the English county of Hampshire: "These forums comprise representatives of parish councils, community environmental groups, interest groups, local residents, business and health sectors" "The quality of debate was of an extremely high standard. It did not take very long for members to get up to speed in terms of the problem and the options for solution. This approach has been successful in some WTE projects. Lisney concludes by stressing "the importance of involving the key stake-holders in debates which have local importance, and to do so in an open and forthright way". The complex relationships between partners in consultation is illustrated in figure 4.

Willingness to embrace a public debate was instrumental in the success of Britain's most recent WTE facility - the SELCHP plant. Planned for south-east London within 200 metres of many local residents, the developers appreciated from the outset that public confidence would be a critical factor. SELCHP's managing director declared "...during a long planning and public consultation process we achieved a high level of public confidence". Throughout construction, developers kept in touch with their neighbours - directly through mail and local newspapers, and indirectly through meetings with an Incinerator Monitoring Group. A representative of this group was able to attend SELCHP board meetings, to hear of progress and register local concerns. Recognition of specific controversial issues is very important and SELCHP soon identified that the emission stack (with a height of 100 metres) would become a significant feature on the sky-line. The company undertook local public exhibitions of alternative designs, asking residents to vote for their preferred design.

Public participation and LA21

Currently, the most significant action being taken with regard to sustainable development, which includes waste management issues, stems from the 1992 Earth Summit held in Rio de Janeiro. The Summit adopted Agenda 21, a comprehensive action plan for the pursuit of sustainable development into the next century, with 40 chapters of detailed recommendations addressed to international agencies, national and local governments and NGOs. Some two-thirds of Agenda 21 applies to the local level, and consequently needs the active participation of local authorities.

As local authorities develop Local Agenda 21 (LA21) strategies, community participation should improve public perceptions and rebuild some of the trust lost in recent years. With public involvement in the LA21 process local authorities are in a position to raise awareness and improve perceptions. Worthington and Patton²⁵ found little agreement on which departments within local authorities should be responsible for the initiative, only half had developed formal means of co-ordinating the process, there had been minimal contacts with local environmental and business groups. Municipalities experiencing successful public participation made the following suggestions:

- Local authorities should nominate a key individual responsible for LA21 matters;
- Across-functional body should be established to transcend formal functional lines of responsibility within the municipality;
- An environmental forum should be established, to provide a focal point for all interested groups;
- Public awareness should be raised by a variety of means;
- Central government should be lobbied for direct (financial) support.

It is unlikely that there will be a return to the former dependency on experts by the general public. However, although it has been seen that the public do have an ability to deal with specialist areas, they are not in a position to collect, analyse and evaluate the large amounts of data needed to understand the environment. They will still depend on experts for this function. Any uncertainties generated through the imperfect communication between expert and public could be minimised through partnership.

Industry and participation

Understanding people's psychology and their behaviour is an important facet of business. Industry has recognised the importance of environmental awareness and the concerns that are expressed by the public about the effect of the activities of industry on the environment. As Elkington et al²⁶ have written "Big business has discovered that it cannot work effectively within a society that does not like its methods and refuses to buy its products". However, waste contractors will need to change their attitude, for as Petts²⁷ found in an assessment of a Community Involvement Programme, "The one group not fully

involved in the first phase of community consultation was the waste contractors themselves. While representatives of some contractors attended meetings, it is known that contractors in general have a poor appreciation of the importance, and methods, of communication and seem often to regard public concern as irrational and communication to be merely an 'education' exercise.

Environmentalism and participation

The 'Green Movement' is far from uncriticised. As seen earlier, environmental doom-mongers have developed low levels of trust due to their apparent failures in the light of their acquired expertise. Indeed all environmental groups are involved in public relations as are business and industry. These groups claim to be the 'voice of the environment', driven by environmental ethics. They are subject to the same communication problems that affect businesses, or other organisations out to promote their interests.

Facilitating Participation

Some people appear to need further encouragement to participate in decision-making activities. There are many reasons why people may not participate, including four outlined by Petts and Eduljee²⁸:

- They may feel adequately represented by others;
- They may not feel that the impacts justify participation;
- They may be unaware that they might be affected;
- They may feel powerless to influence the decision.

Petts and Eduljee go on to state that "Whether or not they participate, will be a reflection of the information available to them. Furthermore, by not providing them with adequate information to allow them to decide on an informed basis whether or not to participate, there is potential for decision making by small 'elites'."

To some extent the success of a public participation campaign can only be judged upon the implementation of any plan derived from the consultation programme, which may take years. However, there are criteria that can be used not only for assessing a community involvement programme but also for its design, such as those used by Petts²⁷:

- Representativeness of the participants.
- Effectiveness of the method.
- Compatibility with the objectives of the participants.
- Degree of awareness and knowledge achieved.
- Impact of the participation programme.

Techniques for participation

These groups and forums are only part of a number of approaches and techniques for public involvement. Petts and Eduljee²⁸ have outlined some of the approaches and techniques put forward in The Canadian Federal Environmental Assessment Review Office's (FEARO) manual on public involvement in Environmental Assessment, which includes descriptions on over 50 different techniques.

Public perceptions of the validity, or value, of information provided, can only be improved by a combination of accurate information provision and involvement in sustainable development. Achieving balanced dialogue will allow perceptions to evolve on both sides and return some confidence that those perceptions depict reality. This will reveal a wider picture to all: the size of problems will be more lucid and solutions more apparent.

Effective communications with WTE projects

Planning any communications strategy requires a clear definition of:

- The audience groups
- The messages to be communicated
- The appropriate media to be used

Audience Groups

The public. Many developers of waste management facilities will often attempt to communicate directly with the public. Usually, these are the nearest neighbours to a proposed development and contact is

through local public meetings, village hall exhibitions, house-to-house leaflet drops and by means of advertisements or editorial coverage in local newspapers.

Public interest groups. Local groups who claim to speak for and represent the public are often quick to rise to what they perceive is a threat to their territory. These groups are often far more enthusiastic to enjoin a debate than the public itself. Early attention should be given to identifying those bodies with a direct interest in local amenity development, environmental, archaeological or other interests. Addressing direct interest groups is an obvious approach to take, but there is also merit in considering a diverse range of less immediately relevant sectors. Having no specific 'axe to grind', these groups can give added buoyancy to support for a proposition. For example, the American League of Woman Voters²⁹ has published a document endorsing the combustion of waste plastics for electricity generation, in conjunction with other waste management techniques. The book states "it does not help the environment to expend large amounts of labour and money to 'over-recycle' inexpensive and benign materials like plastics". This type of 'third party endorsement' can be very supportive.

Industry. Potential supporters of WTE systems can come from unrelated sectors of industry. This has been widely seen in the packaging and other sectors, coming under increasing duties of 'Producer Responsibility', an obligation for their products beyond the point of sale. Many of these sectors are forced to take an interest in the economic and environmental impact of their products, and often advocate a mixed array of recovery options, including WTE.

Government bodies. Many national governments have prepared national waste strategies. The British national strategy¹⁸ was published in January 1996, and set out a clear commitment to support increased WTE systems. Such a commitment needs action if they are to be anything more than posturing. Only at the national level can regulatory or economic incentives be put in place. The UK has seen the introduction of the tax on any solid wastes going to landfill, which is altering the current balance between landfill and WTE. The UK national waste strategy also includes broad resource recovery targets and advice to local authorities and others. The British government has also operated the Non Fossil Fuel Obligation for several years, levying a charge on the generation of electricity from fossil fuels, which then subsidises selected WTE projects.

Municipalities. Local government is in many ways at the focal point of public debate, and has a crucial role in shaping public perceptions. Local government is, by definition, local. It knows the issues that are important. It is also democratically accountable and must strive to reflect and shape public opinion. In waste management terms, municipalities are often charged with responsibility for many links in the chain. Waste collection, regulation, disposal and planning are duties that may rest with different parts of local government. A fine example of progress here has been demonstrated in Brescia, Italy³⁰. In 1992, the town held a series of presentations between the local authority and a technical and scientific committee formed from members of local government and the public. Decisions relating to the project required unanimity before action. Community meetings, press coverage, exchanges of correspondence and a second international conference "Towards New Environmental Solidarity" crowned a successful public consultation process, following which planning consent was granted to develop a 266,000 tonnes/year WTE plant, to start operation in 1997.

Journalists. The media is an important audience, in an indirect way because journalists provide a conduit for information to the above audience groups. Public perception and ultimate fate of many projects may be influenced profoundly by the capricious whims of the media. Local newspapers often become one of the most active spheres of local heated debate on particular topics. Experience in Hamm, Germany³¹ has shown the benefits of favourable media support. This, coupled with annual open days, has contributed to the WTE plant being totally acceptable to the host community.

Familiarity breeds content

The secret to successful WTE project development is likely to rest in its chosen location. There is clear evidence that proposals to develop a new facility on a new 'greenfield' site is far more likely to encounter delays or cancellations, than a project on a site already used for the same purpose. In Britain, proposals to build a new large incinerator near London (Belvedere) continue to be plagued by delays, while an existing unit in London (Edmonton) received planning permission to effectively double its capacity without a murmur. At Tyseley in Birmingham, UK construction of a £95 million WTE plant taking

350,000 tonnes/year is now complete. The planning application was submitted in November 1993 and was approved at its first hearing, with consent granted in February 1994. The unit's managing director declared "There has been very little adverse local reaction to the proposal because we made residents aware of what was involved well in advance of the work starting on site". He added that "...there has been an incinerator there since 1926, so people know what to expect". The main source of complaint came from the local Friends of the Earth representative, who opposed the project as a concept, questioning the justification of the planned scale, its economics and whether there would be sufficient waste to fuel the unit. The project team embarked on a 'consultation and awareness campaign' making 'contact with residents' groups, environmental organisations and other interested parties. Press releases were issued, and press and radio interviews conducted".³²

It is clear that replacing an old unit with a modern state-of-the-art WTE facility is almost certain to be applauded as an improvement, whatever one's feelings about energy recovery in principle.

Messages to be communicated

Acceptance for new projects depends heavily upon public participation in the process of decision-making. It is likely that support for a new WTE scheme will be shaped by the following vectors:

- The level of public involvement in the debate itself
- The degree to which this is seen as a local solution to a local problem
- The extent to which WTE reinforces and does not jeopardise those waste-related activities which the public supports (prevention, re-use, composting and recycling)
- The level of environmental and amenity concern shown by developers
- The presence of any perceived benefits of the proposed facility
- The absence of any perceived dis-benefits, or stigma arising from the project
- The demonstrated public support for the project of independent groups (local government, media, environmental groups).

It follows that the ideal messages to be communicated are those which rigorously establish, defend and reinforce the above vectors.

CONCLUSIONS

It is clear that public acceptance is essential for any developer - industrial or municipal - of a proposed WTE facility. Private individuals have reasonably high expectations of the quality of their lives, socially, economically and environmentally. They are unlikely nowadays to accept without question the opinions of 'experts', on allegedly necessary developments within their communities. The complexity of associated issues as probabilistic risk assessment, sophisticated technologies remote from everyday life, and high profile disagreements between opposing experts erode still further a feeling of public trust and confidence in something which is new, different and remote.

Bridging the gap between public perception of a hostile and perhaps dangerous proposal that brings no direct or personal or immediate benefit, and the necessary development of waste management facilities, falls on the other stakeholders in society. Developers - whether in the private or public sector - have a prime duty to build the trust necessary to achieve or restore public acceptance. Developers must be open, and must be seen to be open. Their communications with the host community must be active, effective and planned. While there are many means of communication open to developers, there can be no doubt that the most effective route will rest in demonstrating a partnership between industry and the community it serves. A proposed WTE unit should be appreciated as part of a wider, but still essentially local solution - and not simply as a site-specific problem.

Local Agenda 21 initiatives provide a valid model for community-based co-operation, and also offer a suitable vehicle relevant to implementing neighbourhood and regional sustainable waste management plans. As part of the route towards global sustainable development, local authorities have a key role to drive forward a productive debate between the public, industry, environmental groups and others, on the way society plans to move into the next century. Securing a really constructive debate is difficult, but experience shows that the municipalities are critical agents in any successful initiatives. Local authorities should work to stimulate LA21 planning through the creation of a high profile, cross-functional body, an environmental forum for interested groups in a continuing exercise to exchange

views and reach agreement. The debates within this type of forum should preferably precede any site-specific discussions, to establish in principle the way that a community believes progress should be made. This will help alleviate the inevitable NIMBY reaction when site-specific details are considered. In this context, national government has a duty to ensure that a broader framework is established. Local authorities should be involved, not simply as a planning authority. The local authority's own waste collection or disposal function will be in partnership with any private sector interest. The fact that the plant addresses the community's own waste arisings shows that the plant is part of a solution, not part of a problem. Local government should not adopt the attitude of impartial observer while industry battles with a community, but should strive to help the community or region address its own waste management issues.

A prospective WTE plant should ideally be planned to replace an older unit. It should be technically and environmentally of higher performance and greater efficiency, offering indirect benefits - for example demonstrating improved materials recovery and less waste to final landfill disposal. It can therefore be seen to be a better replacement, delivering a clear net benefit.

Effective dialogue calls for technical competence on the part of developers and decision-makers, of course. There must also be a willingness to explain the information - some of which will be highly technical - to the wider public. Proponents must listen to views expressed by the groups to whom they speak, and they must be seen to react to views expressed. Hostility will be far greater if a new WTE unit is proposed on a greenfield site. It is crucial that the site is acknowledged to be an integrated part of a planned system, pursuing environmentally sound objectives to the highest standards. Dis-benefits should be honestly recognised, and some form of local compensation addressed. It will be of paramount importance that developers are seen to be open from the outset. Developers also need to recognise that the public will be there for the lifetime of the plant, and beyond. Promises must be kept and dialogue should continue. A successful WTE facility will be one that becomes a part of the community that it serves. The relationship between the public and the operators (who may not be the developers) will be shaped by events at an early stage.

Increased pressure on landfill disposal will mean higher costs of this option. Tighter environmental controls on what may be landfilled will further increase costs, closing the gap between disposal and alternative management techniques. Greater enthusiasm at the international policy level for the application of Producer Responsibility, and for waste reduction (or landfill diversion) targets will tighten this stranglehold. Landfill bans on organics, mean that composting and anaerobic digestion will not suffice. Supplementary treatment will be more attractive. Higher materials recovery and recycling targets will require improved source separation for its cleaner secondary material streams. This will be assisted by isolating non-combustible recyclables and wet organics, which will deliver a higher energy content residue (better suited to energy recovery).

There is good cause to hope that structural limitations, economics, modest targets and waste composition will combine to ensure that materials and energy recovery will be complementary options. Scaling and siting of waste management facilities in the short to medium term will be the most important and difficult decisions. In the longer term, sustainable waste management can only be approached through changed public attitudes and adoption of waste minimisation targets through better design and clean technology.

With traditionally pro-incineration groups calling for a balanced, integrated approach to waste management, and with recycling-oriented bodies re-visiting established policies on energy recovery, the signs of rapprochement are very encouraging.

It is up to governments, local authorities, industry, pressure groups and consumers to ensure that we do not squander this opportunity.

Figure 1

Shaping Public Perception

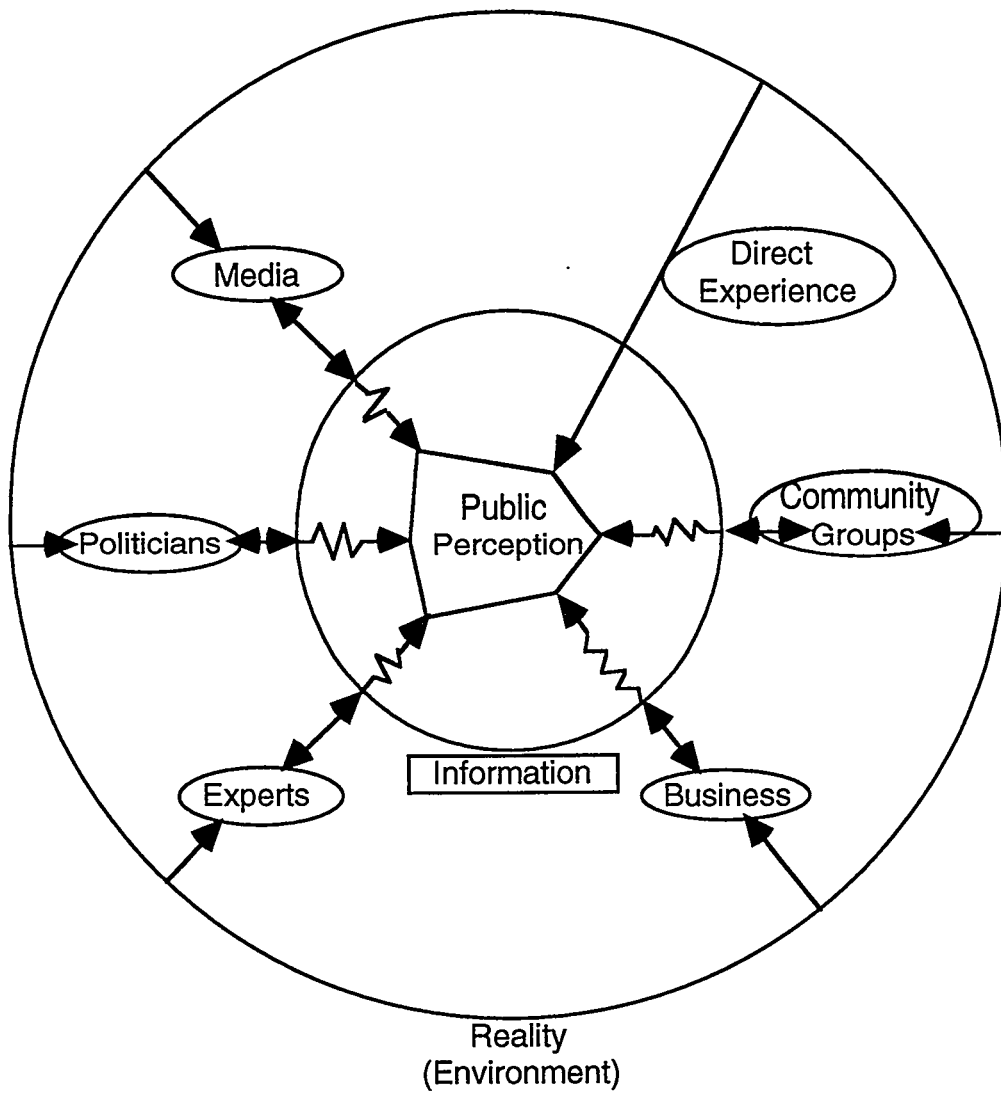


Figure 2.

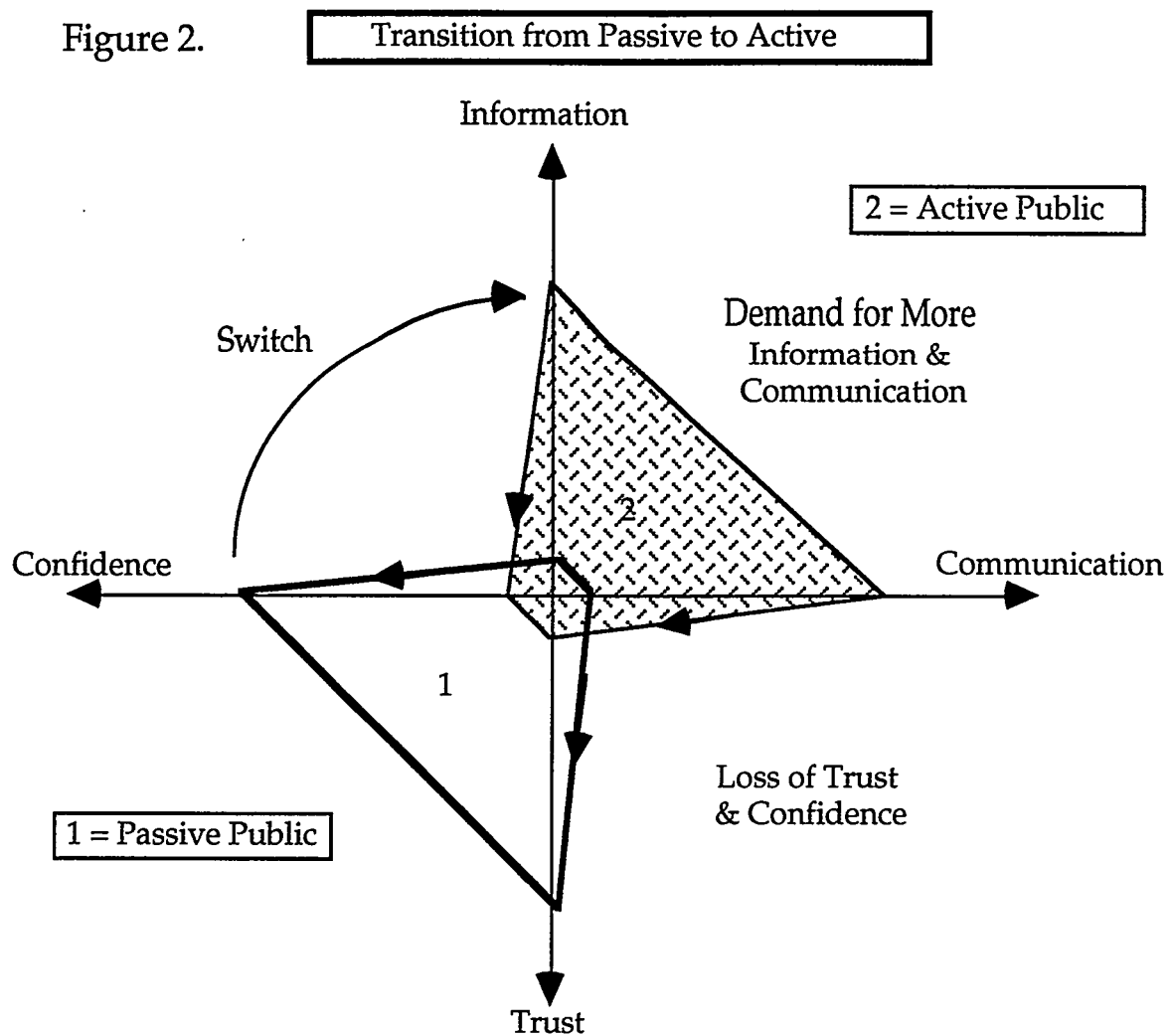


Figure 3.

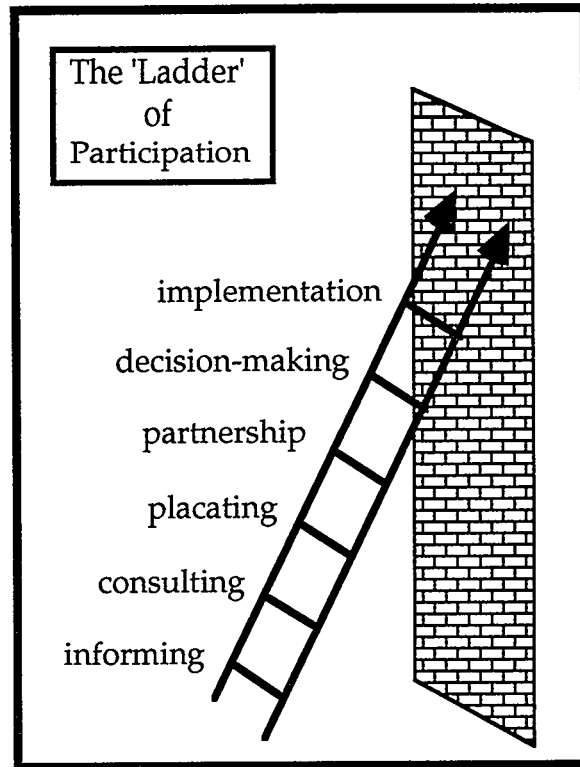
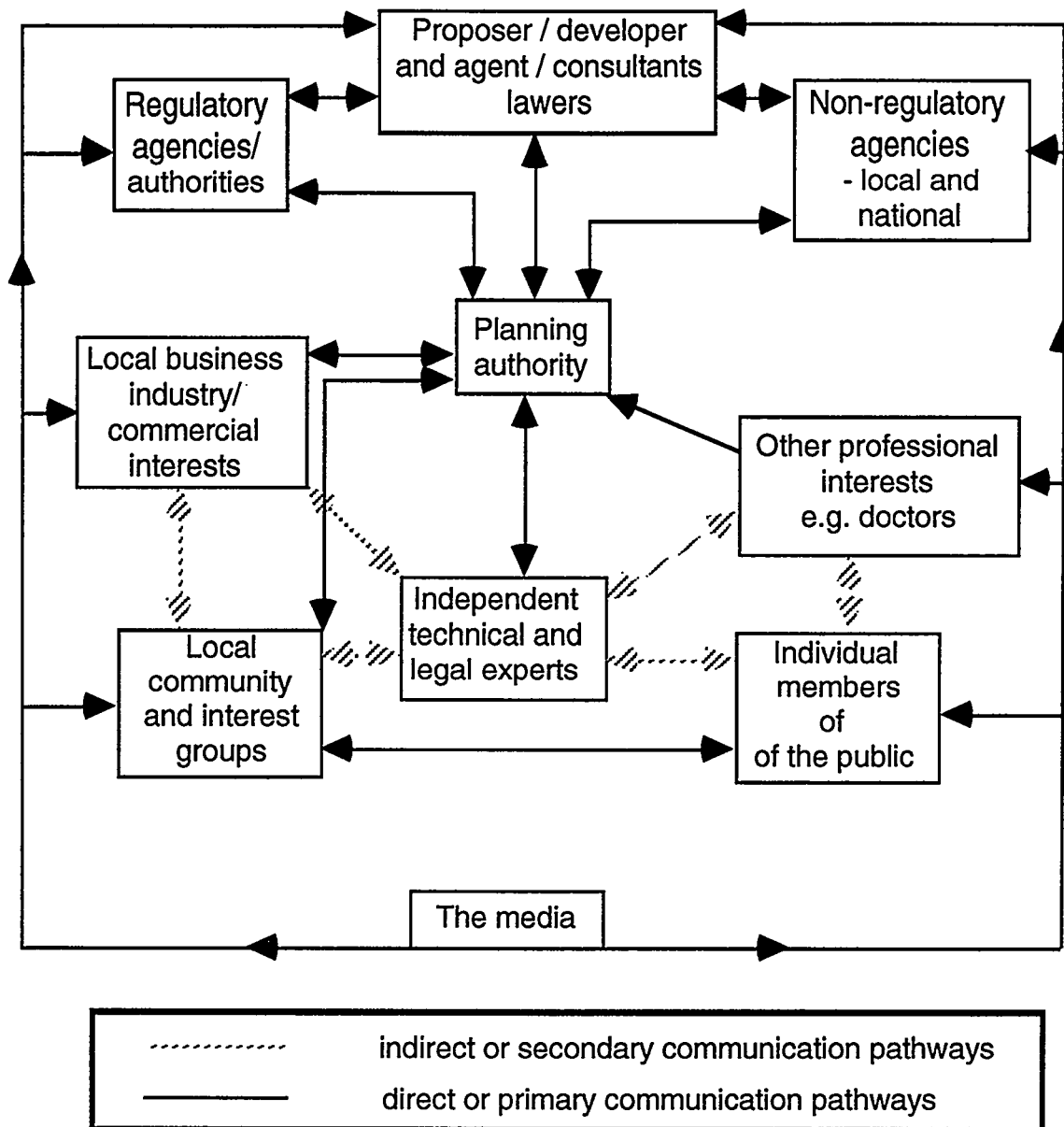


Figure 4. Communication Pathways



Source: Petts & Eduljee²⁸

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TECHNICAL SESSION I

***UTILITY RESTRUCTURING
PANEL***

What is Clean Power ? What is Green Power ?

What is Waste-to-Energy's Role in Utility Restructuring ?

by Leo Pierre Roy, President & COO
Energy Answers Corporation, Albany, NY
April, 1997

Impending utility restructuring and the advent of retail wheeling have created both chaos and opportunity in the electric utility industry, and like earlier deregulation actions (airlines and telecommunications) it promises lower rates to customers. As a result of new competition, in an industry that has never really had any, utilities are being forced to market, for the first time, what has been a commodity product. Your local electric utility is now attempting to do what Frank Perdue did for the chicken: create brand awareness. Not surprisingly, and knowing of the American people's professed environmental sensibilities, a number of utilities have begun to position the electricity that they produce as "clean power," "green power," and "environmentally friendly power." What do these terms mean? How does one assess the relative merits of one source of electricity from another? And where does waste-to-energy, which recovers energy and other resources from waste materials, fit in? In short, what is the best way to produce electricity while treading lightly on the planet?

Before embarking on our journey to define cleaner, greener power, let's assess where we have been. (See Figure 1) In 1994, nearly three quarters of U.S. utility power generation came from fossil fuels. Coal power, at 44%, was the largest source, with natural gas at 20% and oil at 10%. Nuclear power produced 15% of our energy needs. Hydroelectric produced some 11%, and all other renewables were responsible for less than 1%. Worldwide, the production and use of fossil fuels contributed some 60% of all manmade greenhouse gas emissions.¹ By now everyone is aware of concern about air emissions and the debate over global warming, and has heard the notion that sustainability is a good thing-- that our use of natural resources should be sustainable into the future. Utilities are responding to this growing awareness by offering "Green Power" options, purporting to meet our energy needs in "environmentally friendly" ways. But just how eco-friendly are they?

¹ Statement of David I. Bransby, Auburn University, U.S. DOE - National Energy Policy Plan Roundtable, Athens, GA, October 11, 1994.

1994 U.S. Utility Power Generation By Energy Source

	Oil	Coal	Nuclear	Gas	Hydroelectric	WTE	Other Renewables
Megawatts	69,919	301,098	99,148	133,854	75,196	3,268	2,274
Percentage	10.2%	43.7%	14.8%	19.5%	11.0%	0.5%	0.3%

Source: Energy Information Administration, *Electric Power Annual 1994 Volume I*.

Figure 1

Last year Massachusetts Electric (A New England Electric System Company) introduced "Green Options" in a consumer choice pilot program to 10,000 of its residential and small business customers. (The so-called green choices appear in Figure 2.) The options relied heavily on fossil fuel sources, and one was over 50% nuclear. Only one option, Northfield Mountain Energy, was 100% renewable energy, from hydroelectric plants. Kermit the Frog, of Muppets fame, is not alone in observing that "It's not easy being green." Enova Energy has successfully marketed its green power portfolio in a Southern California pilot as well, even though its largest power source is nuclear.² Is this really green power? When one begins to do an analysis of the environmental impacts of electricity generation, one quickly realizes that nothing's perfect. How do we judge energy sources? On the basis of emissions? On the basis of sustainability?

Fossil fuel burning requires strip mining the landscape or otherwise sucking carbon out of the crust of the earth and throwing it into the atmosphere. Coal, gas and oil burners emit greenhouse gases and severely impact natural resources through their extraction and transportation. Dangers of oil spills such as the one from the Exxon Valdez are well known, but environmental damage is also caused by acidic mill tailings and pipelines which often run through sensitive wetlands. While natural gas and clean coal technologies produce cleaner air emissions than most fossil fuels, they're still not sustainable in the long run. It takes far longer to produce this fuel than it takes to burn it. We humans consume in just one year a quantity of fossil fuels that took nature roughly one million years to create.³

What are the environmental impacts of other energy sources? Nuclear power may not emit greenhouse gases, but it is not sustainable, either. There is a natural limit to the availability of radioactive ores, and nuclear wastes create management problems for millions of years. Hydroelectric dams impact fish habitat and can restrict recreation. Windmill farms are unsightly, solar is not yet efficient on a large scale, and geothermal can be exhausted. This leaves biomass waste-to-energy sources.

Biomass is defined by the U.S. Department of Energy as "wood, wood waste, peat, wood liquors, railroad ties, pitch, wood sludge, municipal solid waste, agricultural waste, straw, tires, landfill gases, fish oils, and/or other waste."⁴ Biomass is essentially stored solar energy, captured in either raw or processed plant material. Examples of biomass include fast-growing trees and grasses, like hybrid poplars or switchgrass, agricultural residues like corn fiber or rice straw, wood waste such as sawdust, tree prunings, and yard clippings, or paper, natural rubber, cloth, food waste, and other municipal solid waste. Municipal solid waste is mostly biomass... over 70% is paper, wood, yard waste, cloth, and food waste. (See Figure 3)

² Renewables, *Power*, January/February 1997, p. 12.

³ Rogene A. Buchholz, *Principles of Environmental Management*, p. 403.

⁴ Energy Information Administration, *Electric Power Annual 1994*, Volume I, July 1995, p. 5.

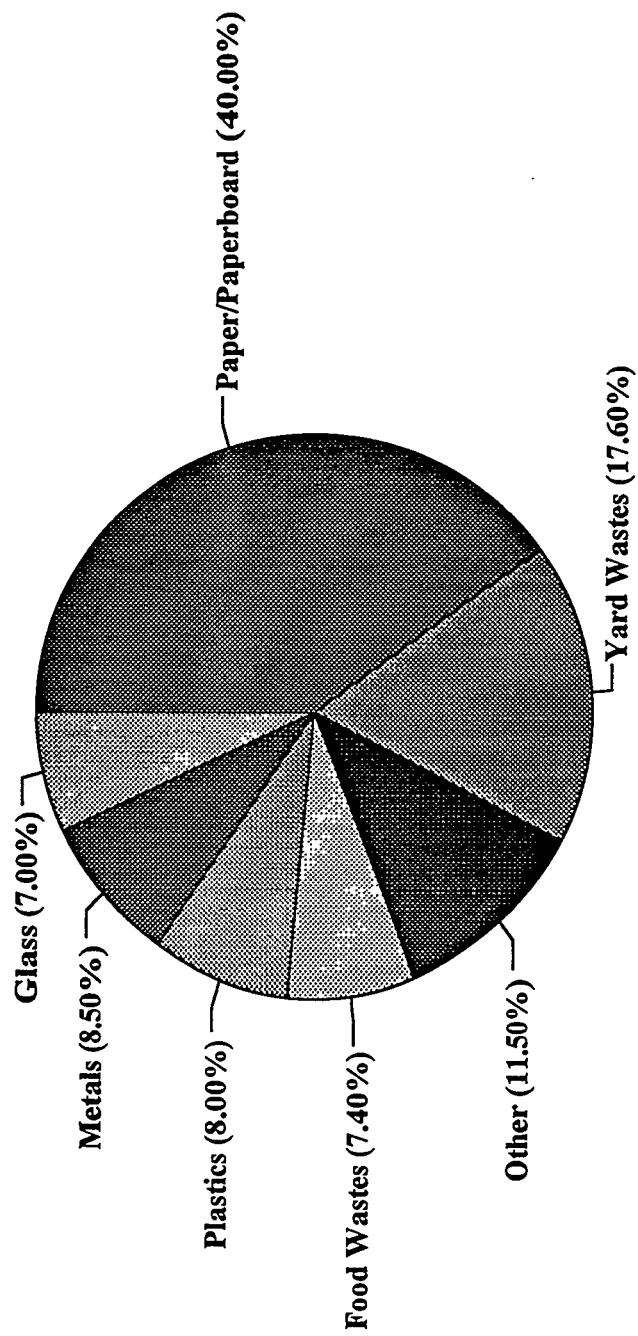
**“Green Options” in Massachusetts Electric’s
Choices: New England Pilot Program**

	Oil	Coal	Nuclear	Gas	Hydro	Other Renewables
AllEnergy	10%	38%	14%	22%	10%	6%
Enova Energy	14%	21%	57%	< 1%	6%	2%
Northfield Mountain Energy					100%	
Working Assets Green Power, Inc.	0-5%			35-50%	30-45%	3-10%

Source: Massachusetts Electric (A NEES Company) brochure.

Figure 2

Municipal Solid Waste Composition



Source: 1990 EPA Report on Solid Waste

Figure 3

Municipal solid waste is destined to oxidize. Whether it is buried in a landfill or burned in a combustion facility with energy recovery, the organic fraction will eventually break down and produce carbon dioxide (CO₂). If the material is landfilled, however, over time it will also produce methane. Methane is a greenhouse gas of great concern, because it is twenty-five times more reactive than CO₂, and contributes to the production of ground level ozone and smog.⁵ It is preferable to convert municipal solid waste to CO₂ under controlled circumstances, without the production of methane, while directly capturing its energy value. In addition, more advanced waste-to-energy plants process their waste before and after combustion, removing metals and other recyclable materials.

The carbon in municipal solid waste and other biomass is already "in play" on the earth's surface and is part of the natural carbon cycle. Burning biomass doesn't add to the net buildup of greenhouse gases in the atmosphere the way fossil fuels do. Burning one ton of trash biomass saves over 9,000 cubic feet of natural gas, or 760 pounds of coal, or 60 gallons of oil. Growing new biomass actually takes carbon out of the atmosphere through photosynthesis, and stores it for later use, as part of the natural carbon cycle. Burning biomass with energy recovery is both renewable and sustainable: the U.S. alone annually produces over 2 billion tons of biomass residue, enough to produce 200,000 megawatts of electricity.⁶ In addition to being a sustainable energy source, waste-to-energy helps to solve the world's ever-increasing municipal solid waste management problem.

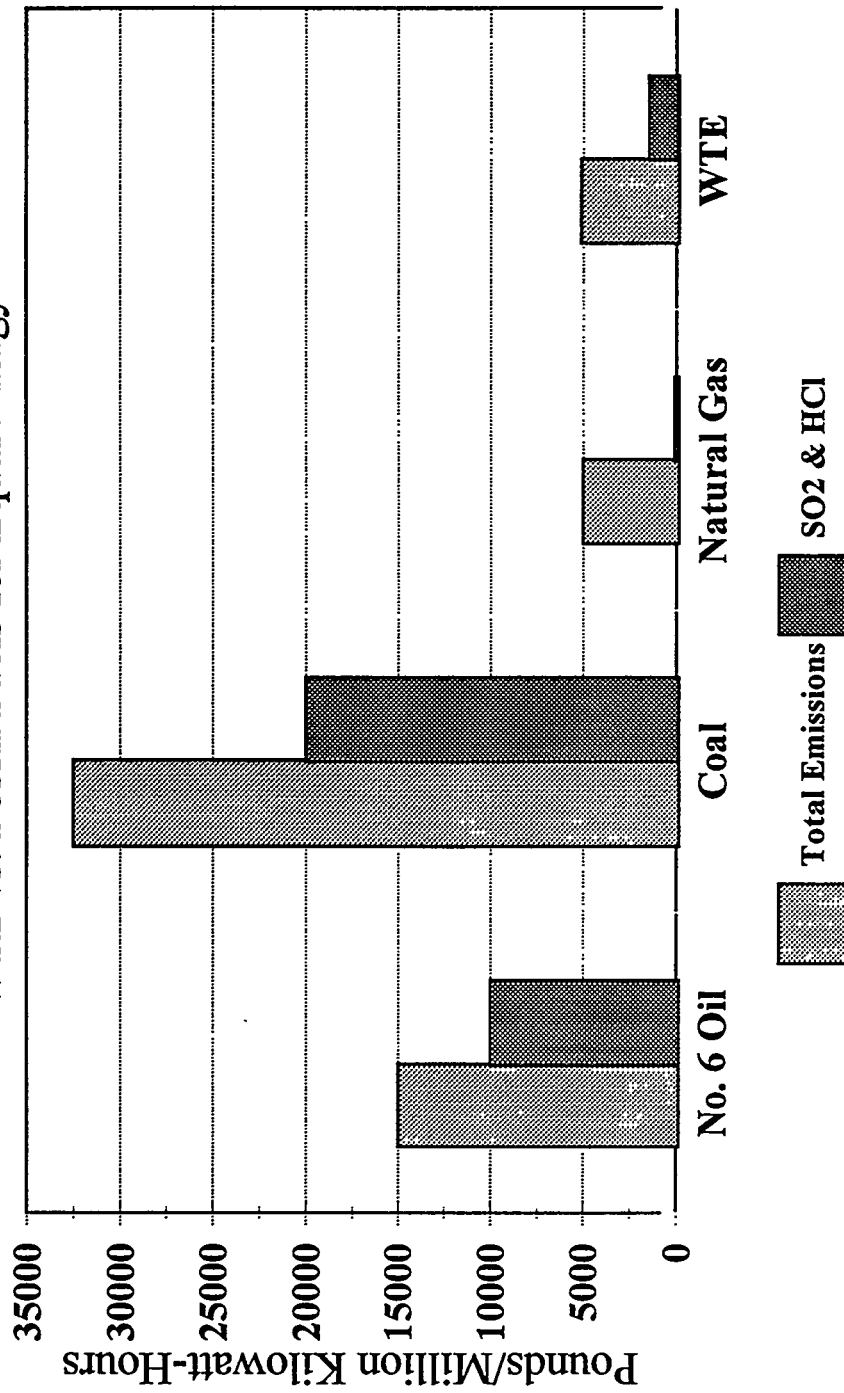
So how do biomass emissions compare to those of fossil fuels? Modern waste-to-energy is cleaner than coal and oil, and comparable with gas. While emissions data for fossil fuel burners are difficult to obtain, there is an abundance of data on waste-to-energy emissions, since these plants are the world's most highly regulated air emission sources. Based on pounds of emissions per million kilowatt hours produced, waste-to-energy is lower than coal and oil on total emissions and acid gases, in part due to stringent scrubbing requirements. (See Figure 4) Norman P. Getz (former Project Manager, Roy F. Weston, Inc.) has done extensive analyses comparing electricity generation emission factors and has found waste-to-energy comparable in NO_x and lowest in particulates. (See Figure 5) These data come from a variety of sources, but are reasonably current. The waste-to-energy data are based on the weighted average of 20 plants, and are conservative; newer plants are much cleaner. Similarly, while the Ozone Transport Commission (OTC), consisting of the northeast states, is pursuing a 65% reduction in NO_x, as waste-to-energy plants implement the new federal regulations (MACT) their NO_x numbers will go down as well.

⁵ Hunter R. Taylor, "Municipal Waste-to-Energy Facilities Reduce Greenhouse Gas Emissions", Institute of Gas Technology Fourth Annual National Symposium on Municipal Solid Waste Disposal and Energy Production, January 1990.

⁶ Susan Williams and Kevin Porter, *Power Plays*, Investor Responsibility Research Center 1989, p. 31.

Air Emission Comparison

WTE vs. Fossil Fuels for Equal Energy



Source: America's Newest Energy Source, The ADMS Coalition, 1994

Figure 4

Electricity Generation Emission Factors

Emission	Pounds of Emission per Megawatt-Hour Generated			
	Oil	Coal	Gas	WTE
Total Organics	0.3	0.1	0.04	0.04
NOx	8.2	9.0	4.1	9.4
SO ₂	12.4	16.4	0.004	5.0
CO	0.003	0.5	0	0.33
Particulates	0.8	0.8	0.2	0.18

Source: One Family's Air Pollution, Norman P. Getz, *Solid Waste & Power/February 1990*.

Figure 5

Trace metals emissions have been made into a big issue for waste-to-energy plants by activists and opponents, but this legitimate concern has not been placed in context with other energy sources. (See Figure 6) On average, waste-to-energy plants emit less cadmium and chromium than coal and oil burners, and less lead than bituminous coal combustors. While emissions of mercury into the atmosphere are of widespread concern, few people are aware that waste-to-energy plants emit less mercury than coal fired boilers. Moreover, the waste-to-energy industry has made great strides towards reducing the amount of mercury in their fuel, through source reduction and battery recycling programs. (See Figure 7). Another little known fact is that fossil fuel burners are not even regulated for mercury or dioxin emissions, while waste-to-energy plants monitor their emissions on a regular basis. As a result of this attention, great strides have been taken to reduce air toxics from waste-to-energy facilities, unlike other energy sources.

Two criteria have emerged in our quest to determine what is clean, green power: air emissions and sustainability. Paul Hawken, in his 1994 book *The Ecology of Commerce*, defines sustainability as "an economic state where the demands placed upon the environment by people and commerce can be met without reducing the capacity of the environment to provide for future generations."⁷ This basically means... "Don't use it all up-- save some for the next guy." Resource conservation is consistent with the philosophy of Dr. Karl-Henrik Robèrt, Swedish founder of The Natural Step. He has observed that the earth is a closed system, and that we can't indefinitely extract carbon and minerals from the crust of the earth, spreading them on the surface of the planet and into the air, without at some point choking on our own waste. He believes that we need to be concerned about carbon; that too much carbon in the atmosphere upsets the natural balance. Fossil fuel burning creates large quantities of air emissions and is not sustainable.

So if fossil fuels are out, what qualifies as clean, green power? In looking at solid waste management, the U.S. Environmental Protection Agency (EPA) established a hierarchy of environmentally acceptable techniques. (See Figure 8) They range from the best-- not creating waste in the first place-- to the worst-- just burying the stuff without recovering the resources. This approach allows the agency and others to create appropriate incentives for those technologies higher on the list, and discouragements for those at the bottom.

Perhaps there should be a similar hierarchy for environmentally acceptable energy sources. (See Figure 9) Conservation would naturally be at the top; demand side management is the cheapest, most efficient way to secure needed capacity. Nuclear power would be at the bottom, due to the difficult waste management issues. Renewable energy sources are sustainable, and do not contribute excess carbon to the natural cycle. Fossil fuel is unsustainable, and greatly increases the greenhouse gases in the atmosphere. For these reasons, renewable energy sources would be higher on the proposed energy hierarchy, and considered to be cleaner, greener energy sources.

⁷ Paul Hawken, *The Ecology of Commerce*, p.139

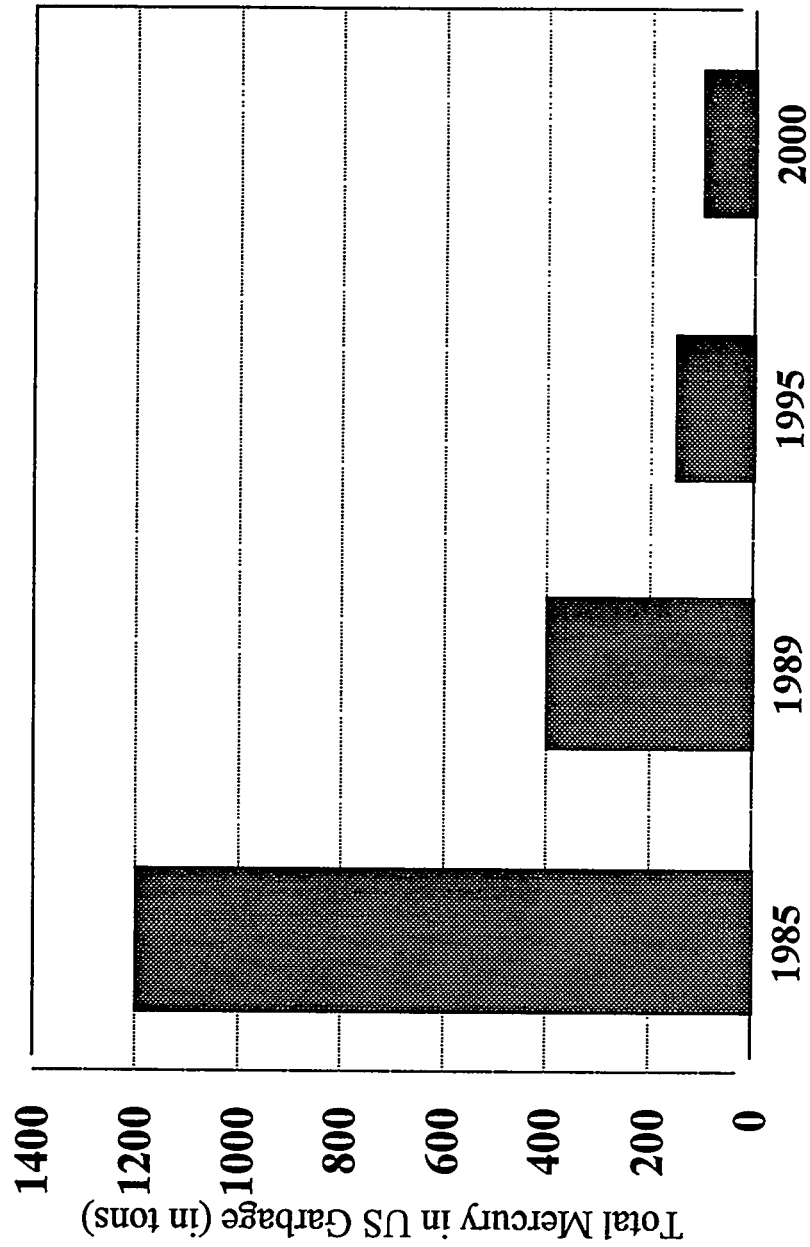
**Comparison of Selected Trace Metal Emissions From Different Power Plant Sources
On A Pounds of Trace Metal Emissions
Per 1,000 Megawatt-hours of Electricity Production Basis**

	Residual Oil (lb/1000 MWh)	Bituminous Coal (Pulverized) (lb/1000 MWh)	Lignite Coal (Pulverized) (lb/1000 MWh)	WTE (average of 20 plants) (lb/1000 MWh)
Arsenic (As)	0.22	0.46	0.91	< 0.033
Beryllium (Be)	0.05	0.03	0.06	< 0.017
Cadmium (Cd)	0.18	0.10	0.11	0.063
Chromium (Cr)	0.24	4.56	5.70	< 0.19
Copper (Cu)	3.19	2.28	3.42	0.43
Mercury (Hg)	0.04	0.23	0.23	0.17
Nickel (Ni)	14.36	3.42	3.42	0.84
Lead (Pb)	0.34	0.57	0.11	0.44
Selenium (Se)	NR	0.29	0.29	< 0.022
Vanadium (V)	3.4	4.0	4.0	0.025
Zinc (Zn)	0.47	5.0	5.0	1.23

Source: How Does Waste-to-Energy "Stack" Up, Norman P. Getz, 1993 International Municipal Waste Combustion Conference, Williamsburg, VA, March 30- April 2, 1993.

Figure 6

Success of Removing Mercury from Consumer Products



Source: U.S. EPA (1992) and Malcolm Pirnie (1992)

Figure 7

EPA's Solid Waste Hierarchy:

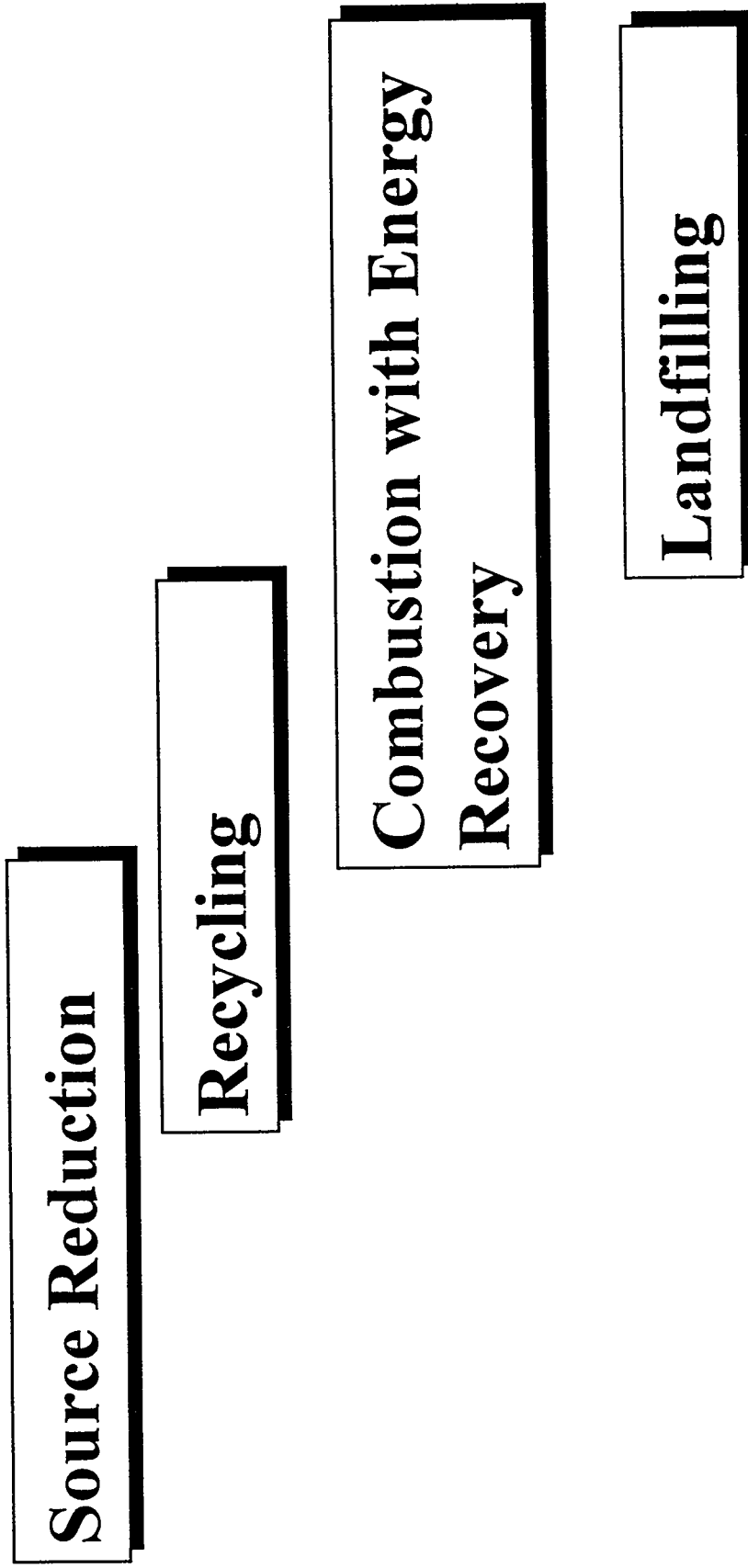


Figure 8

Suggested Energy Hierarchy:

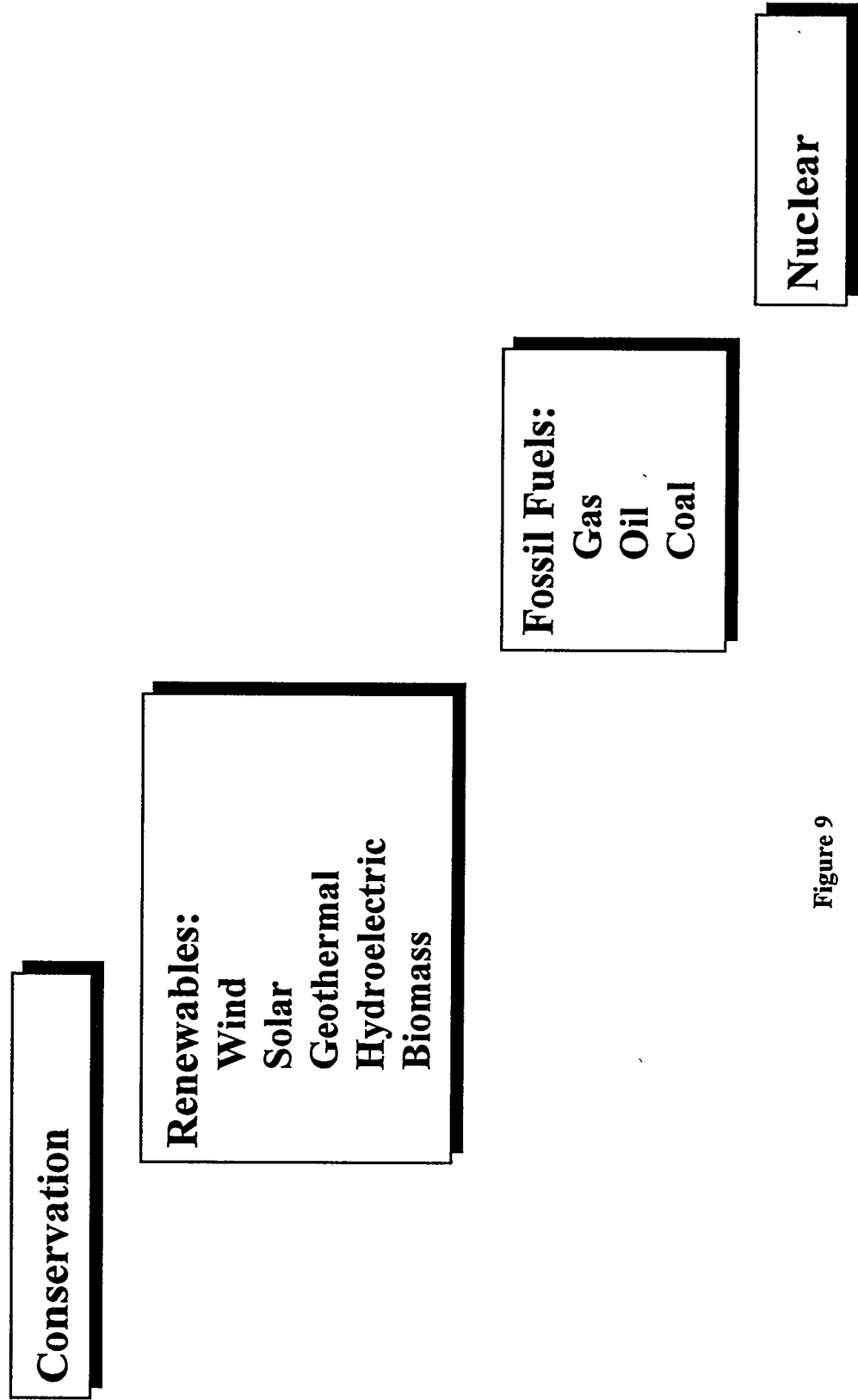


Figure 9

Renewable energy, including wind, solar, geothermal, hydroelectric and biomass waste-to-energy sources, should be the majority of any "clean" or "green" power portfolio. These renewables should be given whatever price supports and tax incentives result from utility restructuring. The economic incentives will help "level the playing field" and enable renewable technologies to compete with the extractive industries such as oil and gas exploration, which have long enjoyed favorable tax positions and other incentives. Today we realize that our future depends not only on cheap energy, but also on clean and sustainable energy. Waste-to-energy industry leaders need to speak out for inclusion of biomass and other renewables in clean or green portfolio standards, in pending state and federal legislation. The chaos and opportunity created by utility restructuring enables us to make truly green choices that will affect not only the lives of the present generation, but those of generations to come.

Law Offices
BAISE & MILLER, P.C.
815 Connecticut Avenue, N.W. - Suite 620
Washington, D.C. 20006-4004
(202) 331-9100
Fax: (202) 331-9060
<baisemil@aol.com>

ERIC P. BOCK

FIFTH ANNUAL NORTH AMERICAN WASTE TO ENERGY CONFERENCE
Panel on Electric Utility Restructuring

Research Triangle Park, N.C.
April 22, 1997

THE ELECTRIC UTILITY RESTRUCTURING DEBATE - A PRIMER

I. Introduction:

Federal and state policymakers continue to push towards more deregulation and greater competition in the supply of electricity in order to reduce its cost to the ultimate consumer. Congress, citing consumer benefits realized by the deregulation of the airlines, telecommunications and trucking, is preparing to act on legislation which would require the states to allow every retail customer to choose its power supplier. Many states, however, are already moving ahead. California, for example, enacted a law last summer which will restructure the state's electric utility industry beginning in 1998 and provide complete retail choice by 2002.

The following information provides a brief overview of the key events which have led the electric utility industry from a stable regulatory regime to this period of unprecedented change. The key issues currently faced by the industry are summarized and those aspects of the debate that are of specific relevance to waste-to-energy development are highlighted. The information is intended as an introduction to the national debate on restructuring of the electric utility industry.

II. Brief Historical Overview

A. The Regulatory Compact

With the advent of the electric light bulb, enterprising companies began to obtain franchises and contracts from towns and cities to provide electric lighting of public streets and other public places. Power plants, fueled primarily by coal and oil, were relatively small and sited near the electric consumers due to the lack of technology for long distance transmission. As the use of electricity grew, competition increased between companies providing electric services to the same general customers. Duplication in facilities and other inefficiencies in service abounded. Eventually, economies of scale led to the consolidation of competing companies but acquisition of duplicative assets by the dominant corporations was, nevertheless, economically wasteful. At the same time, the emergence of the dominant utility raised the potential of unfair price and supply manipulation.

To address these problems, state policy makers established the "regulatory compact" by which utilities were granted an exclusive franchise to provide electric service, and were given a fair rate of return on capital (i.e., regulation based on cost-of service), in exchange for agreeing to reliably meet all electricity demands of the consumers. Interestingly, it is this regulated monopoly structure, which existed at the state level throughout the twentieth century, which is currently being dismantled in order to return to a fully competitive market.

B. The Era of Holding Companies

From 1910 through the 1920s, the number electric utility companies declined, primarily because of consolidation and pyramiding of utilities through holding companies. By 1932, three holding companies controlled 45% of the electricity generated in the United States. Holding companies typically operated in several states preventing any one state from effectively tracking the flow of capital and verifying costs on which the regulated rate of return for an affiliate electric utility company was based. Consequent abuses within the holding company structures, such as self-dealing, cross-subsidization, and issuance of securities based on asset "write-ups", resulted in higher than reasonable rates to consumers and vulnerability for shareholders. More importantly, as the holding companies began to acquire generation and transmission assets in different states, the interstate commerce in electricity could not, under the U.S. Constitution, be regulated by the states but only at the federal level.

C. The Public Utility Holding Company Act (PUHCA) and the Federal Power Act (FPA)

In 1935, Congress responded to these regulatory gaps by enacting PUHCA and the FPA which were to work in tandem.

1. PUHCA

Under PUHCA, holding companies are defined as owning, directly or indirectly, 10 percent or more of a gas or electric utility company. The key provision of the Act limits the operation of a holding company to a single and integrated public utility system and limits diversification to such businesses that are reasonably incidental or economically necessary or appropriate to the functioning of such an integrated system. The Act prohibits inter-company loans, service contracts and sales and strictly regulated, through the Securities and Exchange Commission, asset sales and acquisitions and other financial transactions within the holding company. The Act also provides exemptions for a holding company, which would otherwise be required to register with the SEC and become subject to regulation under PUHCA, if its business operations and those of its subsidiaries occur "predominantly" in one state, or if it is predominantly a public utility and its operations are confined to the state in which it is organized and states contiguous thereto.

2. The FPA

The FPA granted the Federal Energy Regulatory Commission (FERC), then called the Federal Power Commission, authority to regulate the "transmission of electric energy in interstate commerce and the sale of energy at wholesale [sale for resale] in interstate commerce" by private sector utilities, approve sale, merger and acquisition of electric facility assets, set "just and reasonable rates", and "promote and encourage" interconnection of electric utilities within a given region. Generally, where requirements of the FPA overlap requirements of PUHCA, the latter requirements apply. The FPA, as originally enacted, did not give FERC the authority to mandate a transmission owning utility to wheel power for another utility engaged in wholesale sales.

D. Era of Instability

During the 1930's, the federal government focused on expanding the use of electricity in remote and underdeveloped areas of the country through the creation of federal power marketing agencies ("PMAs") to develop and sell hydropower, such as the Tennessee Valley Authority and the Bonneville Power Administration. In the 1960's the federal government's focus shifted to encouraging the development of "cheap" nuclear power and ensuring coordinated planning and operation among utilities for regional reliability purposes. Growth in the sophistication

of the electric utility industry and electricity consumption increased significantly during the four decades.

In the early 1970s, however, the nation experienced a dramatic rise in the cost of generating electricity, resulting from a combination of the 1973-74 Arab oil embargo, high inflation, new environmental regulations, and the demise of the nation's nuclear power plant construction program. Proposed rate hikes by utilities were often suppressed by the public utility commissions. Consequently, the nation began to seek greater efficiencies and stable rates from utilities, a reduction in dependence on foreign oil (as well as domestic oil and gas), and a diversity in the technologies used to generate electricity.

E. The Public Utility Regulatory Policies Act (PURPA) and Non-utility Generators

In 1978, Congress enacted PURPA to encourage energy conservation, energy efficiency through measures such as cogeneration, contingency planning by utilities, adoption of "life line" rates, and development of electricity generation from small renewable resources. PURPA also granted FERC the authority to mandate wholesale transmission wheeling, but placed preconditions to the exercise of such authority which severely limited its usefulness.

Section 210 of PURPA requires utilities to buy power from qualifying cogeneration facilities and qualifying small power production facilities (termed "QFs"), at the utilities' full-avoided cost, i.e. the cost to a utility of generating the same energy or purchasing it from another source. The "must take" aspect of PURPA gave birth to a whole new industry of third party generators, introducing competition into the electric utility industry, and thereafter, aggressively advancing it. In particular, the economics of most waste-to-energy projects, whose development was strongly encouraged by the Resource Conservation and Recovery Act (RCRA) enacted by Congress two years earlier, improved significantly. Proponents of PURPA cite the almost 25% reduction in the nation's electricity prices since 1982 as evidence of the Act's success.

PURPA exempted QFs from regulation under PUHCA and the FPA. However, PURPA prohibits utilities from owning QFs. Additionally, the megawatt capacity of QF's have to meet size limits specified in the Act, and QFs have to meet certain operating, efficiency and other standards established by FERC.

F. Energy Policy Act of 1992 (EPAct)

Two key factors led to the enactment of EPAct. First, the growth of third party generators created a greater demand for guaranteed access to the transmission facilities of traditional

utilities. Secondly, companies that operated non-utility and utility businesses argued that their ability to compete in the wholesale power market was stifled by fear of having their operations regulated under PUHCA. The non-utility generators, in particular, had to develop complex and inefficient corporate structures to avoid PUHCA regulation.

1. Transmission Access

In response, Congress in EPAct provided FERC with clear authority to order any utility owning transmission to provide transmission service (including enlargement of transmission capacity if necessary) to any other entity generating electric energy for resale, and to set rates, terms and conditions for such service. However, the procedure set forth in EPAct for obtaining a "wheeling" order from FERC is time consuming. Recognizing this, FERC used the new authority granted by EPAct to issue Order 888, discussed below, which requires open transmission access to be standard operation for the industry.

A proposal developed during formulation of EPAct, although not included in EPAct but adopted as policy by FERC eight months after the Act's enactment, supported creation of regional transmission groups (RTGs) by which all users of a transmission grid voluntarily coordinate planning, establish dispute resolution procedures, and transmission owners obligated themselves to provide transmission service. Several RTGs have been established in the western part of the nation.

2. Exempt Wholesale Generators

The Act also boosted competition in the electric generation sector by establishing a new category of independent generation facilities to operate in the wholesale market that are exempt from the geographic integration, financial and corporate structure restrictions in PUHCA. Termed exempt wholesale generators or "EWGs", these facilities are not limited by the size, renewable energy source or cogeneration constraints of PURPA. Both registered and exempt holding companies under PUHCA can own and operate EWGs.

Although the EWG does not have to be a separate, but may be an undivided share of, a power plant, a regulated utility may not convert an existing plant into an EWG without approval from its state regulator. In addition, an EWG may not sell power to an affiliated utility unless every state regulating the utility approves. State regulatory agencies are to make these decisions based on considerations of public benefit and fair competition, and they are given authority to examine all necessary financial information of the purchasing regulated utility, the EWG, and any affiliate companies of the EWG.

III. FERC Orders 888/889

In the wake of EPAct, FERC moved aggressively to open the nation's transmission grid. This effort culminated with FERC's issuance of Order 888 and Order 889 in April, 1996.

A. Functional Unbundling

To ensure non-discriminatory open access to transmission for all wholesale power suppliers, Order 888 requires vertically integrated utilities to unbundle their generation/power marketing functions from their transmission functions. Order 889 imposes standards of conduct on the utilities to ensure that employees operating the transmission system do not provide to employees involved in power marketing competitive information which is not available to all other sellers and customers,. Order 889 requires the utilities to establish an electric information network (termed "OASIS") in order to provide information on transmission capacity to potential transmission customers, and requires them to obtain information about its transmission system from the same network when buying or selling power.

B. Open Transmission Access

Order 888 has essentially transformed the nation's transmission grid to common carrier status by requiring open access transmission by all public utilities that own, operate or control facilities for interstate transmission, and requiring them to file tariffs with FERC that offer other generators of wholesale power the same transmission services they provide themselves, under comparable terms and conditions. Utilities must take transmission service for their own wholesale transactions under the terms and conditions of the tariff. These terms and conditions must meet the minimum pro-forma standards, set forth in the Order, for providing transmission services and six specified ancillary services. The ancillary services range from those which are needed to effect the transaction (such as scheduling and dispatching) to services necessary to maintain the integrity of the transmission system during the transaction (such as voltage control). Utilities must establish separate rates for wholesale generation, transmission, and ancillary services to allow customers to compare such rates between utilities and other suppliers.

Intra-pool or intra-system transactions for power pools, some holding companies and other multi-lateral agreements must be under a joint, pool-wide or system-wide tariff in which all previous preferential transmission access and pricing provisions among members have been removed. Finally, the Order requires that any other entity that owns, controls or operates transmission facilities, including government-owned utilities,

and receives open access service must reciprocate by providing open access service to the transmitting utility upon request.

C. Creation of Independent System Operators

Although Order 888 did not require operational unbundling - i.e., require the utilities to establish structural institutional arrangements, short of divestiture, that would separate operation of the transmission grid and access to it from economic interests in generation - it did encourage such unbundling by supporting creation of independent system operators (ISOs). ISOs would operate a geographically-defined transmission grid, independent from the owners of the transmission facilities comprising the grid who would convey control to the ISO, to provide transmission service and the six ancillary services on an open and non-discriminatory basis to all generators of power.

D. Federal/State Jurisdiction

In Order 888, FERC asserts jurisdiction over the rates, terms and conditions of unbundled retail transmission in interstate commerce by electric utilities, but left authority over local distribution, and over the service of delivering electric energy to end users, to the states. The Order adopted seven local distribution function indicators that the Commission will use to determine where to draw the jurisdictional line for facilities used in unbundled retail wheeling transactions.

E. Stranded Cost Recovery

FERC authorized any transmission owning utility to seek recovery of stranded costs from departing wholesale generation customers through either an exit fee or a surcharge on transmission service. For stranded costs associated with new wholesale requirements contracts, stranded costs recovery is only allowed if the contract contains an explicit stranded cost provision that permits recovery. Stranded costs resulting from departing retail customers are to be addressed by the state, but FERC declared it to be the primary forum for stranded cost determinations when a retail customer becomes a legitimate wholesale customer, such as through municipalization.

IV. State Restructuring Efforts

From the beginning of 1995 through the end of 1996, regulators in 46 states and the District of Columbia initiated, completed, or participated in formal generic, company specific, or informal processes that directly addressed retail wheeling, competition, restructuring, or alternative forms of regulation. In some states, retail wheeling pilot programs or experiments have been instituted by regulators. Legislation addressing these

same issues or establishing special study groups have been filed, introduced, or passed in 35 states since the beginning of 1995.

The states with significant restructuring activities currently are California, Arizona, Maine, Massachusetts, New Hampshire, Pennsylvania, Rhode Island, and Texas. In addition, the Pennsylvania-New Jersey-Maryland (PJM) power pool, California's three investor-owned utilities, and the New York Power Pool have filed ISO proposals with FERC. At least five other ISO-type structures are being planned in the Pacific Northwest, the Midwest, Wisconsin, Texas, and in New England. In several cases, the particular ISO is an integral part of an individual state plan to ultimately provide retail access.

V. Key Issues in the Restructuring of the Electric Generation, Transmission and Distribution Markets

The following provides a brief description of the key restructuring issues relative to the three main market components being addressed at the federal and state levels. Additional discussion on some of the issues is set forth in Section VII, Congressional Initiatives.

A. The Electric Generation Market

1. Mitigating Market Concentration

In states where the current regulated market is significantly concentrated and dominated by a small number of large vertically integrated power producers, regulators may decide that the competitive process will not work unless some or all of the generating assets of the concentrated utilities are divested or placed into an independent subsidiary. Such utilities, however, may be opposed to mandatory divestiture or corporate restructuring.

2. Stranded Cost Recovery

Regulators which decide to open electricity markets to competition will no longer regulate traditional utilities and guarantee that they receive a fair rate of return on their investments. Accordingly, the same regulators will have to decide whether such a utility should be permitted to recover prior investments in generation capacity, which were made to provide electric service to its captive customers, when such utility cannot sell some or all of its power in the competitive marketplace for a price high enough to earn a fair return on those investments. Such stranded costs would include liabilities arising from purchased power contracts under PURPA's "avoided cost" rule and long term contracts for fuel or purchased power.

An important collateral decision is the appropriate method for valuation of stranded costs. One approach to determine such costs would be to require sale of the stranded assets and allow recovery of the difference between market price and book value. FERC, in Order 888, proposes to use an administrative proceeding based on the "loss of revenues" that would have been gained but for the introduction of open competition. However, the approach has been criticized because of the tremendous forecast risks.

Additional decisions relate to how stranded costs should be recovered (options include a transmission access charge or surcharge, a utility system exit fee, and an fee for entry into the newly opened market), who should be required to pay for recovering such costs, and to what extent the utility should be required to mitigate or minimize stranded costs (e.g., through buy-outs or buy-downs of PURPA contracts).

3. PURPA Reform and the Role Of Renewables

The reform of PURPA, and specifically the proposed repeal of Section 210, arguably is one of the most important restructuring issues to the waste-to-energy industry. Proponents of PURPA reform suggest that the statute has been overtaken by events - principally the push for a more competitive marketplace in electric power generation. It is argued that PURPA's assumption that utilities would continue to be the exclusive suppliers of electricity and could, therefore, assure retail buyers for QF generated power, is no longer valid.

PURPA opponents further complain that the law has inordinately boosted consumer costs because, in many cases, the avoided cost price was tied to long run forecasts of petroleum prices which proved, ex post, to be far too high, and FERC prevented utilities and the states from adjusting the contract price after the initial contract was signed. It is claimed by traditional utilities that PURPA is the single largest factor in explaining the regional disparity in electric prices and that PURPA contracts compromise a large percentage of the stranded costs nationwide. In response, some states are considering requiring the QF owners to reopen their long-term contracts and negotiate more "realistic" prices with their utility clients as a precondition to allowing the QFs to compete in the retail market. Federal legislation introduced last year would have abrogated existing PURPA contracts under certain situations.

Significantly, the proponents of PURPA reform have argued that PURPA's objective of promoting renewable fuels has not been realized since gas, coal and oil make up 68% of the installed non-utility generating capacity.

Most renewable energy sources still generate power at a cost which will not be competitive in an open and fully interconnected

market. If the "must take" provisions in PURPA are repealed, state and federal policy makers will have to decide whether a different mechanism should be established to encourage development and use of renewable energy sources. Two mechanisms being considered by policy makers are mandatory minimum renewable energy portfolios for all suppliers of power and the imposition of surcharges on transmission service to be used by the states to fund and encourage development of renewable energy projects. However, such mechanisms may be resisted by utilities who have urged that no sector of the industry should be given a "subsidy" and by others who view the competitive stature of most renewables as already comparable to other generators participating in the market.

4. PUHCA Reform

Those seeking reform of PUHCA believe that market competition is stifled by requiring holding companies to adhere to the restrictions of PUHCA on their financing, affiliate transactions, and acquisitions and divestitures of generation and related assets. The latter issue is the key reason underlying the push for reform by the holding companies. They argue that FERC's review of mergers and acquisitions, similar review of acquisitions by states, federal anti-trust statutes, and the recognized efficiencies of holding company ownership of utilities in noncontiguous states in many cases, justify repeal of the ownership limitations in PUHCA.

In addition, many believe that the federal court decision in the *Ohio Power* case, which ruled that FERC is not authorized to evaluate the reasonableness of costs from affiliates of registered holding companies or disapprove affiliate charges that are demonstrably too high, should be overturned. The states have been similarly restricted.

A collateral issue, if the PUHCA restrictions are removed, is what respective authority should be provided to FERC, the states, or the SEC to review books, records and financial transactions of the holding company and its affiliates to ensure that consumers and shareholders are protected. Sub-issues are which companies or subsidiaries of currently registered holding companies would be subject to the review authority, and whether federal access to records should be authorized, and under what conditions, where the sole purpose is to provide them to the state regulators.

Finally, it has been argued that PUHCA's diversification restrictions stifle competition and economic efficiency because they limit the ability of other companies to enter the utility business and limit public utilities from entering into unrelated but profitable businesses.

5. The Role of Government-Owned Utilities

Federally owned utilities, i.e. the federal power marketing agencies such as TVA, and state or local government-owned utilities will be free to compete in the marketplace. However, some private utility interests view such competition to be unfair, because government-owned utilities can use tax-exempt financing to raise capital, are exempt from FERC's authority requiring filing of transmission tariffs, and have preferential access to cheap federal hydropower. It has been suggested that these advantages be removed to "level the playing field" between private and government-owned utilities and that the PMAs be privatized. (Incidentally, the "level playing field" argument has also been used to argue for the removal of existing tax credits and incentives currently provided to specific types of renewable generation sources.)

6. Local Generation

Rapid technological change in generation technology has decreased the benefits of economies of scale inherent in traditional, large central station power plants. The size of these plants have typically required them to be located in remote non-developed lands. Accordingly, long-distance transmission from these plants is required at a cost which can be relatively significant, especially where there is high demand for transmission over capacity limited pathways, raising the total cost of delivered power to the consumer. Current technologies, however, best represented by modular, highly efficient, natural gas-fired generation units, which occupy less land, create the opportunity to site generating facilities nearer to the consumer, within or near urban areas, or at an industrial or commercial site. Additional technological breakthroughs could also create more local generation options, such as electric storage systems and those which will allow economically efficient aggregation of potential local generation resources which, individually, may have marginal economic value(e.g., small local landfills producing methane).

State regulators, in their role of ensuring long term availability of energy and capacity within their states, may support local generation over remote generation sources for several reasons in addition to lowering transmission costs: greater state control over the generation resource itself and to enhance reliability and stability of the regional and local energy supply system. It is worth noting that waste-to-energy projects are ideal local energy sources since locally generated solid waste can supply electricity to the same entities which generated that waste.

B. The Electric Transmission Market

Transmission is a natural monopoly susceptible to monopoly pricing and for this reason is expected to remain regulated. However, efficiencies can be gained if individual but interconnected transmission facilities are subject to coordinated and joint operation. FERC, in Order 888, encouraged states to consider requiring transmission owning utilities to unbundle operation of their transmission from their other utility functions and adopt appropriate structural measures to achieve these efficiencies. A key issue is whether such structural measures should be mandatory, and if so, what those structures should be.

The debate on structure has focused on two broad models for delivery of electricity under deregulation both of which recognize that there must be an independent grid operator (i.e., an ISO) but the models differ on the scope of the ISO's responsibilities. The first is direct access, where buyers and sellers of power are able to negotiate directly and the transmission grid, operated by the ISO, simply functions as a contract path to consummate the transactions. The second is a centralized power pool, where the pool sets a transparent market clearing price and the ISO dispatches power according to the principles of economic dispatch over the grid, which functions as a integrated contract network. An important collateral issue related to the functioning of a pool is how the market clearing price will be determined.

As noted in the earlier discussion on FERC Order 888, to effectuate a transmission transaction at least six ancillary services need to be provided in addition to the actual use of the transmission facilities. Some of these services, such as the provision of sufficient operating reserves, depend on the use of generating units connected to the transmission grid and will be priced and provided on a competitive basis. Existing owners of waste-to-energy projects should determine whether their generating units, in addition to supplying power to their customers, can competitively provide such services to third parties who seek transmission service.

C. The Electric Distribution Market

As is the case for transmission, the consensus is that electricity distribution is a natural monopoly characterized by significant economies of scale and scope, and, therefore, needs to be regulated. FERC, in Order 888, did not propose to require vertically integrated utilities to unbundle their distribution functions from the wholesale transmission functions, leaving it up to the states to decide how to ensure open and non-discriminatory access to distribution facilities.

1. Performance-Based Ratemaking (PBR)

A key issue is whether traditional cost-of service regulation of distribution facilities should be replaced in order to ensure that the distribution functions are done as cost-effectively as possible. As part of a decision to introduce retail access, where the distribution grid becomes a common carrier, some states are considering PBR for regulating the electricity distribution system, which involves setting a baseline revenue requirement, establishing incentives to encourage managers to produce at a cost below this baseline, as well as implementing a quality control mechanism.

2. Metering and Aggregation

Another key issue is how small residential customers can be given both meaningful choice in the electricity market and sufficient bargaining power to exercise that choice. Small customers will be unable to fully optimize on hourly prices in the spot market unless they have appropriate meters that yield both spot prices and level of their usage. The states will have to decide whether such metering should be mandatory and who should pay for their installation and maintenance. Metering concerns may be simplified by authorizing aggregation, where electricity is sold to a single buyer, other than the original regulated monopoly distribution company, which represents a number of customers.

3. Meaningful Consumer Choice

The regulator will have to decide what energy services a supplier at the distribution level must offer to the consumer. Such services could include billing services, availability of "green" energy (e.g., energy produced from the combustion of solid waste), and choice regarding the level and quality of electric service, i.e., quantity, peak v. off-peak, firm v. non-firm, and reliability. The emergence of "one-stop" utility services suppliers is likely if PUHCA restrictions are removed by federal legislation. For example, a company could offer to provide solid waste collection, sell energy generated by combustion of the waste, and provide all related billing services to the customer. Another example, made possible by the recently enacted Telecommunications Act, is a company offering both telecommunications and electric utility services.

VI. Other Issues Related to Restructuring of the Electric Utility Industry

A. Air Quality Concerns

EPA, the environmental community, and, in particular, states in the Northeast have expressed strong concerns that deregulation

of the electric utility industry will complicate the efforts of states and regions that are struggling to come into attainment with the Clean Air Act. Their position is that deregulation will drive-up demand for cheap coal-based power from plants currently subject to less stringent air pollution control requirements, primarily located in the Midwestern states. The result, it is argued, would be an increase in ozone forming nitrogen oxide emissions which would travel into the Northeast and damage state attainment plans there. Some have proposed that a mandatory system be established that would place a surcharge on any power that is wheeled from an area without heavy environmental restrictions to an area that faces more stringent technology control requirements.

The concern over air quality impacts resulting from a restructured industry, has raised related arguments, by some in the environmental community, that all generating resources should be ranked and their price of power set to reflect "an environmental impact balance sheet" where all externalities of the respective generating units are considered. Greenhouse gases are perhaps the most often cited externality. Certainly, waste-to-energy projects should fare well in such a system due to their value in disposing of solid waste while generating electricity. Although some states are looking at evaluating "externalities" in making power resource decisions (e.g., Oregon is considering applying a CO₂ emissions standard in decisions on siting generating units), it is presently not clear whether the restructuring debate will be expanded to seriously deal with the issue.

B. Stranded Benefits: Public Responsibility Programs

Virtually all state regulatory agencies have mandated so-called "public responsibility programs" that impose on electric utilities requirements, beyond simply delivering reliable electricity at lowest costs, in order to further social and environmental policies. Utilities have been required to participate in low-income ratepayer assistance programs; energy conservation programs, including adopting baseline rates established both to protect ratepayer as a class from high rates and to require surcharges for energy use above the baseline; research and development programs; and programs to encourage energy efficiency and renewable energy production. With restructuring, such programs could become "stranded benefits" since it would be unfair to require the regulated utility to alone fund them after it no longer is the sole provider of utility services. Unless new policies and, likely more complex, regulations are put in place to ensure sufficient funding, these programs are in jeopardy.

VII. Congressional Initiatives

Key members of the House and Senate have made federal legislation to comprehensively restructure the electric utility industry down to the retail level a top priority for the 105th Congress. The two key bills introduced this year are S 237 by Senator Dale Bumpers (D-AR), Ranking Member on the Senate Energy and Natural Resources Committee, and HR 655 by Congressman Dan Schaefer (R-CO), Chairman of the Energy and Power Subcommittee of the House Commerce Committee. The Clinton Administration is also drafting legislation which is likely to be based on a preliminary draft bill prepared by the Department of Energy (DOE). The discussion below compares how the three bills address the critical issues identified in the previous section.

An additional and critical issue to be resolved at the federal level, and not clearly addressed by the three bills, is whether, or to what extent, federal legislation should preempt actions which may have already been taken by the states. Depending on how one has fared under a restructuring approach taken by a state, federal preemption may or may not be desirable. For example, California's abandonment of a mandatory minimum renewable resource portfolio for all suppliers of power and adoption, instead, of a mechanism to collect \$540 million over a four year period (through the imposition of a distribution system usage fee) to enhance renewable energy development, has been criticized by the renewable energy industry but supported by the state's electric utility companies.

Finally, demands by the traditional electric utility companies that the competitive "playing field be leveled", through elimination of tax-exempt financing by local government utilities and special tax subsidies to particular types of power generating technologies, may result in separate action by Congress on legislation amending the tax code.

A. Retail Access

HR 655 and S 237 would establish a federal mandate for all electric utilities, including public power systems, to implement retail wheeling by December 15, 2000 and December 15, 2003, respectively. Retail access plans adopted prior to enactment of the bills cannot be preempted if the plans satisfy the bills' requirements. Under the DOE bill, states would have until January 1, 2000 to decide whether or not they will require retail wheeling or implement a wholesale competitive procurement model.

Under HR 655, if a state failed to adopt retail access, FERC would be authorized to act as a "backstop" and implement retail wheeling in the state. Upon the effective date for retail choice in a state, the state regulatory authority will be prohibited from regulating the rates of retail providers of electricity.

B. Stranded Costs

Both HR 655 and S 237 authorize state regulatory agencies to recover stranded costs through a separate charge as a pre-condition to a retail transaction by a former customer. S 237 expressly authorizes the state regulatory authority in calculating the amount of its stranded costs to require utilities to mitigate such costs or require the utility to sell, or to ask FERC to order sale of, all of its generating facilities and subtract the revenue received from the book value of the assets sold.

C. PURPA Repeal

The three bills all would repeal the mandatory purchase provisions of PURPA on a prospective basis. Repeal would occur under HR 655 once a state determines that all customers of an electric utility have retail choice; under S 237, upon its enactment, but only for PURPA facilities beginning commercial operations thereafter; and under the DOE bill, if a state regulatory authority adopts either the retail competition or wholesale competition models set forth in the bill.

All three bills would establish a minimum generation requirement for renewable energy, a so-called "portfolio" standard. All generators of electricity that sell power would be required to submit renewable energy credits to FERC on an annual basis. Credits could be obtained either by directly investing in renewable energy generation or by purchasing renewable energy credits on the open market from those having made such investments. The minimum renewable energy that would be required equals: two percent of a utility's generation increasing to four percent in 2010 under HR 655, five percent in 2003 increasing to twelve percent in 2013 under S 237, and five percent under the DOE bill.

The benefits of the renewable portfolio requirement to the waste-to-energy industry depends on how a "renewable resource" is defined. HR 655 and the DOE bill do not exclude energy derived from municipal solid wastes from the definition of a renewable resource. Unfortunately, S 237 currently defines the term to exclude this energy resource because of opposition from certain environmental groups to the use of waste-to-energy technology. The opposition appears to be based on two main concerns: air emissions, and in particular dioxins; and fear that waste-to-energy facilities could absorb a large amount of whatever set-asides/subsidies/or credits Congress may provide to the renewable industry to the disadvantage of less technologically mature renewable energy sources.

A bill expected to be introduced by Congressman Markey (D-MA), a key member of the House Commerce Committee on the

restructuring issue and a strong supporter of renewable energy, would condition relief from PURPA within a given state on whether the state instituted retail wheeling or mandatory generation divestiture by utilities and met minimum standards intended to preserve renewable energy development, energy conservation, and low-income consumer protections. The legislation is expected to allow a state, until full retail competition is established, to establish a bidding process to meet the state's energy capacity needs in which a specific percentage of bidding QFs would have to be renewable energy sources. Such a provision would overturn a portion of FERC's 1995 ruling invalidating California's proposed methodology of calculating full-avoided cost which took this approach.

D. PUHCA Repeal

Under HR 655, PUHCA would cease to apply to holding companies, on an individual basis, once each state in which the holding company operates determines that all customers have retail choice of electricity. S 237 would repeal PUHCA one year after the date of enactment. The DOE bill would allow FERC to remove a PUHCA restriction relative to a holding company if it determines that the restriction is not relevant to the power rates charged by the holding company or its affiliates. All three bills require holding companies (including their subsidiaries, affiliates and associate companies) to maintain and make available to FERC all books, records or other documents that FERC deems relevant to power costs and necessary for the protection of consumers. State regulatory agencies are authorized to gain access to the books and records of the holding company and its affiliated companies.

E. Mitigation of Market Power

Under the DOE bill, for states that adopt retail competition, if the state commission believes that a utility in the state has market power, FERC may order remedial action including divestiture of generating resources.

F. Public Benefit Programs

HR 655 and S 237 authorize state regulatory agencies to impose charges to fund public benefit programs, including universal service, provided such charges are imposed on a nondiscriminatory and competitively neutral basis. The DOE bill establishes a National Electric Systems Benefits Fund (NESBF) to provide matching funds to states to support conservation and energy efficiency, renewables, universal service, and research and development.

G. The Level Playing Field

HR 655 prohibits the resale of federal preference power by state and local government utilities to customers outside their current service territory. S 237 authorizes TVA to sell retail and wholesale electric energy outside of its service territory but authorizes TVA's retail and wholesale customers to buy energy from other sellers.

H. Independent System Operators (ISO)

S 237 requires that FERC, within two years, establish transmission regions and designate an ISO to manage and operate all of the transmission facilities in each region beginning on December 15, 2003. States making up a particular transmission region can form a Regional Transmission Oversight Board to oversee the ISO and would be given the same authorities FERC currently has over transmission pursuant to the Federal Power Act.

I. Regional Regulatory Agencies

Under the DOE bill, two or more states may agree to establish a regional regulatory agency (RRA), which will have authority over transmission of electric energy and sales for resale in interstate commerce (including the authority to require transmission access and to set rates and terms of service).

J. Air Quality Impacts

S 237 requires EPA to submit a study to Congress by January 1, 2000, on the impacts of restructuring on the emissions of air pollutants, and to recommend necessary changes to law to protect public health and the environment.

VIII. Conclusion

Proponent of waste-to-energy projects need to be familiar with the many restructuring issues that directly and indirectly affect the viability of these projects. Vigilant monitoring of developments to restructure the electric utility industry will be required, first at the state level, where the majority of action is currently taking place, and secondly in Washington, D.C., both at FERC and in Congress. Active participation in the debate at the state and federal levels is encouraged. Above all, proponents of waste-to-energy projects should avoid being taken by surprise and have the capability to intervene on a timely basis if necessary.

TECHNICAL SESSION I

Recycling Issues

Recycling Steel Automatically—Through Resource Recovery

Walter J. Foley
General Manager, Federal Relations
Steel Recycling Institute
1667 K Street, NW Suite 460
Washington, DC 20006

ABSTRACT

Last year, more than 55 percent of all steel cans were recycled. But no matter how effective the local recycling programs may be, some steel cans and other steel products are overlooked and appear in MSW. This missed steel fraction is automatically recycled by resource recovery facilities through magnetic separation.

More than three-fourths of the operating resource recovery plants magnetically separate steel cans and other discarded steel items either pre- or post-combustion. Recovering ferrous scrap clearly reduces the post-combustion material that is landfilled and heightens the facilities' environmental performance.

Both the resource recovery and steel industries must heighten public awareness of the benefits of automatic steel recycling. Magnetic separation at resource recovery facilities is a simple method of diverting what would otherwise be relegated as solid waste to the landfill. It should be recognized as an increasingly important and valued part of the resource recovery and steel industries' overall recycling efforts.

This paper will discuss the status of steel can recycling in the United States, describe how recovered ferrous is beneficiated before recycling by the steel industry, and make recommendations for heightening awareness of the steel recycling contribution made by resource recovery facilities.

INTRODUCTION

Communities, businesses and institutions collect steel cans for recycling through curbside and dockside programs throughout the country. Last year, about 55.9 percent of all steel cans were recycled. Ferrous scrap dealers, the "original recyclers," collect and process enormous tonnages of scrap iron and steel for recycling. But no matter how effective local recycling efforts may be, some steel cans slip through recycling's nets and appear in the municipal solid waste stream. And the many other smaller iron and steel scrap items that do not routinely go to the scrap yard are also discarded. In areas served by resource recovery, however, this missed steel fraction is automatically recycled through magnetic separation.

More than three-fourths of the operating resource recovery plants magnetically separate steel cans and other discarded steel items either pre- or post-combustion. Automatic recycling of steel clearly reduces the post-combustion material that is landfilled and heightens the facilities' environmental performance through tangible recycling achievement. Magnetic separation at resource recovery facilities is a simple and desirable method of diverting what would otherwise be relegated as solid waste to the landfill. It should be recognized as an increasingly important and valued part of the resource recovery and steel industries' overall recycling efforts.

SOURCES OF STEEL SCRAP

It's important to understand how all forms of steel recycling take place and how it relates to resource recovery. The steel industry has a healthy appetite for steel scrap. The two types of steelmaking furnaces in use today, the basic oxygen furnace and the electric arc furnace, were designed to make fullest use of scrap resources. In fact, 70 million tons of steel scrap were recycled in 1995 alone.

This scrap is obtained from three sources: mill scrap generated during the steelmaking process itself; industrial scrap generated from the manufacturing process; and post-consumer scrap, or old steel products. Mill and industrial scrap resources never enter the municipal solid waste stream. They are routinely collected and shipped to ferrous scrap processors which prepare them for recycling.

However, more than half of the steel industry's supply of steel scrap comes from post-consumer scrap resources, some of which is derived from or never enter the municipal solid waste stream. These include the millions of tons of steel cans, cars, appliances and construction and demolition materials

recycled each year. For the most part, each of these commodities have a collection system that captures a large portion of them for recycling. There are some instances, though, where they will show up at a waste-to-energy plant.

Automobile recycling is a success story of huge proportions—with a virtual 100 percent recycling rate. Cars are not buried but are stripped, flattened and shredded, enroute to steel mill consumption. Various automobile parts, however, including oil filters and body components, incidentally enter the municipal solid waste stream and can be captured through resource recovery.

Appliance recycling is now also growing through communities across America. The recycling rate for appliances in 1995 was 74.8 percent. Appliances should be collected, processed and recycled routinely without ever entering the waste stream. Various components, such as replaced parts, and small appliances like toasters and fans show up in the municipal solid waste stream and are gathered by resource recovery.

Construction and demolition projects affect resource recovery by adding ferrous tonnage to the scrap iron and steel automatically recycled through magnetic separation. New construction or demolition on smaller jobs generate incidental iron and steel scrap that go to the municipal solid waste stream and can only be efficiently recovered through resource recovery. Larger jobs create significant quantities of scrap, however, that goes directly to a scrap dealer for mill preparation.

Therefore, through magnetic separation, waste-to-energy plants play an important role in capturing for recycling those ferrous components of the municipal solid waste stream that evade traditional recycling programs. Clearly, automatic recycling by magnetic separation at resource recovery facilities is a simple and desirable method of diverting what might otherwise be relegated as solid waste to the landfill. It is an increasingly important part of the resource recovery and steel industries' overall recycling efforts.

THE STEEL INDUSTRY: RECYCLING STARTED HERE

Most resource recovery facilities, recognizing the inherent recyclability of steel, magnetically separate scrap iron and steel rather than landfill it. When properly prepared, this recovered ferrous scrap is readily marketed. In addition to melting steel cans and other ferrous derived through resource recovery, the steel industry is also a major consumer of source separated steel cans, appliances, automobiles and steel construction and demolition materials. Iron and steel foundries also consume source separated steel cans in significant quantities, therefore providing additional incentive for steel cans to be included in curbside and drop-off programs. We need to look at why steel cans as well as other municipal solid waste derived ferrous are desirable when this has not always been the case.

Steel Mills and Foundries Recycle Steel Cans and Other Ferrous Scrap

Recycling steel scrap has always been an integral part of the steelmaking process. In fact, for the past 50 years, more than 50 percent of the steel produced in the United States has been recycled into a multitude of new steel products. These new steel products will eventually be remelted again by mills to make new steel.

Due to technological advances in the art of steelmaking, the two types of furnaces used in today's steel mills require steel scrap to make new steel. The first, the basic oxygen furnace, combines molten iron with approximately 28 percent steel scrap. The other, the electric arc furnace, melts virtually 100 percent steel scrap.

Through advances in technology and increases in efficiency in the steelmaking and manufacturing processes, less mill and industrial scrap is being generated. This has created a demand for post-consumer scrap.

Increasingly since 1988, steel food, beverage, paint and aerosol cans, which are recyclable as scrap themselves for new steel production, have been filling this shortfall. Manufactured from the highest grade of steel, they are recognized as an excellent source of steel scrap and have gained great acceptance as a desired commodity. One of the reasons why is that steel cans no longer have the restrictive amounts of tin that melters once feared. They can now be directly charged into a steel mill furnace rather than be routed to a detinning facility first. As a result, the steel industry is prepared to consume all steel cans collected, recycling them into new steel.

In addition to new steel, steel cans are also being recycled into iron products. A study performed by the University of Wisconsin-Madison first confirmed how steel cans could serve as a scrap resource for foundries across the United States. Taking part in the study, Waupaca Foundry in Wisconsin recycled more than 15,000 tons of steel cans into iron products. Since then, several other foundries are recycling steel cans and are using or considering using municipal solid waste derived ferrous from resource

recovery. There are more than 1,500 iron and steel foundries, which will potentially provide end markets for many communities across the United States.

METHODS OF COLLECTION FOR RECYCLING

In the last seven years, old steel products have become a more desirable scrap resource. Automobile and construction and demolition material collections have long supplied steel mills and foundries with enormous quantities of steel scrap, while steel can and appliance collection programs have more recently taken root and now share a greater portion of the steel industry's overall recycling efforts. Magnetic separation at resource recovery facilities supplement these collection programs and, often in the case of steel cans, may even serve as the only steel recycling program in the community.

Source Separation Recycling Programs

Most residents are serviced by curbside recycling, or a combination of curbside and drop-off programs, that accept steel cans. In a curbside program, residents are responsible for commingling recyclables together into a storage bin and placing the bin at the curbside for collection. Recyclables are collected by truck and delivered to a secondary processor for sorting, preparation and shipment to end markets.

Drop-off programs may operate as the sole recycling program in rural areas where curbside recycling is not feasible. To participate in this recycling program, residents bring their steel cans and other recyclable materials to a drop-off site. These sites may also supplement curbside collection, giving residents additional opportunities to recycle steel cans. Multi-commodity buyback centers operate somewhat similarly. In the United States, there are now more than 16,000 curbside, drop-off and buy back collection programs that accept steel cans for recycling.

Steel cans and other recyclables generated by schools, businesses, hotels, restaurants and other commercial/institutional establishments are collected through their own dockside recycling programs. Employees separate empty steel cans and store them in a large container or roll-off for recycling. Haulers collect and deliver recyclables to secondary processors for handling and shipment to end market.

Many communities have established temporary or permanent collection programs to ensure that appliances do not enter the municipal solid waste stream. By weight, the typical appliance consists of about 75 percent steel, which is largely why 1,600 ferrous scrap processors across the country process ship them to steel mills for recycling. Since 1990, the national recycling rate for major home appliances has risen from 32 percent to 74.8 percent due in part to increased private and public sector awareness and the continuing development of a strong infrastructure for recovery of ferrous scrap from appliances.

Despite their complex construction, automobiles are one of today's most recycled commodities. Whole automobiles are simply not landfilled. The reason why is that the steel and iron components, which make up about 70 percent of the weight of the average vehicle, are too valuable. Instead, automobiles are shredded at ferrous scrap processing yards. In 1995, approximately 13 million tons of steel from shredded automobiles was shipped to steel mills for recycling.

The sheer size and number of construction and demolition projects in the United States produce a considerable amount of steel scrap. Each year, the steel industry recycles approximately 30 million tons of steel recovered from construction and demolition projects.

Automatic Recycling of Steel Cans and other Ferrous from Resource Recovery Facilities

Whether source separation recycling is available or not, resource recovery facilities offer unique advantages. It takes steel mill temperatures in excess of 2800 degrees Fahrenheit to melt steel. The typical waste-to-energy facility's furnace temperature rises as high as 1800 degrees Fahrenheit, but far short of the temperature needed to melt steel. But, by magnetically separating steel scrap before or after combustion, resource recovery facilities avoid landfilling this recyclable steel scrap. The incremental costs of cleaning and processing of steel scrap for reuse by steel can end markets is largely offset by the incremental revenue and cost avoidance. The intangible value of recyclability itself is even higher and is suggested as a benefit for all concerned.

When seeking to maximize the diversion of recyclable material from the solid waste stream, curbside and drop-off collectors and processors are largely dependent upon the participation of area residents in a traditional recycling program. However, magnetic separation of steel cans at resource recovery facilities automatically recovers more than 90 percent of the steel can scrap generated from a community. Residents participate in recycling steel cans just by disposing of them normally. For instance, it was determined in Florida in 1994 that steel cans are being recycled at a rate exceeding 64.4 percent. This

higher than national average recycling rate for steel cans is rightfully credited to magnetic separation by resource recovery facilities across the state.

Just as importantly, steel cans and other ferrous scrap are automatically recycled from the entire community serviced by resource recovery. This means that in addition to all households being covered, area businesses, schools, and other commercial and institutional establishments automatically recycle their used steel cans, old bicycles, tools and other used items. Therefore, magnetic separation of steel at resource recovery facilities achieves tremendous economies of scale by fulfilling the functions of both residential and commercial/institutional recycling programs for steel items.

Finally, resource recovery facilities magnetically separate all types of steel products, including steel food, beverage, paint and aerosol containers, appliance and automobile components, and construction and demolition debris from a community's solid waste stream. Steel paint and aerosol cans, in addition to steel food and beverage cans, are part of the steel industry's overall recycling efforts—even though they may not be included in a community's source separated recycling program. Minor or even major product contamination of these containers is handled in a very forgiving nature by the combustion process. In addition, ferrous scrap not normally recoverable—such as steel box springs from a mattress—are recovered for recycling from the 80 percent of the facilities that separate steel post-combustion.

According to the Steel Recycling Institute's most recent statistics, 98 resource recovery facilities across the country separate steel cans and other ferrous for recycling, accounting for more than 40 million residents serviced. Of these, more than 18 million residents are serviced exclusively by resource recovery, meaning their steel cans and other post-consumer steel products would not be recycled if it were not for the presence of these facilities.

PROCESSORS OF STEEL CANS AND MUNICIPAL SOLID WASTE-DERIVED FERROUS SCRAP

All steel products, whether collected from communities through source separation recycling programs or through magnetic separation with other ferrous scrap at resource recovery facilities, require processing for shipment to steel industry end markets.

Source Separation Recycling Programs

When collected through community recycling programs, steel food and beverage cans should initially be rinsed clean. Steel aerosol cans must be empty of their contents, and steel paint cans should only have a thin skin of dry paint left on the inside of the can. All steel cans may be processed and baled together, regardless of type.

Ferrous scrap dealers have long supplied the steel industry with processed scrap. More recently, many of these businesses have added steel cans to their collections of appliances, automobiles and construction materials as the demand for steel cans has risen. Scrap processors are effective processors of source separated steel can scrap because much of the necessary equipment to process steel cans is already in place, and the links to end markets for steel cans are well developed.

Material recovery facilities also process steel cans recovered from communities through community recycling programs. These facilities magnetically sort steel cans from commingled recyclables for baling and shipment to end market.

Appliances, automobiles and construction and demolition material are processed at ferrous scrap yards for recycling. Automobiles and appliances are shredded and the steel is magnetically separated from the remaining material. Depending on their size, construction and demolition materials may be sheared, baled or shredded before shipment to end market.

Cleaning Steel Cans and Other Ferrous at Resource Recovery Facilities

Before they are recycled, steel cans and other ferrous scrap generated from resource recovery facilities must first be upgraded through additional processing. This is necessary because ferrous recovered from the estimated 20 percent of facilities that separate it before combustion has residue from solid waste, while ferrous recovered after combustion is coated with ash.

Specialty vendors typically perform the necessary steps. Methods vary from vendor to vendor, but ordinary proven mechanical processes are used, such as shredding, air blowers, screening, trommeling and additional magnetic separation. Cleaning the ferrous scrap produces a marketable material with predictable chemical characteristics.

Most operators would agree that this process should be performed on the site of the resource recovery facility. When performed on-site, no additional arrangements or negotiations need to be made regarding leftover residue. It can just go back into the resource recovery plant—or, if ash—be

appropriately managed. Off-site cleaning of the steel does occur, however, when there is limited space at the site of the facility, or when existing equipment for process already exists off-site. Residue is disposed of in accordance with local, state and federal laws.

CONCLUSION

Steel cans, automobiles, appliances and construction materials are already recycled in enormous quantity. Automatic steel recycling through resource recovery assists the steel industry in recovering the smaller ferrous components that would otherwise be landfilled. Performing magnetic separation decreases a resource recovery facility's costs associated with the disposal of post-combustion material and generates incremental scrap revenue. Whether recovered pre- or post-combustion, ferrous scrap is a marketable material. These facilities, through automatic recycling, recover virtually all steel cans from the community— independent of active participation by residents. The increased diversion of steel cans and other ferrous items from the solid waste stream accordingly improves the measured statistical rate of steel can recycling and provides a measurable recycling statistic for resource recovery.

Scrap Tire Derived Fuel: Markets and Issues

John Serumgard
Scrap Tire Management Council
Washington D.C. 20005

For Presentation at the
Fifth Annual North American Waste to Energy Conference
Research Triangle Park, NC
April 22 - 25, 1997

INTRODUCTION

More than 250 million scrap tires are generated annually in the United States and their proper management continues to be a solid waste management concern. Sound markets for scrap tires are growing and are consuming an ever increasing percentage of annual generation, with market capacity reaching more than 75 % of annual generation in 1996. Of the three major markets - fuel, civil engineering applications, and ground rubber markets - the use of tires as a fuel is by far the largest market. The major fuel users include cement kilns, pulp and paper mills, electrical generation facilities, and some industrial facilities. Current issues that may impact the tire fuel market include continued public concern over the use of tires as fuel, the new EPA PM 2.5 standard, possible additional Clean Air Act emissions standards, access to adequate supplies of scrap tires, quality of processed tire derived fuel, and the possibility of creating a commodity market through the development of ASTM TDF standards.

Scrap Tires are an ubiquitous by-product of contemporary social and economic society. Our personal mobility is almost entirely dependent on the pneumatic tire, whether in automobiles, buses or even airplanes. The transport and delivery of most goods is also dependent on the pneumatic tire. To recall an old slogan of the American Trucking Association, "If you got it, a truck brought it", and it goes without saying that the truck was riding on pneumatic tires.

Tremendous strides have been made over the last several years in both the durability and the longevity of tires. Auto tires routinely provide 40,000 mile or more of travel, almost four years of life for the average car, and many give 60,000, 80,000 or more miles of life. Medium truck tires, those used on the typical over the road semi-trailer, are heading toward a 500,000 life (with the advantage of one, two or more retreadings). Ultimately however, all tires reach the end of their useful lives as tires and then become a solid waste issue.

In the past there were many poor management practices routinely used for scrap tires, some of which resulted in adverse environmental impacts (and frankly we are still living with the some of those consequences). However, in the last few years much attention has been devoted both to imposing responsible restrictions on the handling of scrap tires and on the development of reuse, recycling and recovery markets for scrap tires. As with any other material being diverted from the solid waste stream, the development of alternative use markets is imperative to making diversion a success.

In 1990, as the Scrap Tire Management Council was being organized, the USEPA estimated the markets for scrap tires as being less than 11% of annual generation. After several years of growing scrap tire markets, the Scrap Tire Management Council estimates that as of the end of 1996, scrap tires markets had the capacity to consume over 75% of annual generation. This is a tremendous expansion of the sound markets for scrap tires and a real life success story for an industry that largely did not exist only seven years ago.

ABOUT THE SCRAP TIRE MANAGEMENT COUNCIL

The Scrap Tire Management Council (STMC) is a non-profit advocacy organization, organized and supported by the North American tire manufacturing industry to be the spear-head of efforts to identify and promote environmentally and economically sound markets for scrap tires. The primary goal of the Council is to assist in the creation of market demand for 100 percent of the annually generated scrap tires in the United States. Based on current market demand and projected market growth, it is envisioned that this goal should be met by the turn of the century.

NATIONAL GENERATION RATES

For the past two years, this country generated approximately 253 million scrap tires, or approximately one scrap tire per capita. This number should increase gradually to approximately 260 to 275 million by the turn of the century.

A question is often raised about the number of tires in stockpiles. As part of the 1994 market update, the Council undertook a survey of all state regulatory agencies to compile the most comprehensive listing of stockpile inventories. According to the data collected, the numbers suggest that there are approximately 700 to 850 million scrap tires in inventory. This is a far cry from the two to four billion number some sources including the United States Environmental Protection Agency have been using.

The significance of this finding is two fold. First, it places into perspective the actual dimensions of the stock pile situation. Second, those scrap tires in stock piles have only two market applications; as tire-derived fuel or in civil engineering applications. If the tires must be shredded, rough shred applications such as lightweight fill, would then become available for these tires.

MARKETS FOR SCRAP TIRES

There are three major markets for scrap tires:

- Tire-derived fuel (TDF), including both whole tires and processed tires;
- Products (including those made from size-reduced rubber and stamped, punched or cut rubber products); and
- Civil engineering applications.

In addition there are other markets for tires, including:

- Export of good used tires and retreadable casings; and
- Agricultural and miscellaneous applications

Over the past six years the number of annually generated scrap tires having markets has increased from 11 percent (25 million units) in 1990, to 38 percent (95 million) in 1992 to almost 56 percent (138 million) in 1994. At the end of 1995, 69 percent (174 million) scrap tires were being sent to markets. And as of the end of 1996, STMC preliminary projections indicate that sound scrap tire markets have the capacity to consume more than 75 % of annually generated scrap tires, or more than 190 million scrap tires (Table 1). While this has been a very dynamic growth rate, current events suggest that it will be unlikely for a continuation of this rate of market expansion.

Table 1: Estimated Scrap Tire Market Capacity at January 1, 1997 (preliminary)
(Millions of Tires)

Fuel	145.5
Products	
Cut, Punched, Stamped	8.0
Ground Rubber	10.0
Civil Engineering	10.0
Export	15.0
Agriculture & Miscellaneous	2.5
TOTAL:	191.0

Although the Scrap Tire Management Council (STMC) is predicting a slower rate of market growth, the STMC is confident that, ultimately, the market demand for 100 percent of the annually generated scrap tires will be developed.

At present, the markets for scrap tires include the following.

Tire Derived Fuel currently consumes 145.5 million scrap tires annually. Tire derived fuel includes both whole tires and processed, or cut up, tires. The principal market segments utilizing tire derived fuel include:

- cement kilns;
- pulp and paper mill boilers;
- utility boilers;
- industrial boilers; and
- dedicated scrap tire to energy facilities.

The newest market to develop is the use of tires in the metal industry, including foundry cupolas. The combined fuel market segment has the ultimate capacity to consume some 250 million scrap tires a year, or nearly all that are generated. The TDF requirements range from whole tires (i.e., as used in cement kilns or dedicated scrap tire to energy facilities), to rough shreds (i.e., as used in cement kilns & dedicated scrap tire to energy facilities) to 1" X 1" to 2" X 2" shreds (i.e., as used in pulp and paper mills, industrial and

utility boilers). The type of TDF necessary for any end-user will be a function of the type of combustion facility, the type of primary fuel used and, the feeding system used.

Products include products cut, punched or stamped from tire carcasses (usually only from bias ply tires), and products manufactured using ground crumb rubber produced from scrap tires and other scrap rubber. Cut, punched and stamped products include dock bumpers, heavy duty flooring, muffler hangers and various other industrial and consumer products. Ground rubber is produced by grinding up scrap tires and removing the steel and fiber. Other sources for ground rubber include factory scrap from both tire and non-tire rubber products manufacturing and the rubber buffing dust produced as a by-product of the tire retreading process. Ground rubber is used in some new rubber products such as mats, in asphalt rubber, in friction products, in products produced using a binding agent such as polyurethane, and in sports surfaces.

Civil engineering applications include the use of shredded tire material as light weight fill material, as leachate field material in on site septic systems, as alternate daily cover and in leachate layers and gas collection layers in landfill operating and construction, and in such constructions as artificial reefs and floating breakwaters. In these applications the tire derived materials substitute for the materials normally used and bring new engineering value to the application.

CHARACTERISTICS OF TIRE-DERIVED FUEL

Eighty-eight (88) percent of the tire is composed of carbon and oxygen, which accounts for its rapid combustion and relatively high heating value. Tires contain approximately 14,500 - 15,000 BTU's per pound. This compares favorably to coal which, on the average, contain some 12,000 BTU's per pound. Subsequently, when substituting tire-derived fuel (TDF) for coal, a kiln operator can reduce coal by 1.25 pounds for every pound of TDF used.

Tire-derived fuel is also a consistent material. Tires, regardless of where they were manufactured, or by whom, typically contain 1.2 - 1.5 percent (by weight) sulfur, 1.5 percent (by weight) zinc, less than one percent moisture, two and one half pounds of high grade steel per passenger car tire and a short list of trace metals. Tires are also very low in nitrogen, relative to other fossil fuels.

The consistent composition, and the relatively low quantities of certain constituents (i.e., sulfur, nitrogen) and the relatively high heating value of TDF are the primary reasons TDF can be used successfully in a wide array of combustion facilities. It is also the reason why TDF can have a positive impact on the emissions from these facilities.

CURRENT ISSUES AFFECTING THE TIRE FUEL MARKET

Even as the use of tire derived fuel is expanding, there are issues that could complicate future expansion, or cause questioning of current uses. In addition, there are steps that can be taken to improve the climate and the market for tire derived fuel. Discussed below are several of these current issues.

Continued public concern over the use of tires as fuel

Whenever a facility proposes to begin using tires or TDF as a supplemental fuel, it may encounter various levels of public concern or opposition. For example, some people may be concerned about black smoke or adverse odors while others may be concerned about possible harmful emissions. Yet another group may oppose the use of tires as fuel because it is not recycling or a higher value reuse.

For many people, the only experience they may have with burning tires is a TV news story about a major tire fire with raging flames and lots of smoke. Or they may have encountered an actual burning tire somewhere in their experience, and it probably wasn't all that pleasant. What they have seen or experienced is the products of incomplete combustion of tires. In fact, when tires are used in a properly controlled combustion environment, such as a fuel boiler or a cement kiln, they make an excellent fuel with no adverse smoke or emissions. And this conclusion has been reached by a number of responsible organizations, including the US EPA and the California Integrated Waste management Board, in a variety of published studies. Usually, the presentation of this evidence to the concerned public will help dampen their concerns.

Likewise there has developed a considerable body of emissions data from facilities that have gone through the fuel permitting process and conducted emissions tests. This data universally demonstrates that tires are generally a better and a cleaner fuel than coal, the fuel it normally replaces. Most facilities seeking to use tires as fuel will have to undergo their own air emissions testing as part of the permit modification process. Again, when this data is presented, reasonable people normally accept that TDF can be used safely in the facility seeking to use it. For those people concerned that using tires as fuel is not the highest value use for tires, the fact that these higher value markets may not exist in the local market area, or may be developing so slowly that they can not begin to consume large volumes of tires in the reasonably foreseeable future. In the meantime, markets are needed for tires.

With the expansion of the TDF market to more than 100 using facilities across the country, and about an equal number in the considering or testing process, the possibility of public opposition seeming more wide spread is apparent. It is to be hoped that continued presentation of the facts, and of sound data derived from emissions testing, will dissuade all but the most irrational opposition. Or in other words, that good science will offset shrill voices.

The new EPA PM 2.5 standard

The US Environmental Protection Agency has recently issued a new proposed standard to regulate particulate emissions down to the 2.5 micron level. Many industries are deeply concerned about this proposed standard both because in their view there is little evidence of real hazard from particulate of this small size and because of the perceived difficulty in meeting it. To date, facilities using tires as fuel has been able to meet existing particulate standards. In fact, in many applications, the use of TDF fuel results in **reduced** particulate emissions when compared with the baseline fuel. It is to be hoped that this past experience suggests that the PM 2.5 proposed standard will not adversely affect the use of TDF. However, until we have some actual testing results, this will be an area of concern.

Possible additional Clean Air Act emissions standards

The Clean Air Act of 1990 adds significantly to the range of substances that will eventually be subject to air emissions standards. Of course many of them will not be of any concern for tires. However, tires are composed largely of petrochemical based compounds and thus there may be compounds or substances that could possibly of concern. Until we know the standards which will have to be met, this issue will continue to be an area of concern for the use of TDF.

Access to adequate supplies of scrap tires

It probably sounds somewhat implausible to discuss the issue of access to supplies of scrap tires when there are around 800 million in stockpiles and probably 60 to 70 million that are not currently going to markets. However, the economics of scrap tire markets limits the distance that tires or even tire derived fuel can be transported. Typically whole tires are limited to around a 150 mile transportation distance before the cost of transportation outweighs the value of the tires. Processed TDF can be transported a longer distance, but that distance is also a function of the value being placed on the TDF as reflected by the amount being paid for it. TDF markets also tend to develop in states where there is an effort being made to develop scrap tire markets. As a result, fuel users could find themselves being in a locally competitive market for tires, even as other parts of the country are finding difficulties in creating scrap tire markets. Some states have developed such a high level of market demand that they are importing scrap tires from other states (i.e. Connecticut, Maine, Illinois and South Dakota).

As for those stock piles, unless there is some funding available to clean them up and process them, either from the stock pile owner or a state agency, they won't make it to any market. The amount a fuel user would be willing to pay for the TDF normally would not be enough to remove tires from a stock pile and process them to the proper size. The economics of scrap tires generally requires both a front end tip fee, usually collected from the original owner of the scrap tire, and the price received when the final scrap tire derived product is sold. Many stock piles have been effectively abandoned by their owners, or the owners have no financial capacity to remediate their piles.

Quality of processed Tire Derived Fuel

At present, there are more than 500 companies in the latest edition of the Scrap Tire Users Directory who claim to be producing tire derived fuel. It is likely that a significant number of those producers are not capable to producing a quality TDF product on a consistent basis. They can probably produce some good product when their shredder knives are new, and they are operating at a slow enough rate to allow reprocessing of out of spec product. But give them a few weeks or months on the knives, and a processing speed needed to keep up with their tire collections, and the product they are producing might be useful only for civil engineering uses. That would be fine, if that's where they were marketing their product. But some of them seek to market this product to fuel users that other producers may have developed, and the lure is of course price. If the fuel user changes suppliers and then finds that the quality of material being delivered is not up to specification, and is causing problems in the boiler, the user may just stop using TDF. In the long run, we believe that TDF suppliers able to consistently deliver quality product will be the ones who will survive in the market place. Unfortunately, in the meantime, the quality of TDF being supplied to the market will be an issue of concern.

This is not to imply that the fuel user is entirely without blame. It is the basic imperative of the tire fuel market that most fuel users' main motivation for using tires is economic—that is they are seeking reduced fuel costs by replacing a percentage of their basic fuel with TDF. Unfortunately some fuel users believe that they should receive all of the benefits of using TDF, that they should be entitled to squeeze the last cent out of their suppliers. This attitude can be initially productive for the fuel user, but if the TDF processor is not making enough to meet its costs, including maintenance and knife replacement needs, then the quality of the TDF will drop and the user will experience problems. The better scenario will be for the fuel user to be willing to pay a fair price for the TDF, one that will allow the TDF supplier to be competitive for tire supply and to operate in such a fashion as to be a consistent supplier of quality TDF.

The development of ASTM TDF standards

Most every fuel product has a series of size and quality standards accepted by the fuel market place that allow the fuel product to be bought and sold as a commodity. At present, we do not have such a set of standards, accepted by both TDF suppliers and TDF users, that would allow TDF to be traded as a commodity. The Scrap Tire Management Council is taking an active leadership role is one major effort to develop such a set of standards, just as it has done with the ground rubber market. In the case of the TDF standards, the venue for this activity is the American Society for Testing and Materials (ASTM) and its D34.08 subcommittee. The D34 committee deals with waste management and the D34.08 subcommittee deals with thermal treatment. The STMC is working to develop a draft standard for this committee to consider, and to involve the TDF producer and user communities in this effort. If a standard can be developed, it is

hoped that it would become the basis for efforts to trade TDF as a commodity, such as on the Recyclables Exchange of the Chicago Board of Trade.

CONCLUSION

All scrap tire markets are expanding, including the use of tire derived fuel. There may come a time when the use of tire as fuel begins to decline as other markets place a higher value on tires and their consumption begins to cut into the supply of tires available. However, this situation is likely to be several years off. In the mean time, the tire derived fuel market must be encouraged and promoted. A significant part of this effort will be to deal with the issues raised in this discussion that could potentially harm the scarp tire fuel market. Everyone interested in the markets for scrap tires should take an active part in the efforts to develop sound scientific information about scrap tire use, and to implement and expand scrap tire fuel markets in a responsible manner.

**Advanced Thermal Processing Alternatives
for Solid Waste Management**

**Walter R. Niessen
Camp Dresser & McKee Inc.
10 Cambridge Center
Cambridge, MA 02142**

ABSTRACT

The 1990's have seen a resurgence of interest in the development of new thermal processing alternatives for municipal solid waste (MSW). Sparked by increasingly stringent environmental regulations, much of this creative energy has been applied to technologies for the gasification of MSW: converting the solid, hard to handle material into a clean, medium- to high-Btu fuel gas. Other developers have focussed on full combustion technology but with a "twist" that lowers emissions or reduces cost.

A comprehensive study of these new technologies was recently completed under the sponsorship of the National Renewable Energy Laboratory of the U.S. Department of Energy¹. The study characterized the state-of-the-art among emerging MSW thermal processing technologies that have reached the point of "incipient commercialization." More than 45 technologies now under development were screened to develop a short list of seven processes that have passed through the "idea" stage, laboratory and bench-scale testing, and have been prototyped at an MSW feed rate of at least several tons per hour. In-depth review of these seven included inspections of operating pilot or prototype units and a detailed analysis of technical, environmental and economic feasibility issues.

No attempt was made to select "the best" technology since "best" can only be defined in the context of the constraints, aspirations and circumstances of a specific, local situation. The basic flowsheet, heat and material balances and available environmental data were summarized to help the reader grasp the underlying technical concepts and their embodiment in hardware. Remaining development needs, as seen by the study team are presented. Economic analysis shows the general balance of capital and operating costs.

INTRODUCTION

Several new or enhanced technologies that thermally process MSW are now well established. They include those that burn waste in the same physical form in which it is generated (grate-fired, mass burn incinerators) and those that first process the waste to a refuse derived fuel (RDF) and then burn the RDF (alone or with fossil fuels) using a spreader stoker grate. Mass burn and RDF combustion facilities are supplemented with elaborate back-end flue gas and residue treatment. Beyond these well-proven combustion processes, a new technology class has emerged: refuse gasification. Here, the organic fraction of MSW is heated to drive off a combustible gas with a substantial fuel value. The gas can be cleaned and burned in a gas engine or gas turbine to generate electricity. Alternatively, the gas is very usable as a boiler fuel either in thermal power plants or in industrial boilers. Emission data for combustors burning this gas generally show very low emission rates of dioxins, acid gases and other problematic pollutants. The processes studied in detail; identified with the name of the developer, are:

- Energy Products of Idaho (EPI)
- Battelle
- TPS Termiska Processer AB
- Pedco Incorporated
- Proler International Corporation
- ThermoChem Inc.
- Thermoselect Inc.

Of the seven emerging technologies discussed here, two (Energy Products of Idaho and Pedco Incorporated) use full combustion but in novel contexts. The other five processes (TPS Termiska AB, Proler International, Thermoselect Inc., Battelle, and ThermoChem Inc.) use gasification methods followed by fuel gas clean up. In niche market sectors and in the broader market, the five gasification technologies studied here are emerging as “commercially ready” alternatives.

The rate of penetration of the thermal processing market by new technologies will be paced by their environmental acceptability, their economic acceptability and their performance acceptability. From an environmental viewpoint, the seven technologies appear as a sound response to the regulatory challenges of the revised New Source Performance Standards (NSPS) and the Maximum Achievable Control Technology (MACT) rules². Table 1 summarizes the process features and environmental characteristics of the seven processes.

Economics has always been a critical and probably pacing factor that affects the penetration of thermal processing technology in U.S. MSW practice. Table 2 summarizes preliminary economic data characterizing the seven processes. One must use caution in using these estimates since most of the processes are still evolving. Most of the processes have capital costs that are comparable to the \$121,000 per Mg/d (\$110,000 per t/d) typical of contemporary mass burn systems. The net operating cost, which is equivalent to the break-even tipping fee, for the gasification technologies are comparable to those for *owner-operated* mass burn facilities. The revenue stream from selling energy continues to be critical to overall economic acceptability.

The results are less clear concerning “performance.” Most of the processes studied (excepting Thermoselect) require an RDF feed. Landfills are still required for RDF residues and/or ash. Historically, most RDF facilities have incurred substantial post-construction rework, capital investment, down-rating of capacity etc. Most of the seven systems have significant development tasks ahead of them. Unfortunately, the catalyst of vigorous U.S. market activity is lacking to push this development and to foster risk-taking. Further, many systems are quite complex. This presents some problems in gaining acceptance by client communities, by regulatory authorities and from the financial and engineering entities involved in concept selection and project accomplishment.

APPROACH TO THE ANALYSIS

Initially, more than 45 firms were identified as possible candidates. A two-stage screening process selected seven firms to be evaluated in detail. Data received from the 45 were analyzed to produce the recommendation for the list of seven firms as limited by available study funds. The scope of the detailed evaluation effort for the seven selected technologies was broad. Data for the detailed evaluation were obtained from the developers based on a faxed request, a detailed questionnaire, and extensive technical discussions before and after site inspection visits.

The evaluation included exploration of *technical issues* affecting the basic process feasibility, reliability, workers’ safety, operability, and maintainability. Very important was the remaining degree of scale-up from the present level of development to commercially useful equipment. Also, operating experience was seen as critical.

Environmental issues concerned the total emission profile of the operations. Environmental acceptability is a basic requirement for the viability of any process. Since almost any process can comply with regulations if sufficient resources are assigned to the task, this requirement is one of assuring that each process system includes the necessary features, equipment, and staff to achieve 1996 emission codes.

Business issues revolved about the financial and work force resources of the firms to achieve commercial viability. The capital and operating costs of the system are important factors in the award of disposal contracts. To keep the focus on the thermal processing core of the processes, standardized costs were developed for the processing of MSW to an RDF. Also, cost curves were developed for conversion of the energy product of the processes (high pressure steam or a fuel gas) into electricity. The resulting technology cost information is then an economic picture of a generic plant that may not be optimal with standardized feedstock and energy conversion components. A serious buyer should contact the developer organizations to give them the opportunity to propose their costs for any specific situation.

TECHNOLOGY SUMMARIES

1. Energy Products of Idaho (EPI)

EPI is a limited partnership headquartered in Coeur d'Alene, Idaho. EPI's basic business is the design and fabrication of fluid bed combustion systems. Their corporate experience favors full combustion mode for their systems, they have pilot plant and commercial plant experience (three commercial systems) in a "starved air," gasification mode. Their most proven product, however, is the full combustion system. The EPI incineration system uses a bubbling-type fluid bed concept accepting a prepared 10 cm (4 in.) top size RDF (Figure 1). Within the bed, RDF particles are exposed to a vigorously turbulent, hot, oxidizing environment that promotes rapid drying, gasification, and char burnout. EPI proprietary design features in the bed provide continuous removal of oversized non-burnable materials. Hot gases from the bed are passed through a boiler to generate high pressure, superheated steam used to generate electricity or for process applications. A conventional dry scrubber-baghouse with carbon injection can achieve current air emission standards².

EPI combustion technology is commercially available now. EPI has installed five furnaces in the U.S. with capacities of more than 55 Mg/d (60 t/d) burning an RDF fuel. They also designed and built three wood-fired, gasification-mode systems (1982-1985). They have acquired in-house operating experience with an RDF in their pilot plant gasifier, but by early 1997, they had no operating commercial-scale plants using RDF in the gasification mode.

Therefore, in matters of technical maturity and commercial verification, the full combustion mode EPI system is implementable with limited risk. The gasification mode requires additional testing, operating experience and design maturation and, thus, presents potential users with much greater risk.

2. TPS Termiska, AB

TPS Termiska Processer (Thermal Processes), or TPS, is a small, independent Swedish company of about 50 employees working in the specialized field of energy and environmental process research and technology development. Their technology involves starved-air gasification of an RDF in a combined

bubbling and circulating type fluid bed (Figure 2). The lower, bubbling bed section provides the extended residence time for the burnout of massive or very wet feedstocks. As the particles shrink, they enter the circulating bed zone where gasification is completed and the ash is swept from the furnace. Following the gasification bed, TPS inserts a second circulating bed “cracker” unit. In the second bed, a ground magnesium-calcium carbonate (dolomite) is injected to catalyze the conversion of high molecular weight tarry gasification byproducts into low molecular weight, non-condensable compounds. Also, the alkalinity of the dolomite reduces acid gas concentrations. The TPS system produces medium heat content fuel gas.

The technology offered by TPS is presently close to commercial availability. In 1992, a commercial, two-bed unit was installed in Gréve-en-Chianti, Italy with a combined capability of 30 MW to gasify 100 percent pelletized RDF fuel or coarsely shredded wood or agricultural residues.

The manufacturing methods for the TPS-design gasifier systems, the long-term operability of their beds with acceptable management of bed solids, the projected emission control performance, the feeders, etc., have all been tested at Gréve in MSW-based RDF service. Therefore, it is believed that the TPS system should be implementable with only moderate technological risk.

3. Proler International Corporation

The Proler SynGas Process is a patented technology to reform hydrocarbon-containing wastes into a gaseous product. It is represented by a 1.8 Mg/h (2 t/h) demonstration plant in Houston, Texas. The process was originally developed to gasify automobile shredder waste (ASR) but limited test results show its suitability to process MSW. Proler feeds preshredded material into a rotating, kiln-like reactor (Figure 3). In the proposed commercial process, the reactor is fired with the hot exhaust gases from a “Vitrifier” auxiliary unit that uses part of the product gas, carbon char and oxygen to melt the mineral residue. The overall process produces a medium heat content fuel gas that, after cleanup, is suitable for power generation or other fuel uses. The residue is discharged as what is stated to be a “commercially useful byproduct”.

Proler states that preliminary design work has been completed for a full-scale 865 Mg/d (960 t/d) commercial facility using MSW as feed stock and consisting of two process lines at 18 Mg/h (20 t/h) each. However, some technical issues require resolution before successful commercialization for MSW can be assured:

- The demonstration plant is now processing an RDF at a top size of 5.8 cm (2 in.). Proler expects the commercial plant to accept shredded material with a top size of 15.24 cm (6 in.) as a process change to achieve cost reduction in waste processing. This substitution may have adverse process impacts and has not yet been sufficiently tested to accept the change as acceptable.
- The demonstration plant has operated only on a limited basis with shredded MSW. An extended campaign of operation is essential to evaluate potential problems.
- The reliability and performance of the Vitrifier and the integration of this equipment with the existing gasifier have not yet been accomplished.

- The planned commercial size at (40 t/h) of MSW represents a scale-up of 5.5:1 on a per line basis over the demonstration plant. Experience with other MSW combustion and thermal process development shows that such a substantial step implies a high risk factor.

Further testing with MSW to resolve these issues seems desirable. Proter has an intent to continue their development efforts and to offer a comprehensive performance guarantee.

4. Thermoselect Inc.

The Thermoselect system processes co-mingled MSW into what are stated to be environmentally-safe products (Figure 4) that include reactor gas, vitrified solid granulates, elemental sulfur and sodium salts. No liquid effluents are discharged into the environment. The process is intended to reduce formation and emission of particulates and other pollutants.

Gasification is achieved at a high temperature. The mixture of solid refuse and char reaches a temperature of 800°C (1470°F) as it reaches the discharge end of a preprocessing section described by Thermoselect as the Degasification Channel. The products of gasification are then held in a reactor at a temperature of 1200°C (2192°F) for more than four seconds. Ash and metals fall out and are fused and granulated in a chamber called the “Homogenizer”. The reactor gas is quenched in a spray chamber to below 90°C (194°F). Data suggest that this combination of time and temperature destroys the complex organic compounds produced in the gasification process and yields a gaseous product (primarily CO, H₂, CO₂ and steam) that has nearly reached chemical equilibrium. The raw gas is cleaned in a gas purification system that removes acid gases, hydrogen sulfide, particulate and volatile heavy metals. Air emissions result from the combustion of the cleaned reactor gas in turbines, gas engines, boilers and other means for the generation of electric power or other useful energy forms.

The Thermoselect demonstration facility in Fondotoce, Italy consists of one process line with a nominal capacity of 4 Mg/h (4.4 t/h) or 100 Mg/d (106 t/d). The line at the pilot plant includes all of the process units (acid and alkaline scrubbers, a hydrogen sulfide removal scrubber, coke filters, etc.) that are envisioned for the full scale, commercial plant. Tests results show only minute traces of organic compounds in the cleaned reactor gas. No chlorinated aromatic hydrocarbons other than traces of polychlorinated dibenzo p-dioxin (PCDD) and polychlorinated dibenzo furan (PCDF) were detected.

This system should comply with U.S. environmental regulations. The demonstration plant is stated to have gone through 15,000 hours of operation and operates continuously for five days a week processing unshredded municipal and industrial wastes. The plant uses the product gas to drive an engine generator.

Major unresolved areas are:

- Optimization of energy use.
- Use of Thermoselect’s reactor gas in gas turbines is untested as of early 1996, but is not expected to be a problem.

- Waste heat recovery to improve overall plant thermal efficiency to include finding uses for low grade heat.
- Continuity and reliability of operation needs to be confirmed. The demonstration plant has only been operated on a five day per week cycle. Continuous, seven-day per week, around the clock operation is yet to be shown.
- Scale-up. The current demonstration plant is reported to have a “nominal capacity of 4 Mg/h (4.4 t/h)” but, experience to date shows that the unit appears to operate at an actual throughput of only 3.8 Mg/h (4.2 t/h). The “Standard Design” two-line capacity is 10 Mg/h (11 t/h) or 240 Mg/d (264 t/d). Therefore, the scale-up factor based on actual operational experience is about 2.7:1. The success of the planned commercial size facility is yet to be proven.

5. Battelle

The Battelle High Throughput Gasification System (BHTGS) uses indirect heating in a twin circulating fluidized bed (CFB) gasifier and combustor (Figure 5). RDF is gasified in a CFB using steam as the fluidizing medium to generate a medium heating value gas 18.6 to 22.4 MJ/Nm³ (500 to 600 Btu/sft³) without oxygen. Residual char is consumed in an associated CFB combustor. A circulating sand phase exchanges heat between the separate reactors.

Battelle's process development began in 1977. Detailed process development activities were begun in 1980 with the construction of Battelle's process research units (PRUs). Experimental data have been generated in gasifiers of 15 cm (6 in.) diameter and 25 cm (10 in.) diameter with a throughput of 0.22 and 9.1 Mg/d (0.24 and 10 t/d) dry RDF, respectively. Data from these showed that extremely high throughput, more than 19.5 Mg/h-m² (4,000 lb/hr-ft²) could be achieved.

Tests showed the technical feasibility of the gasification process and provided the basis for detailed process conceptual design and economic projections to be generated. Testing was conducted in 1989 in a 25 cm (10 in.) internal diameter gasifier with a height of 6.9 m (22.7 ft) and a 1.0 m (40-in.) internal diameter combustor with a height of 3.5 m (11.5 ft). The throughput was 0.65 Mg/d (0.72 t/d). The longest continuous operating run was approximately 100 hours at 9.1 Mg/d (10 t/d) dry RDF. A 200 kW gas turbine has been installed on the PRU and operated with recharges from wood for about 60 hours as an integrated gasifier-turbine system.

Battelle has licensed its BHTGS Process to Future Energy Resources Corporation (FERCO) of Atlanta, Georgia for the North American market. A commercial scale demonstration is underway at the Burlington Electric's McNeil Generating Station in Burlington, Vermont using wood chips.

The BHTG process is said to produce gaseous emissions from the reactor complying with the EPA's MACT standards and NSPS for municipal waste combustors (MWC)¹. Wastewater from the process contains only trace quantities of organic materials. The outlet of a simple industrial treatment system at Battelle's test site showed wastewater to be within the EPA's drinking water standards.

Major unresolved development and demonstration needs include:

- Important process development issues relate to fuel preparation and reactor gas cleanup.

- The specific level of fuel preparation necessary for the process has yet to be determined. Data suggest that fine shredding of the feedstock will not be required. Feed size range will be dictated by the feed system requirements and the rate of gasification processes.
- Product gas cleanup developments include tar cracking and particulate removal.
- Much more operating time with refuse at PRU scale is necessary to confirm the preliminary results obtained during the 1989 study at Battelle.
- The overall design concept needs to be expanded from a development focused on gasifier technology to a full plant with all auxiliaries and subsystems.

6. Pedco Incorporated

Pedco Incorporated is headquartered in Cincinnati, Ohio. The firm was originally formed in 1967 and has gone through several stages of growth and spinoff since. The present firm was formed in 1984 to pursue, among other interests, the development and commercialization of an innovative solid fuel combustor.

The Pedco Rotary Cascading Bed Combustor (RCBC) is, in essence, a robust solid fuel burner and heat recovery system. It is not a gasifier. Beyond conventional solid fuels (such as coal or wood chips) it can burn prepared MSW. Pedco's basic business is involved with the design of industrial combustion systems for steam generation based on the RCBC concept.

The RCBC burner consists of a rotating, horizontal, cylindrical combustion chamber (Figure 6). A bundle of boiler tubes projects into one end of the chamber. The rotational speed of the chamber is high enough such that a substantial fraction of the bed material is continually airborne. This produces an environment similar to that of a fluid bed but, here, a mechanically fluidized bed. The hot falling solids cascade across the whole diameter so that the boiler tubes are submerged in hot fuel and bed material. The hot solids recycle preheats the combustion air and dries and ignites the incoming fuel.

Pedco has two furnaces now operating in the U.S., a development unit at North American Rayon Corporation and a specialized unit based on Pedco design principles used by a commercial hazardous waste management firm in the Houston, Texas area. The plants are reported to have shown acceptable reliability, environmental emissions, and basic operability and maintainability characteristics.

Pedco prefers to provide their RCBC system as a factory assembled RCBC burner with a waste heat boiler configuration that is of a size where shipping by truck or rail is feasible. The design heat release rate of the Pedco basic RCBC system is approximately 233,000 MJ/h (100×10^6 Btu/h) corresponding to daily RDF rates of 168 Mg/d (185 t/d). Air pollution trains (besides the addition of low cost, coarse limestone screenings to the bed for acid gas control) would normally involve a fabric filter unit. Pedco believes that its in-bed limestone addition and consequent acid gas absorption eliminates the necessity for the spray dryer absorber used in many mass burn plants. Additional data are needed to confirm this position.

Pedco has yet to develop and adopt a front-end waste system to produce a sized RDF feed for the RCBC system. Pedco has only limited experience with an RDF and has not yet established a firm basis on

which to specify their optimum top size. Development of a generalized RDF flow sheet should not be problematic. One notes, however, that most RDF facilities have required extensive redesign and reconstruction effort to bring the RDF processing elements to an acceptable level of reliability and performance.

Major unresolved development and demonstration needs include:

- Pedco must select or develop a full system concept and associated detailed specifications starting with RDF receipt and processing and including electrical generation and residue handling.
- Continuity and reliability of operation of an RCBC system must be confirmed in RDF service. Problems associated with fouling and/or plugging of the ash handling chutes with wire and oversized non-combustible materials; fouling problems with boiler tubes; air emissions; and tube abrasion and corrosion problems must be assessed in continuous RDF service.
- Experience to date with the cluster of boiler tubes inserted into the RCBC device has been limited to low pressure, saturated steam. To maximize power production, higher pressures and superheated conditions are preferred. Higher skin temperatures on the tubes may affect erosion and corrosion sensitivity and should be evaluated before commitment to a full scale facility.

7. ThermoChem Incorporated

The Manufacturing and Technology Conversion International, Inc. (MCTI) Steam Reforming Process is an indirectly heated fluidized bed reactor using steam as the fluidizing medium (Figure 7). Under license from MCTI, ThermoChem, Inc. (TC) have the exclusive rights to apply its Pulse-Enhanced™ heater and steam-reforming technology to a variety of applications.

Pulse Enhanced™ indirect heating technology combined with fluid-bed and steam-reforming provides a process for converting the organic material in an RDF to fuel gas while separating the inorganic without oxidation or melting. The key to the process is the array of Pulsed Enhanced™ heater tubes immersed in the fluidized bed. Gaseous fuel is burned in the tubes such as to create an oscillating pressure. The effect of the pulsing flow is to significantly enhance heat transfer between the combustion products and the tube wall. This greatly increases the efficiency of energy exchange between the fuel and the bed material. The organic waste fed to the fluid-bed steam reformer reacts with steam to produce a medium heat content fuel gas.

MCTI's development efforts began in 1984. Experimental data have been generated in different scale reactors from 9.1 to 2,722 kg/h (20 to 6,000 lb/h) using various biomass and waste feedstocks. A 13.6 Mg/d (15 t/d) demonstration unit was operated on rejects from a cardboard recycle paper mill in Ontario, California in 1991-1992. Later, this unit, moved to TC's test facility in Baltimore, processed coal, woodchips and straw.

Based on 6.8 kg/h (15 lb/h) pilot plant tests, the TC Process appears to comply with the EPA NSPS for MWC's. Tests suggest the residue meets EPA TCLP leachability criteria set for landfill disposal as a nonhazardous waste. Wastewater contains only trace amounts of organic materials.

Major unresolved development and demonstration needs include:

- TC must select or develop a full system concept and associated detailed specifications starting with RDF receipt and processing and including electrical generation and residue handling.
- Continuity and reliability of operation of a TC system must be confirmed in RDF service. Of particular concern are problems with tube corrosion, erosion, and plugging.
- Problems with the cyclone capturing particulate in the bed off-gas must be evaluated in RDF service. The cyclones are subject to pluggage as they are in conventional atmospheric fluid beds.
- Solids removal from the bed must be evaluated and robust, reliable solids handling systems must be developed and tested.
- Considerable demonstration work is needed to address remaining uncertainties regarding air emissions, residue quality, plugging of the spaces between the tubes with wire, metals, rocks, etc. These uncertainties translate into persistent risks that should be carefully considered before use.

CONCLUSIONS

Intense developmental activity applicable to the thermal processing of MSW is underway in the U.S. and Europe. One can identify more than 45 distinct efforts at some stage of process development now. Most of the processes are based on MSW gasification (as opposed to full combustion). In part, the focus on gasification reflects the current stringent regulatory situation in both the U.S. and Europe regarding the control of air emissions. Thus, processes that allow clean-up of the reactor gases before its combustion offer potential economy since the volume flow treated is small. The cleaned fuel gases can then either be burned in gas engines or gas turbines to generate electricity or sold as a fuel in conventional boilers.

Although many of the 45 processes are still at the bench or laboratory scale, several have progressed to a pilot or semi-works level where the difficult problems of reliability, flexibility etc. appear. The seven processes selected for study are all very near to commercialization. One technology has been carried out in four, full-scale commercial facilities and another in a two-furnace commercial plant. That means that most processes still present some risk to a prospective owner. This risk could show itself as higher capital or operating costs, lower reliability or lower energy recovery efficiency than have been forecast at this time. The development record for new MSW processing technologies suggests that such problems are probable for some processes as they move into full scale commercialization.

Based on data from pilot facilities, each of these processes can probably achieve full compliance with the U.S. EPA Maximum Achievable Control Technology (MACT) standards and the New Source Performance Standards (NSPS) for Municipal Waste Combustors promulgated in final form in December 1995². Only one process matches a technology group as used by the EPA in their standard setting. Many are gasifiers and not the full combustion systems referenced in the EPA standards. Therefore, knowing how the federal standards will be applied is uncertain. As with most permitting issues, the ultimate resolution of these questions must wait until actual permits have been submitted and final regulatory action is required.

The residues from the processes do not present problems in the Toxicity Characteristics Leaching Procedure (TCLP) leaching tests. The quantity of data in this area, however, is limited and experience in mass burn plants suggests that significant variation in TCLP results can be expected. Two of the processes (Thermoselect and Proler) include process steps where the residues are melted (vitrified). For these processes, the TCLP results are exceptionally low since the metals are bound in a glass structure and cannot be readily solubilized. Both firms believe that the vitrified residue granules may be marketable and, therefore, that their process will have a lower operating cost than is shown in Tables 2a,b. As yet, however, the value of the granules, if any, has not been established in the U.S. marketplace.

The overall conclusion that can be drawn is that competitive alternatives to conventional mass burn or refuse derived fuel (RDF) combustors exist. The alternatives may not offer exceptional economic advantages. Most of the processes studied present a much lower air emission profile than do conventional plants. This may merit investigation by communities or regional jurisdictions considering volume reduction technology where air emissions are of particular concern. One should note, however, that conventional mass burn technology can also meet the recently promulgated MACT and NSPS² emission requirements. The economic data in Table 2 is intended to provide perspective; not to be directly applicable to a specific situation. *To obtain fair, applicable economic data, cost issues should be addressed directly with the firms (see Appendix A).*

The preceding technical descriptions, many of the economic estimates and the prospective environmental performance would suggest that these new technologies define the future of WTE facilities. However, with the exception of EPI and, to a degree TPS, all of the processes have important development and/or demonstration steps between the present status and proven commercial availability. All except Thermoselect require processing of MSW to an RDF, possible but always problematical. Experience with Purox, Landgard, Torrax and many other processing technology developments in years past has shown that commercial and technical success does not come easily if at all. The unrelenting crucible of 24 hours a day, seven days a week operation in combination with the malevolent nature of refuse clearly presents a profound challenge to the process developer.

Also, most of the process developers suggest optimistic overall energy recovery levels. However, almost all lose energy in the RDF-making step. Some use a water quench to cool the synthesis gas, thus losing 400 to 600 Btu/lb MSW in sensible heat. Others achieve superior environmental characteristics at the price of greatly increased process complexity and higher capital and operating costs. Several firms are small and will suffer with the extended facility development schedules and under the draconian financing requirements of most U.S. system procurements.

Still, the adventure and excitement of technical innovation and the promise of successful commercial development spurs these firms forward. The professionalism, the high technical standards, and the business commitment in most of the seven development firms were impressive. Further, despite a weak U.S. market, most firms are aggressively seeking clients for that vital "first plant." I wish them well.

ACKNOWLEDGEMENTS

This paper is based on research funded by the National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy. The support of NREL and DOE is gratefully acknowledged as are the technical contributions of the members of the Steering Committee representing NREL, USEPA and Southern California Edison Company.

REFERENCES

1. Niessen, W., Marks, C., and Sommerlad, R., "Evaluation of Gasification and Novel Thermal Processes for the Treatment of Municipal Solid Waste," Contract YAR-5-15116-01 report to the National Renewable Energy Laboratory, July 1996.
2. Federal Register, *December 19, 1995* - 40 CFR Part 60.

Appendix A

Offices of Development Firms

1. Energy Products of Idaho (EPI) Ltd. Partnership

4006 Industrial Avenue
Coeur d'Alene ID 83814
Tel: (208) 765-1611
Fax: (208) 765-0503

2. TPS Termiska Processer AB

Studsvik, S-611 82
Nyköping, Sweden
Tel: 011-46-155-22-13-00
Fax: 011-46-155-26-30-52

3. Proler International

4265 San Felipe, Suite 900
Houston, Texas 77027
Tel: (713) 963-5940
Fax: (713) 627-2737

4. Thermoselect Inc.

201 West Big Beaver Road ,Suite 230
Troy, Michigan 48084
Tel: (810) 689-3060
Fax: (810) 689-2878

5. Battelle

505 King Avenue
Columbus, Ohio 43201
Tel: (614) 424-4958
Fax: (614) 424-3321

6. Pedco Incorporated

214 East 9th Street
Cincinnati, Ohio 45202
Tel: (513) 361-8643
Fax: (513) 351-8646

7. ThermoChem, Inc.

10220-H Old Columbia Road
Columbia, Maryland 21046
Tel: (410) 312-6300
Fax: (410) 312-6303

Table 1 Environmental Comparison of Developing Technologies

Process Name	Thermal Treatment Technology	Air Pollution Control	Water Pollution Control	Residue Treatment or Disposal
EPI, Inc.	Bubbling Fluid Bed Combustor	Lime Spray Dryer Absorber, Fabric Filter, Selective Noncatalytic Reduction, Activated Carbon Injection	None: Dry System.	Landfill
TPS Termiska AB	Circulating Fluid Bed Gasifier with Dolomite Cracker	Scrubbing of Fuel Gas to Remove Particulate Matter, Condensable Organics, and Acid Gases, NO _x ¹	Cleanup of Scrubber Liquor. Not specified. ²	Landfill
Proler International	Rotary Reactor Gasifier and Cyclonic Ash Vitrifier	Fabric Filter, Wet Scrubber, NO _x ¹	Cleanup of Scrubber Liquor. Not specified. ²	Proposed Sale as Vitrified Aggregate; Otherwise landfill.
Thermoselect, Inc.	Raw Waste Gasifier	Acidic and Alkaline Scrubber, H ₂ S Removal, Activated Coke, NO _x ¹	pH Adjustment, Metal Precipitation, Filtration, Distillation.	Proposed Sale as Vitrified Aggregate; Otherwise Landfill.
Battelle	Circulating Fluid Bed Gasifier and Combustor	Wet Scrubber, NO _x ¹	Cleanup of Scrubber Liquor. Not Specified. ²	Landfill
Pedco Incorporated	Rotary Cascading Bed Combustor	Lime Spray Dryer/Absorber, Fabric Filter, Selective Noncatalytic Reduction, Activated Carbon Injection.	None. Dry System.	Landfill
ThermoChem	Pulse-Heated Circulating Fluid Bed Gasifier		Cleanup of Scrubber Liquor. Not specified. ²	Landfill

Notes:

1. NO_x control may be required for the gas engine or turbine combustor.
2. Details of treatment were no specified by the developer.

Table 2 Summary of Statistics for Developing Technologies (per ton quantities relate to raw MSW)

Process	Product Energy Form	Plant Size Evaluated (Mg/d _{raw})	No. Burnaces	Capital Cost (\$000)	Process Capital (\$000)	Proprietary Capital (%)	Capital Cost (\$/Mg/d)	Energy Product (MJ/Mg) _{raw}
EPI Inc.	Steam	780	2	79,415	28,015	35.3	101,800	12,918 _{net}
TPS Termiska Processor AB	Gas	1600	2	170,675	58,875	33.3	106,700	7,602 _{net}
Proler International Corp.	Gas	1247	2	153,625	57,625	37.5	123,200	11,385 _{net}
Thermoselect Inc.	Gas	1440	6	236,790	192,790	81.4	164,400	7,404 _{net}
Battelle	Gas	849	2	80,532	12,532	15.6	94,900	11,548 _{net}
Pedco Incorporated	Steam	800	2	87,067	28,167	32.4	108,800	10,387 _{net}
ThermoChem Inc.	Gas	849	1	91,733	20,983	22.9	108,800	7,857 _{net}
Generic Mass Burn	Steam	1365	3	150,000	30,000	20.0	109,900	6,860 _{net}

Process	Gross Operating Cost (\$/Mg)*	Prime Mover#	Gross Power (kWh/Mg)	Net Power (kWh/Mg)	Net Operating Cost (\$/Mg)†	Gross Heat Rate (MJ/kWh)\$	Net Heat Rate (MJ/kWh)\$
EPI Inc.	85.21	ST	1088	895	52.71	9.69	11.78
TPS Termiska Processor AB	71.84	GT/ST	1230	1024	38.91	8.57	10.29
Proler International Corp.	99.15	GT	1281	1091	59.47	8.23	9.67
Thermoselect Inc.	123.24	GT	1083	778	94.92	9.74	13.55
Battelle	79.37	GT	1001	871	47.63	10.53	12.11
Pedco Incorporated	78.87	ST	886	868	52.29	11.89	12.15
ThermoChem Inc.	81.17	GT	1149	1004	44.56	9.17	10.50
Generic Mass Burn	85.88	ST	633	578	63.11	18.35	20.10

*Gross operating cost/ton raw refuse—total of capital charges, insurance, labor, maintenance, and supplies before energy credits.

†Net operating cost/ton raw refuse—gross operating cost less energy credit.

\$Heat rate—factor relating the fuel value in the raw refuse (assumed at 11.6 MJ/kg, 14 MJ/kg as RDF) to the gross or net generation.

Prime Mover---ST=Steam Turbine, GT=Gas Turbine, GT/ST=Gas Turbine with heat recovery and additional generation using a steam turbine

Conversion factors: MG times 1.1 yields tons; kWh/MG times 0.826 yields kwh/ton; MJ times 1147.9 yields Btu.

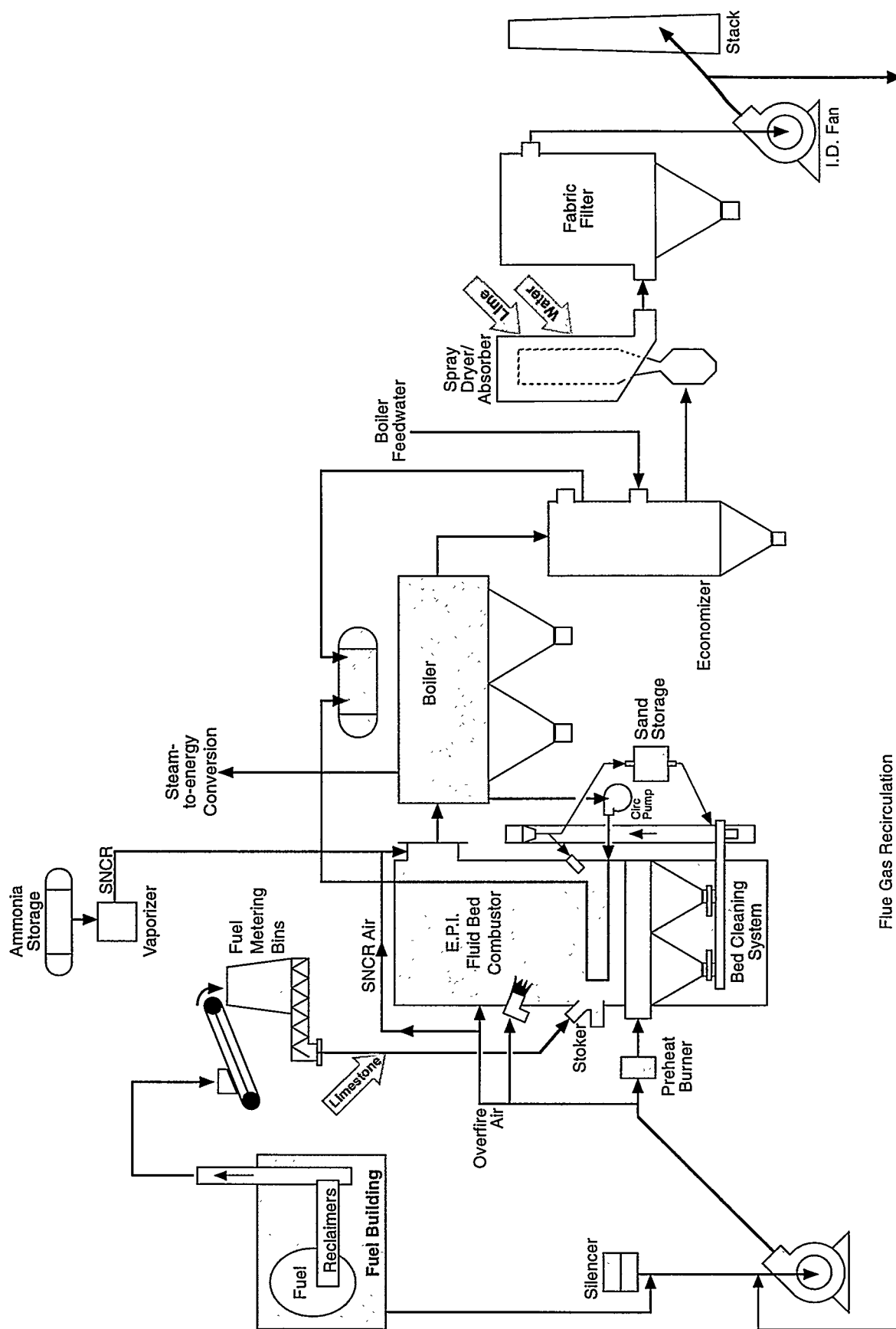


Figure 1. Energy Products of Idaho Process Flowsheet

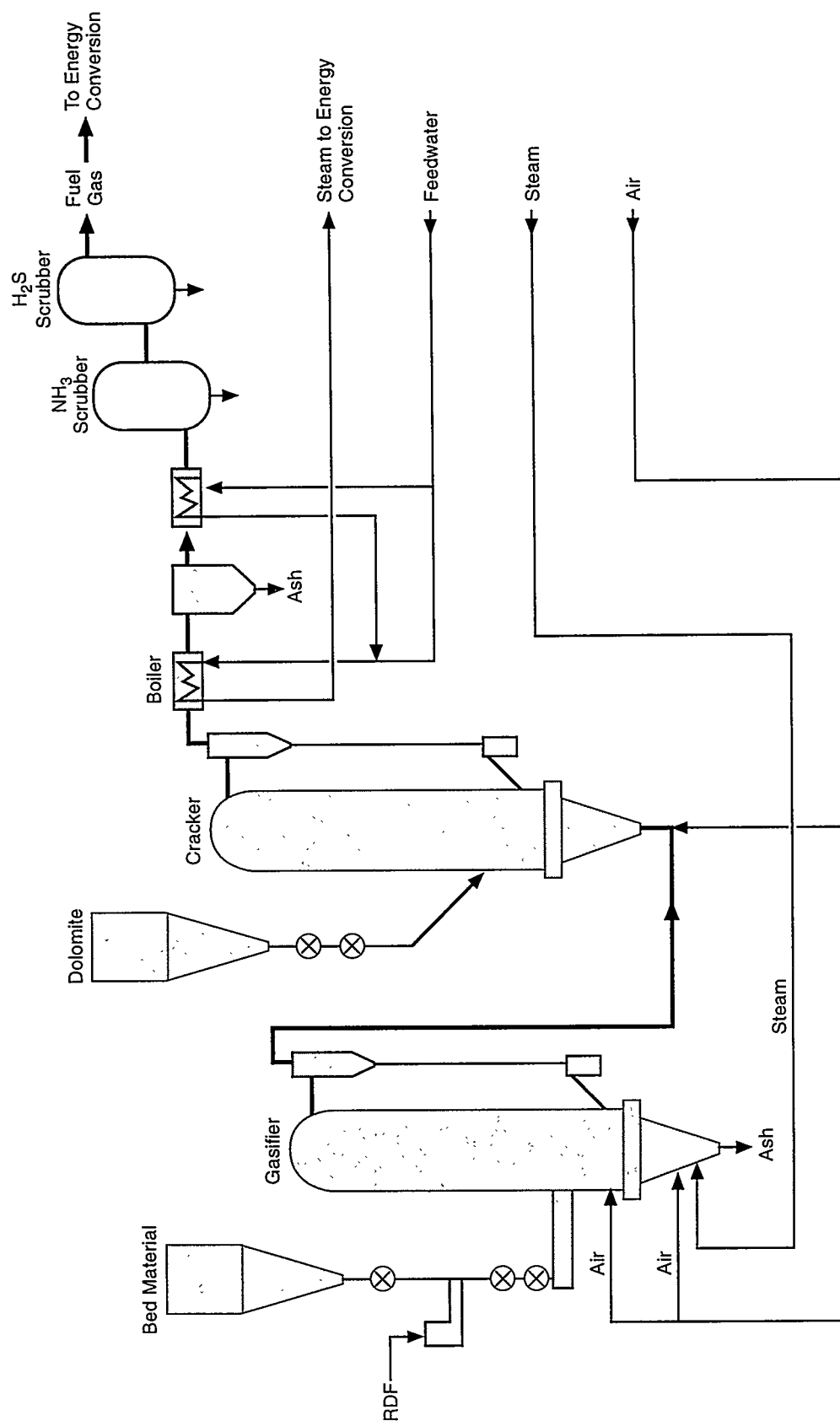


Figure 2. TPS Termiska Processor AB – Process Flowsheet

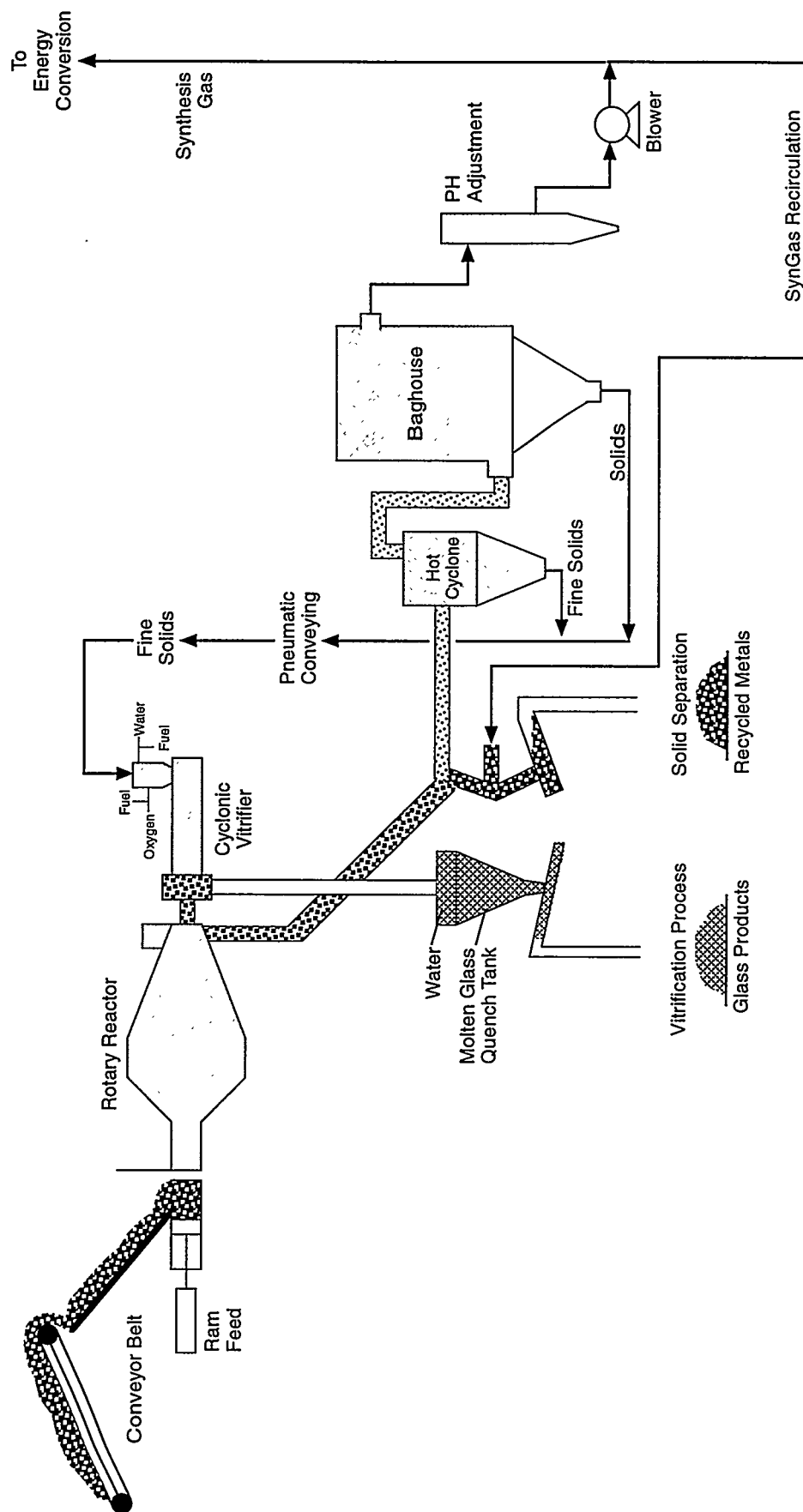


Figure 3. Proter Process Flowsheet

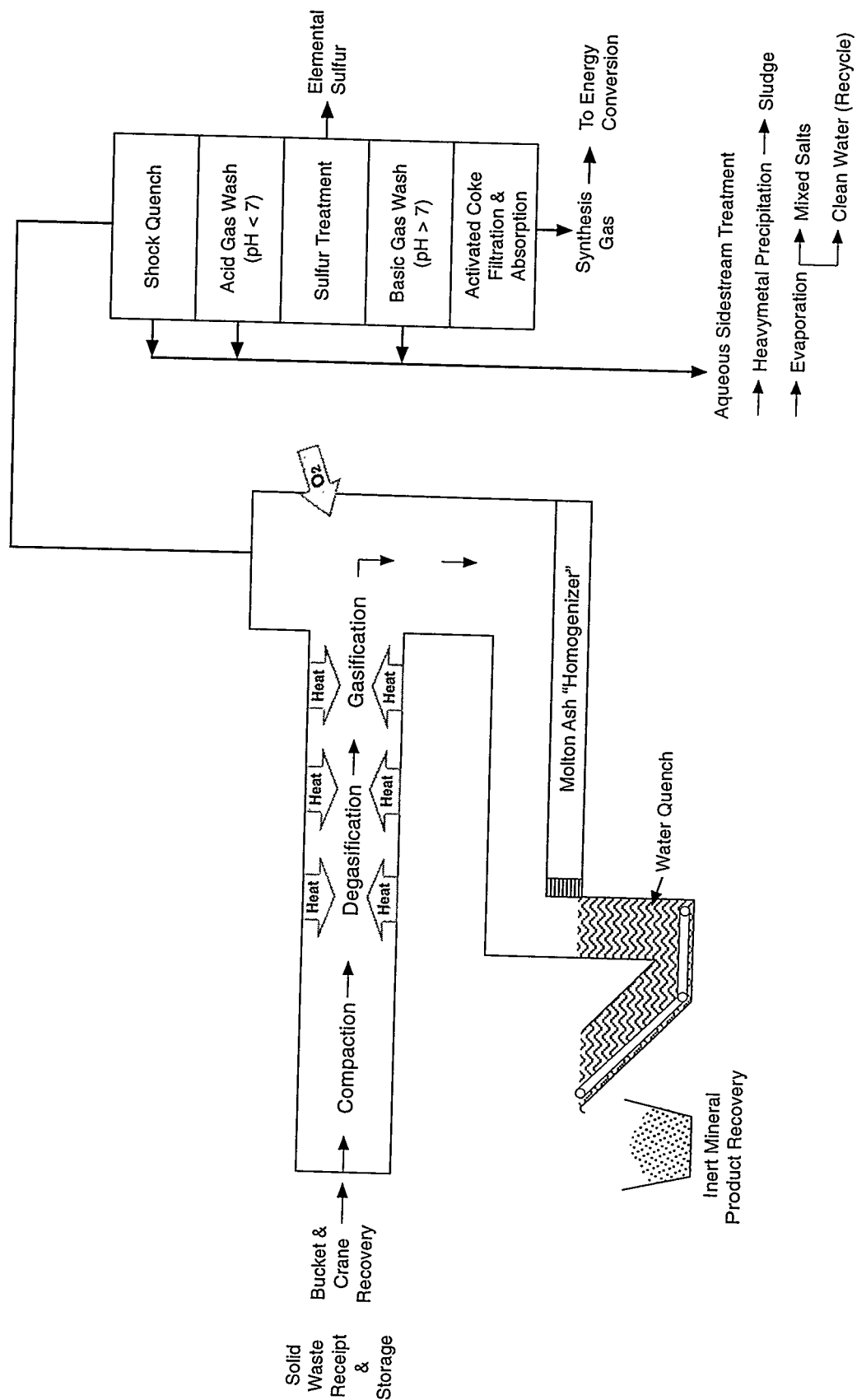


Figure 4. Thermostelect Process Flowsheet

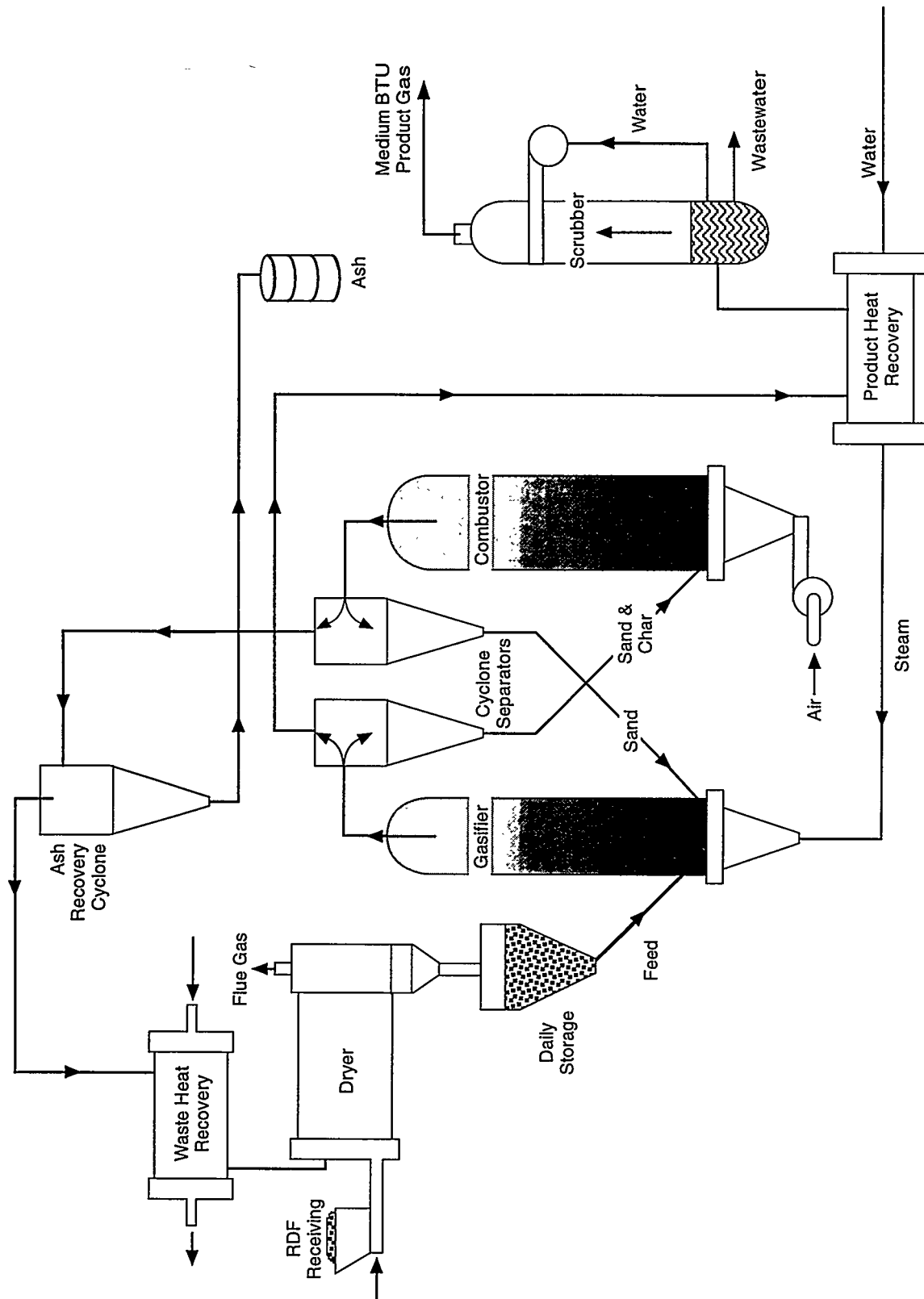


Figure 5. BHTGS Process Flowsheet

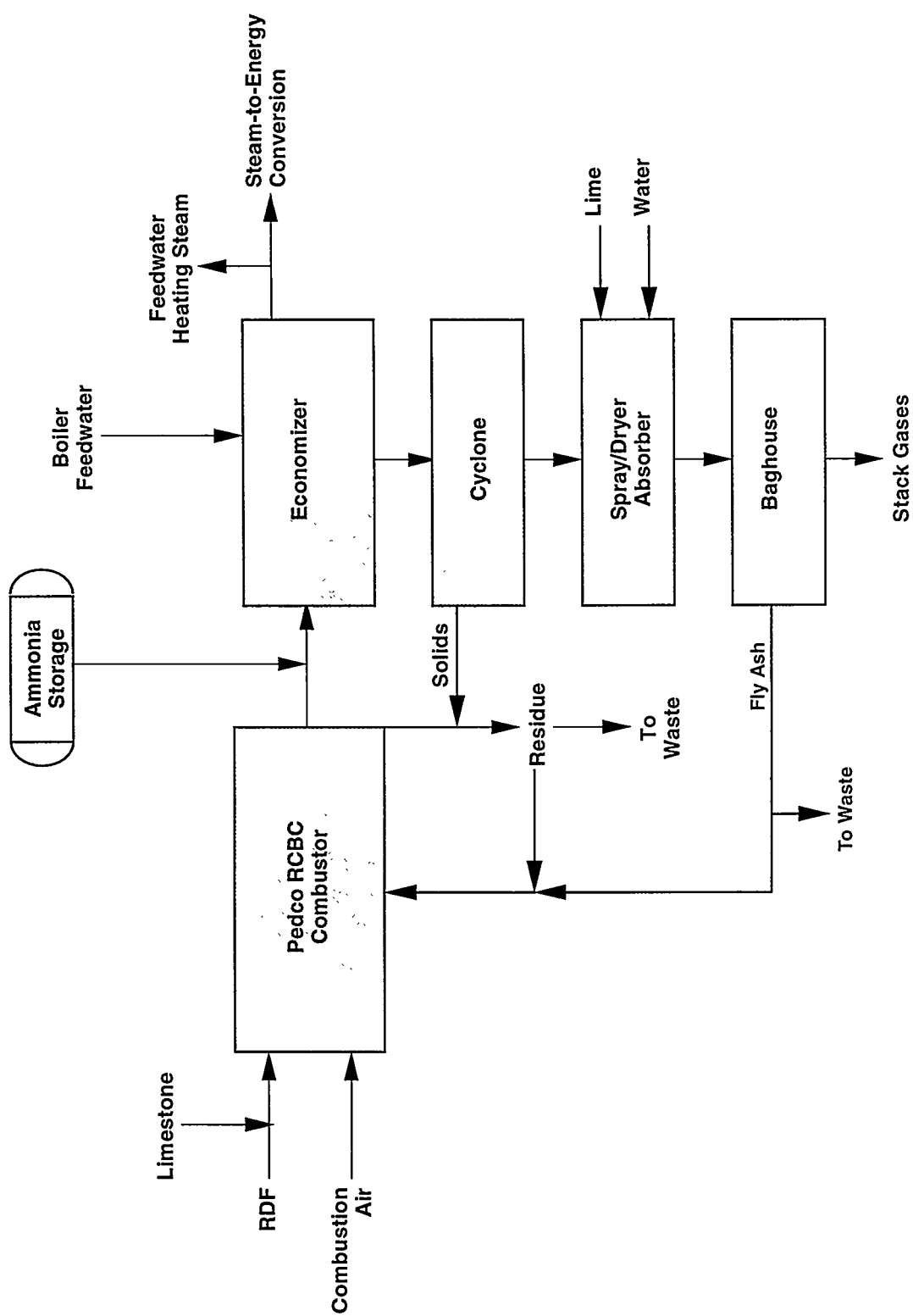


Figure 6. Pedco Process Flowsheet

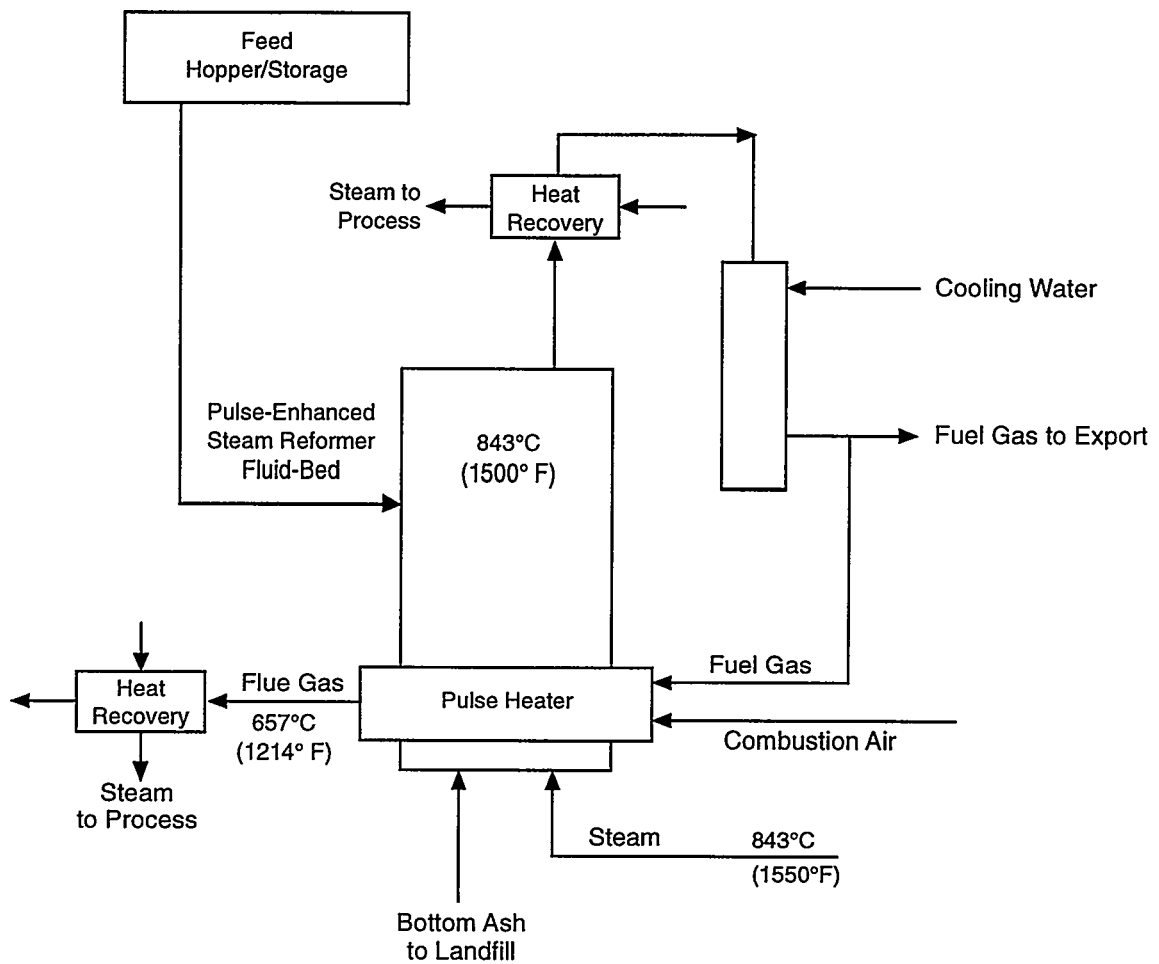


Figure 7. Thermochem's Process Flowsheet

Production of Biomass Fuel for Resource Recovery: Trash Recycling in Dade County, Florida

Paul J. Mauriello, AICP and Kathie G. Brooks, AICP

Department of Solid Waste Management

8675 N.W. 53rd Street

Suite 201

Miami, Florida 33166

ABSTRACT

Dade County, Florida has been in the forefront of resources recovery from municipal solid waste since the early 1980's. The County completed its 3,000 tons per day (six days per week) refuse derived fuel waste-to-energy facility in 1982. The Resources Recovery facility is operated under a long-term agreement with Montenay-Dade, Ltd. The trash processing capability of this facility was upgraded in 1997 to process 860 tons per day (six days per week) of trash into a biomass fuel which is used off-site to produce electrical energy. Under current Florida law, facilities like trash-to-fuel that produce alternative clean-burning fuels for the production of energy may receive credit for up to one-half of the state's 30 percent waste reduction goal.

Introduction

Prior to waste diversion problems, and the U. S. Supreme Court decision invalidating waste flow control by local government, Dade County, Florida was preparing to expand its 3,000 tons per day refuse derived fuel waste-to-energy facility by 50 percent. Industrial revenue bonds in the amount of \$190 million were sold in 1990 to finance the expansion, and to retrofit the facility with a new air quality control system to meet federal maximum available control technology standards.

Localized opposition to the expansion resulted in formation of a Citizens Task Force For Solid Waste Management in 1991. This group, appointed by the Board of County Commissioners, was charged with evaluating the need for additional waste disposal capacity and the appropriateness of the planned expansion to fulfill that need. The Task Force was staffed by a consultant team, hired by the County to prepare its master plan for solid waste management, and members of the County's solid waste management department. After two years, thirty meetings, and countless hours of staff time, the Task Force agreed that additional waste disposal capacity was needed and that the expansion of the Resources Recovery facility was the appropriate technology.

The Board of County Commissioners, however, was not convinced and asked the consultant to continue to evaluate other technologies. At approximately the same time, Montenay-Dade, Ltd. was approached by Okeelanta Corporation, a central Florida sugar producer, regarding Montenay's ability to provide biomass fuel for an electric power plant Okeelanta was planning. The Trash-to-Fuel (TTF) alternative was born. TTF had several advantages over expansion of waste-to-energy capacity at the Resources Recovery facility. The process was less costly than on-site combustion, off-site combustion was more attractive to residents in the vicinity of the facility, and in 1993 the County was successful in its effort to have the state legislature amend the state's Solid Waste Management Act to allow clean-burning fuels, used for the production of energy, to count toward achievement of the state's 30 percent waste reduction goal for counties.

Although waste diversion problems and associated financial impacts were threatening to derail the TTF project, the County and Montenay were able to mutually agree on modifications to their operations and

management agreement that take into account unstable waste flows to the facility. The new agreement, dated September 1, 1996, requires the County to deliver all the garbage available in the County's solid waste management system, up to 936,000 tons, but no less than 572,000 tons. The County must also deliver a minimum of 400,000 tons of trash for TTF and on-site combustion, the on-site portion of which may be displaced by garbage (130,000 tons). The result is an overall annual minimum waste delivery requirement of 972,000 tons and a maximum of 1,206,000 tons depending on waste flow (refer to figure 1). Moreover, to assist with the financial impacts of the loss of revenue producing waste tonnage, the revised agreement provided for a reduced fee of approximately \$5 per ton for 234,000 tons of the 936,000 tons to be combusted on-site, thereby reducing overall facility costs by more than \$1 million per year.

The TTF Process

The TTF process was constructed at a cost of approximately \$26 million and is currently in start-up mode. Under the County's operations and management agreement with Montenay, the operator guarantees that TTF will process 270,000 tons per year of trash (862 tons per day, six days per week). The TTF processing fee to the County is \$22.41 per ton, plus an additional fee of \$1.36 per ton for the resulting processed fuel that qualifies for recycling credit under state law. When debt service cost and transportation of rejects and residue for TTF are factored in, the total cost per ton is approximately \$38.

The primary components of the process are a trash sorting floor where reject and non-processable materials are removed from the trash stream, a material storage pit (existing), hoppers, conveyors, shredders, ferrous metal separation, material sizing trommels, material storage bunkers, load-out area, and outbound scale. The biomass fuel material produced must contain no more than 3 percent oversize material (over 5 inches in diameter) in order to meet customer specifications.

TTF outputs include biomass fuel 50 percent, fines 30 percent (dirt, grit and stones), rejects 17.6 percent (non-biomass materials sorted from the incoming trash stream), and ferrous metals 2.4 percent (refer to figure 2). The fuel is hauled out by Okeelanta at its sole cost, and no payment is made to Okeelanta for taking the fuel. The fines are categorized as primary (loamy dirt material) and secondary (stones). The primary fines will be supplied to a third party for plant nursery use. The County is responsible to accept up to 10 percent of the total incoming TTF material as primary or secondary fines annually (27,000 tons). This material may be used as landfill cover by the County. Disposition of fines above the 10 percent fines guarantee is the responsibility of Montenay. A special unmanned scale was constructed to weigh-out the fuel and fines. The County is responsible for disposal of up to 17.6 percent of the total incoming TTF material as rejects annually (47,520 tons). Disposition of rejects above the 17.6 percent rejects guarantee is the responsibility of Montenay. Ferrous metals recovered from the TTF process are transferred to the Resources Recovery ferrous bunker for further processing by Namco International Corporation, an on-site third party metals processing company under contract with Montenay.

Conclusions

Dade County was successful in negotiating unique waste delivery guarantees and financial enhancements to ensure that this innovative expansion of its Resources Recovery facility would proceed without WFC. Without reinstatement of local government waste flow control (WFC) authority by the federal government, however, the formation of public/private partnerships to develop facilities similar to Dade's TTF process elsewhere in the State of Florida, or elsewhere in the nation is unlikely. In South Florida, the potential for development of such facilities is reduced further by the abundance of low cost waste disposal alternatives, primarily landfills.

References

1. Official Florida Statutes 1995. Published by the State of Florida, Tallahassee.
2. Third Amended and Restated Operations and Management Agreement by and between Metropolitan Dade County, Florida and Montenay-Dade, Ltd., September 1, 1996; Resolution number R917-96.
3. Non-Exclusive Agreement Between Metropolitan Dade County, Florida and Waste Management Inc. of Florida for Provision of Municipal Solid Waste Disposal Services, October 27, 1995.

**DADE COUNTY, FLORIDA
RESOURCES RECOVERY FACILITY
GARBAGE AND TRASH COMMITMENTS**
September 1, 1996

From:
September 1, 1996

AOSWGT* Garbage Minimum 572,000
 Trash Maximum 364,000
Total 936,000

After:
RTIAPCD**

AOSWGT Garbage Minimum 572,000
 Trash Maximum 130,000
 Subtotal 702,000

ARTGT*** 270,000

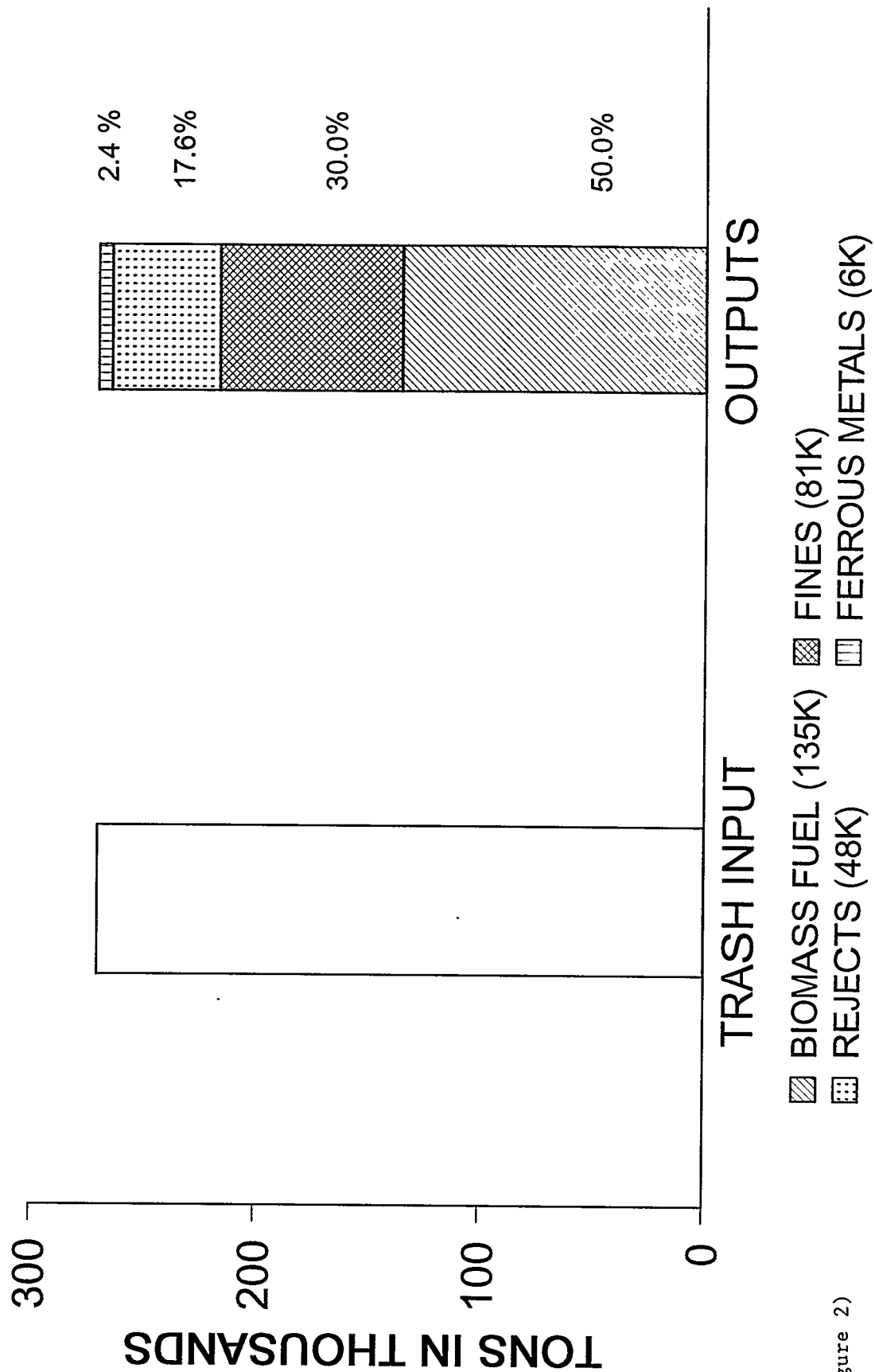
Total 972,000

<u>MAXIMUM WASTE DELIVERY AMOUNTS</u>	
If garbage is available for delivery, County must deliver up to -	936,000
ARTGT -	270,000
Maximum Waste Delivery Amount -	<u><u>1,206,000</u></u>

*AOSWGT - Annual On-site Waste Guaranteed Tonnage
**RTIAPCD - Recyclable Trash Improvements Actual Performance Completion Date
***ARTGT - Annual Recyclable Trash Guaranteed Tonnage

(Figure 1)

DADE COUNTY, FLORIDA TRASH-TO-FUEL PROCESS



(Figure 2)

TECHNICAL SESSION I

***Retrofits & Emissions
Characteristics***

**Design, Operation, and Performance
of a Modern Air Pollution Control System
for a Refuse Derived Fuel Combustion Facility**

**Edwin H. Weaver
Belco Technologies Corporation
7 Entin Road
Parsippany, NJ 07054**

**Cosmo Azzinnari
Belco Technologies Corporation
7 Entin Road
Parsippany, NJ 07054**

ABSTRACT

The Robbins, Illinois refuse derived fuel combustion facility was recently placed into service. Large and new, the facility is designed to process 1600 tons of waste per day. Twenty-five percent of the waste, or 400 tons per day, is separated out in the fuel preparation process. The remaining 1200 tons per day is burned in two circulating fluidized bed boilers.

The system is designed to meet new source performance standards for municipal waste combustion facilities, including total particulate, acid gases (HCl, SO₂, HF), heavy metals (including mercury), and dioxins. The system utilizes semi-dry scrubbers with lime and activated carbon injected through dual fluid atomizers for control of acid gases. Final polishing of acid gas emissions, particulate control, heavy metals removal, and control of dioxins is accomplished with pulse jet fabric filters. This paper discusses the design of the facility's air pollution control system, including all auxiliary systems required to make it function properly. Also discussed is the actual operation and emissions performance of the system.

INTRODUCTION

The air pollution control system for this facility consists of one semi-dry scrubber and pulse jet fabric filter for each of the two refuse combustion trains. Reagent preparation and delivery and compressed air for atomization of the reagent are provided in a system common to both air pollution control trains. A general system schematic is shown in Figure #1.

Each air pollution control system is designed to treat the flue gases from the combustion of 600 TPD of refuse derived fuel (RDF). This refuse firing rate translates to approximately 176,000 ACFM of flue gas at a temperature of 475°F. All of the system inlet design parameters are provided in Table #1.

To comply with new source performance standards for municipal waste combustion facilities, the system is designed to remove 95% of the HCl entering the system, or achieve an outlet emission rate of 25 ppm @ 7% O₂. SO₂ emissions are designed for 30 ppm @ 7% O₂ or an 85% reduction of the SO₂ entering the system. Particulate emissions are limited to 0.010 gr/DSCF @ 7% O₂. Mercury emissions are limited to 80 ug/Nm³ @ 7% O₂ or an 85% reduction of the mercury entering the system. Dioxins are controlled to a maximum of 30 ng/Nm³ @ 7% O₂. Certain heavy metals are also controlled. A summary of the mandated emission levels for the facility is provided in Table #2.

SEMI-DRY SCRUBBER

The flue gas from the incinerator enters the top of the semi-dry scrubber through flow tubes. In each flow tube, calcium hydroxide along with a small amount of activated carbon for dioxin and mercury control is introduced through a dual fluid nozzle in a finely atomized liquid form. The calcium hydroxide mixes with the flue gas and reacts with the acid gases to form solid particulate. As the flue gas and reaction products flow downward in the scrubber, the reaction products are completely dried. Although some of the particulate drops into the hopper under the semi-dry scrubber, most of the particulate is carried to the fabric filter where it is removed from the gas stream.

The design of the semi-dry scrubber for this process necessitates the satisfaction of two major criteria. First, the reagent slurry must be atomized to produce a droplet spectrum that provides for the optimum acid gas absorption and reaction. Second, the vessel must be configured to ensure that the droplets evaporate and the reaction products produced dry before reaching the wall of the vessel or exiting the vessel. This prevents buildups which would impede the operation of the system.

The semi-dry scrubber utilizes dual fluid nozzles to atomize the lime slurry. A total of 10 nozzles per scrubber vessel were provided. The flue gas entering the vessel is equally divided into three gas streams. Each gas stream passes through a "flow tube" where a dual fluid nozzle sprays the atomized slurry concurrently downward with the gas flow. A sketch of this arrangement is shown in Figure #2. The cool liquid contacting the hot flue gas induces turbulence and mixing. At the same time, a gas velocity reduction of approximately 90% occurs as the flue gas enters the main body of the scrubber vessel. The combination of these two processes induces a thorough mixing of the reagent and acid gases. During this mixing, the acid gases are absorbed by the reagent, creating solid particulate and removing the acid gases from the flue gas stream.

In order for this reaction to occur efficiently, the droplet spectrum from the dual fluid nozzles must be such that the droplets are not too small and therefore flash dry nor are they too large, which reduces the surface area available for reaction and causes a problem with particle drying. A useful measurement of the droplet spectrum is the sauter mean diameter (SMD). The SMD is defined as the droplet diameter which has the same surface to volume population as the entire droplet population. This number helps define the size distribution of the droplets. A wide size distribution, which is not desirable for semi-dry scrubbing, will have a higher SMD than a narrow size distribution of droplets. Field testing on this process has shown that an SMD of 60 to 70 microns produces a droplet spectrum which does not have an excessive amount of large droplets and also does not have too many fine droplets. The theoretical drying profile for the droplet spectrum for the BELCO nozzle used in this installation is shown in Figure #3.

Overall geometry of the scrubber vessel is also an important consideration. The vessel must be designed so that the flue gas expands and utilizes as much of the vessel as

possible for drying of the particulate. The unit must also be designed such that, considering the trajectory of any large droplets, no large droplets reach any wall surface before drying. The flue gas exit from the vessel is arranged so that the gas is turned out of the vessel without disturbing the gas flow patterns in the vessel and without the use of any internal turning devices which would create a point of buildup for solids. The key physical dimensions for this vessel, which incorporate the above items, are shown in Table #3.

REAGENT PREPARATION AND DELIVERY

A critical part of the system design is the delivery slurry, dilution water, and compressed air for liquid atomization. The slurry must be prepared, stored, and delivered in a manner that avoids the typical operating and maintenance problems that are associated with slurry handling and delivery.

For system redundancy, two 100% capacity lime storage and slurry preparation systems were provided. Each lime storage silo has a capacity of 143 tons of pebble lime which represents 7 days of storage at maximum acid gas loadings. The pebble lime is slaked in a detention type slaker, each of which is rated at 7,000 lb/hr. The lime slurry produced is stored in a tank, each tank having a capacity of approximately 24,000 gallons of slurry.

Activated carbon for the system is stored in a silo. This silo has a capacity of approximately 15 tons, or one truckload of activated carbon. The activated carbon is added to the lime slurry in a batch type process. When the slaker operates and lime slurry is added to the storage tank, activated carbon is mixed with water and transported to the slurry storage tank. The amount of activated carbon added is adjustable and coordinated with the slaking operation so that the desired concentration of activated carbon in the slurry can be maintained. A schematic of the slurry and activated carbon preparation system is shown in Figure #4.

Slurry from the storage tanks is delivered to the scrubber vessel through a series of pumps. The first pumps deliver slurry to the atomization level of the scrubber. Most of the slurry pumped is recirculated back to the lime slurry storage tank. This allows for a slurry velocity of approximately 4 to 7 ft/sec in the piping which avoids erosion from high velocity or settling from low velocity. Redundant pumps and recirculation loops were provided to ensure the ability to continuously deliver slurry to the scrubbers. Slurry is delivered to the vessel by diaphragm type pumps. The speed of these pumps is variable and controlled by a signal from the acid gas monitor. This ensures that the proper and optimum amount of slurry is continuously delivered to the scrubber. Again, redundant pumps were provided to ensure continuous operation. A schematic of the slurry delivery is provided in Figure #5.

Dilution water is added for temperature control, assuming that the liquid in the slurry is insufficient to reduce the gas temperature to the desired level. A control valve

regulates the amount of dilution water, which is mixed with the slurry in a small manifold just prior to entering the nozzles. The amount of compressed air delivered to the nozzles is controlled to ensure optimum atomization of the liquid. This entire system is shown in Figure #6.

PULSE JET FABRIC FILTER

A modular pulse jet fabric filter with roof access doors was selected for this facility. The use of full roof doors allows for easy accessibility and a large area for storage when maintenance or filter bag changeout is required. Flue gas enters each module in the hopper area where a manual damper is provided for insulation. A series of vanes turn the gases up toward the filter bags. Gas is drawn through the filter bags, removing particulate and providing a surface for secondary removal of acid gases. The clean gas exits the module through a poppet valve which is used for module isolation during off line cleaning or module maintenance. Compressed air for cleaning the filter bags is provided through pulse pipes located above the filter bags. Cleaning air is controlled by Goyen valves located on each pulse pipe. A general schematic of a filtering module is shown in Figure #7.

The pulse jet fabric filter for this facility has a total of eight modules. The eight modules allow for maintenance to be performed in one of the modules at the same time one module is off line for cleaning, with the remainder of the modules in service to filter the particulate from the flue gas. Each module has a total of 256 bags, with each bag 6 inches in diameter by 16.5 feet long. This results in a net-net air to cloth ratio of 4:1 at maximum design conditions. The filter bags are constructed of 16 oz/yd² fiberglass with 10% Teflon B coating. The cages are 20 wire cages constructed of mild steel with a light galvanized coating. A summary of the fabric filter specifics is provided in Table #4.

SYSTEM OPERATION AND PERFORMANCE

This facility was first placed into operation in October, 1996. Facility acceptance testing was performed in January, 1997. To date, operation of the air pollution control system has been excellent. The scrubber has operated without any problems, except for some minor issues with the strainers and slurry hoses. There is no evidence of buildups inside the vessel and there have been several internal inspections during outages for boiler related issues. The fabric filter has operated reliably, with pressure drops typically ranging from 5 inches to 5.5 inches.

The first formal emissions testing from the facility showed excellent performance, with emissions well below the permitted levels. A summary of this test is provided in Tables #5 and #6.

SUMMARY

Well designed refuse incineration facilities with state of the art air pollution control systems provide an efficient and effective method of reducing waste volume. Semi-dry scrubbers utilizing dual fluid atomizers have been developed to a state of the art technology which provides excellent performance and low emission levels. The emissions from this facility show that environmentally sound emission levels are readily achievable, allowing a facility such as this to be a "good neighbor" at the same time that it helps to solve the problem of waste disposal.

Table 1. System Design Parameters

Refuse Firing Rate	600 tons per day per train
Flue Gas Flow to APC Equipment	176,026 acfm
Flue Gas Temperature	475 °F
Maximum Inlet HCl	1,500 ppm @ 7% O ₂
Maximum Inlet SO ₂	600 ppm @ 7% O ₂

Table 2. System Design Emissions

HCl Emissions	25 ppm @ 7% O ₂ or 95% removal
SO ₂ Emissions	30 ppm @ 7% O ₂ or 85% removal
Particulate Emission	0.010 gr/dscf @ 7% O ₂
Mercury Emissions	80 µg/Nm ³ @ 7% O ₂ or 85% removal
Cadmium Emissions	10 µg/Nm ³ @ 7% O ₂
Lead Emissions	100 µg/Nm ³ @ 7% O ₂
Dioxin Emissions	30 ng/Nm ³ @ 7% O ₂

Table 3. Semi-Dry Scrubber Design

System Type	Downflow
Atomizers	Dual Fluid Nozzles
Number of Atomizers	10
Scrubber Diameter	30.0 feet
Scrubber Cylindrical Height	40.0 feet
Residence Time at Design Flow Rate	11.7 seconds

Table 4. Fabric Filter Design

Fabric Filter Type	Pulse Jet
Number of Modules	8
Number of Bags per Module	256
Total Number of Bags	2048
Bag Dimensions	6" diameter by 16.5 feet long
Total Cloth Area	51,343 ft ²
Net-Net Air to Cloth Ratio	4.00 : 1
Bag Material	16 oz/yd ² Fiberglass with 10% Teflon B Coating

Table 5. Emission Test Results (100% RDF Firing)

Pollutant	Emissions Unit A	Emissions Unit B	Permit Limit
HCl (ppm)	4.6	6.2	25
SO ₂ (ppm)	1.0	0.5	30
Particulate (gr/dscf)	0.0015	0.0056	0.010
Arsenic (μg/dscm)	0.2	0.2	10
Cadmium (μg/dscm)	ND	0.3	40
Chromium (μg/dscm)	4.8	5.6	120
Lead (μg/dscm)	3.6	30.9	490
Mercury (μg/dscm)	15.8	2.9	80
Nickel (μg/dscm)	3.1	3.1	100
Total Dioxin-Furans (ng/dscm)	2.1	4.9	30

Notes:All concentrations are at 7% O₂.

ND-below detection limits.

Table 6. Emission Test Results (50% Residential Waste & 50% Wood)

Pollutant	Emissions Unit B	Permit Limit
HCL (ppm)	2.4	25
SO ₂ (ppm)	0.6	30
Particulate (gr/dscf)	0.0047	0.010
Arsenic (μg/dscm)	0.3	10
Cadmium (μg/dscm)	0.1	40
Chromium (μg/dscm)	5.9	120
Lead (μg/dscm)	22.1	15.8
Mercury (μg/dscm)	0.5	80
Nickel (μg/dscm)	3.1	100
Total Dioxin-Furans (ng/dscm)	2.1	30

Note:All concentrations are at 7% O₂.

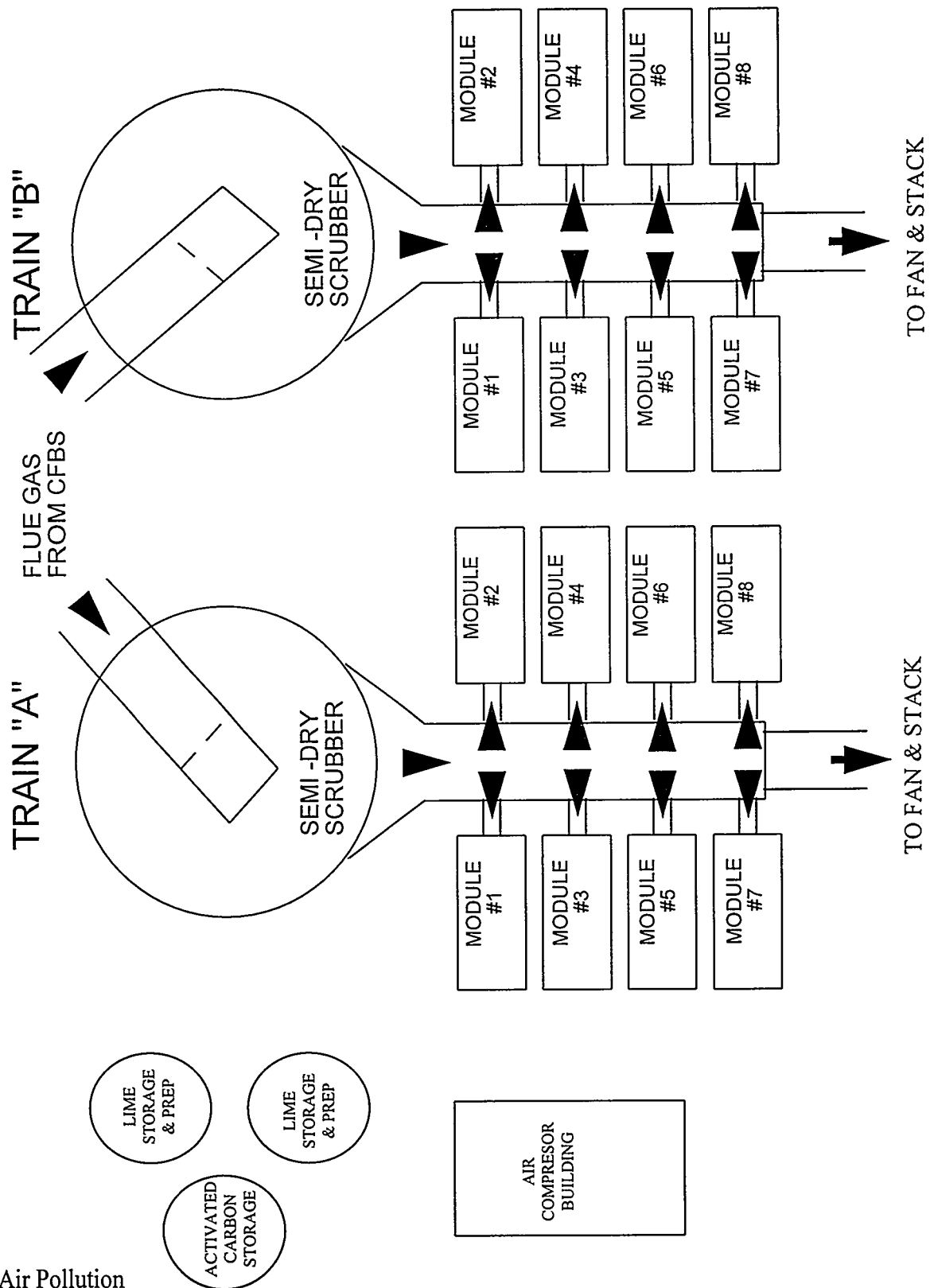


Figure #1- Air Pollution Control System

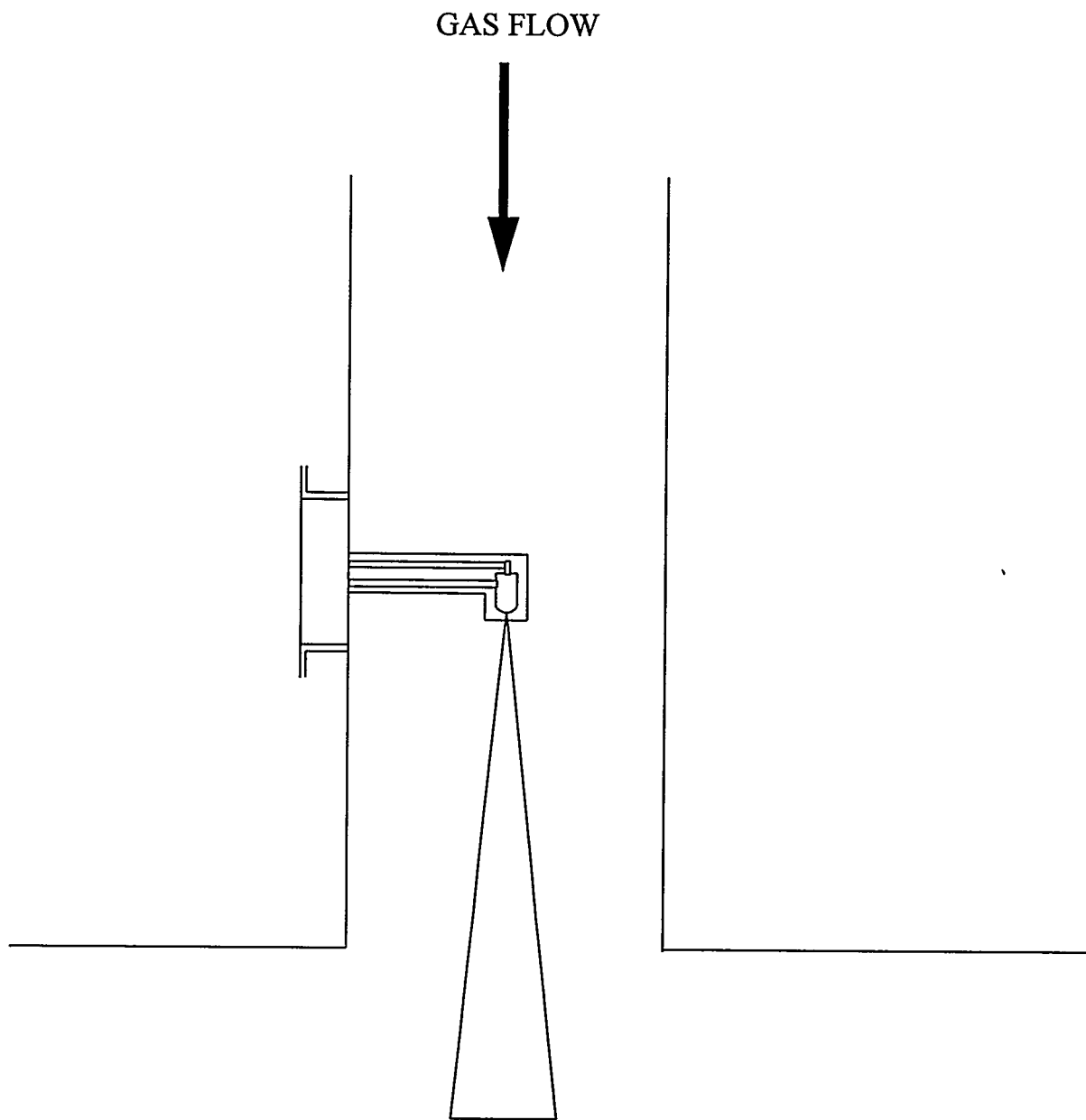


Figure #2
Atomization and Mixing

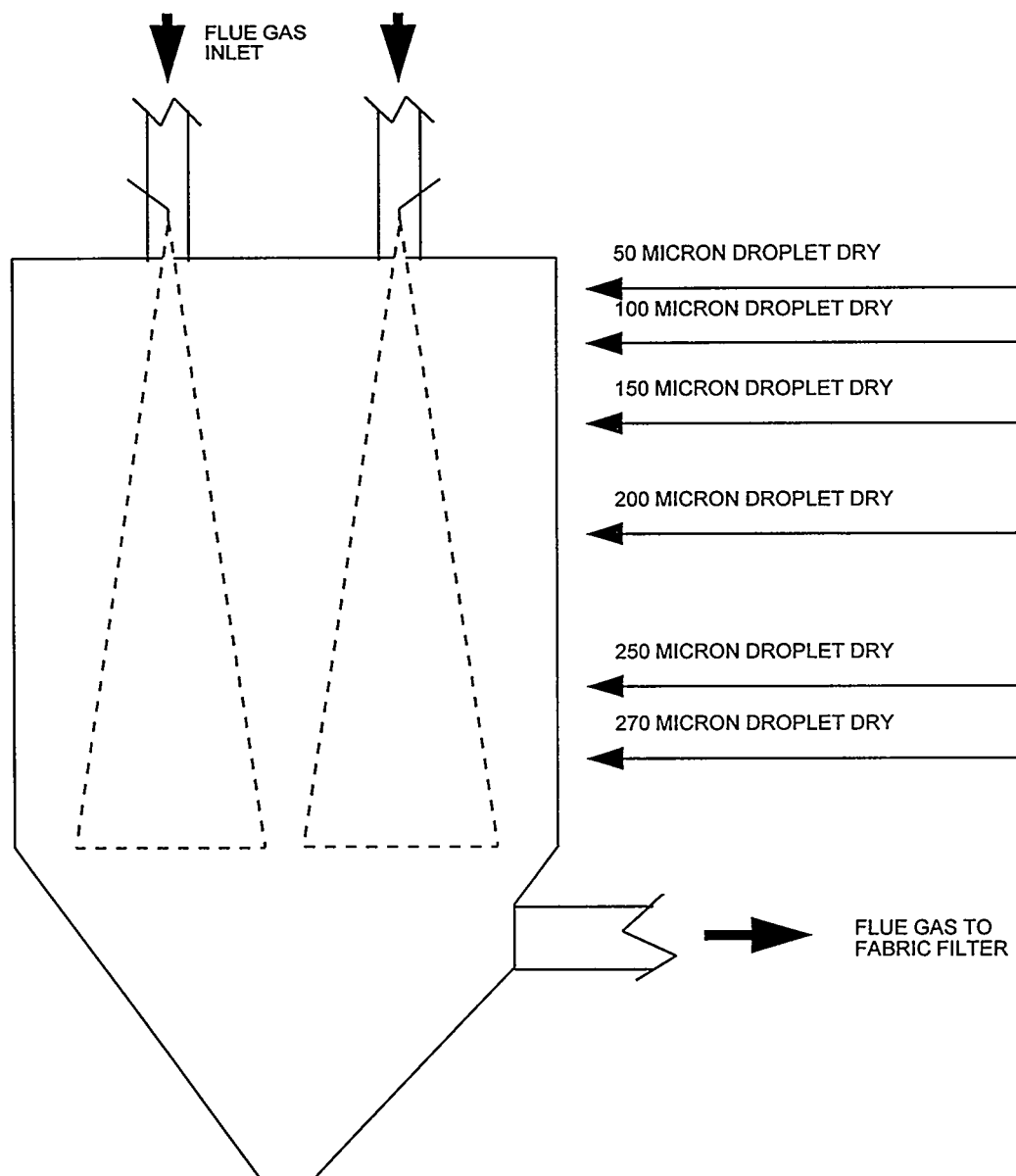


Figure #3
Typical Drying Profile

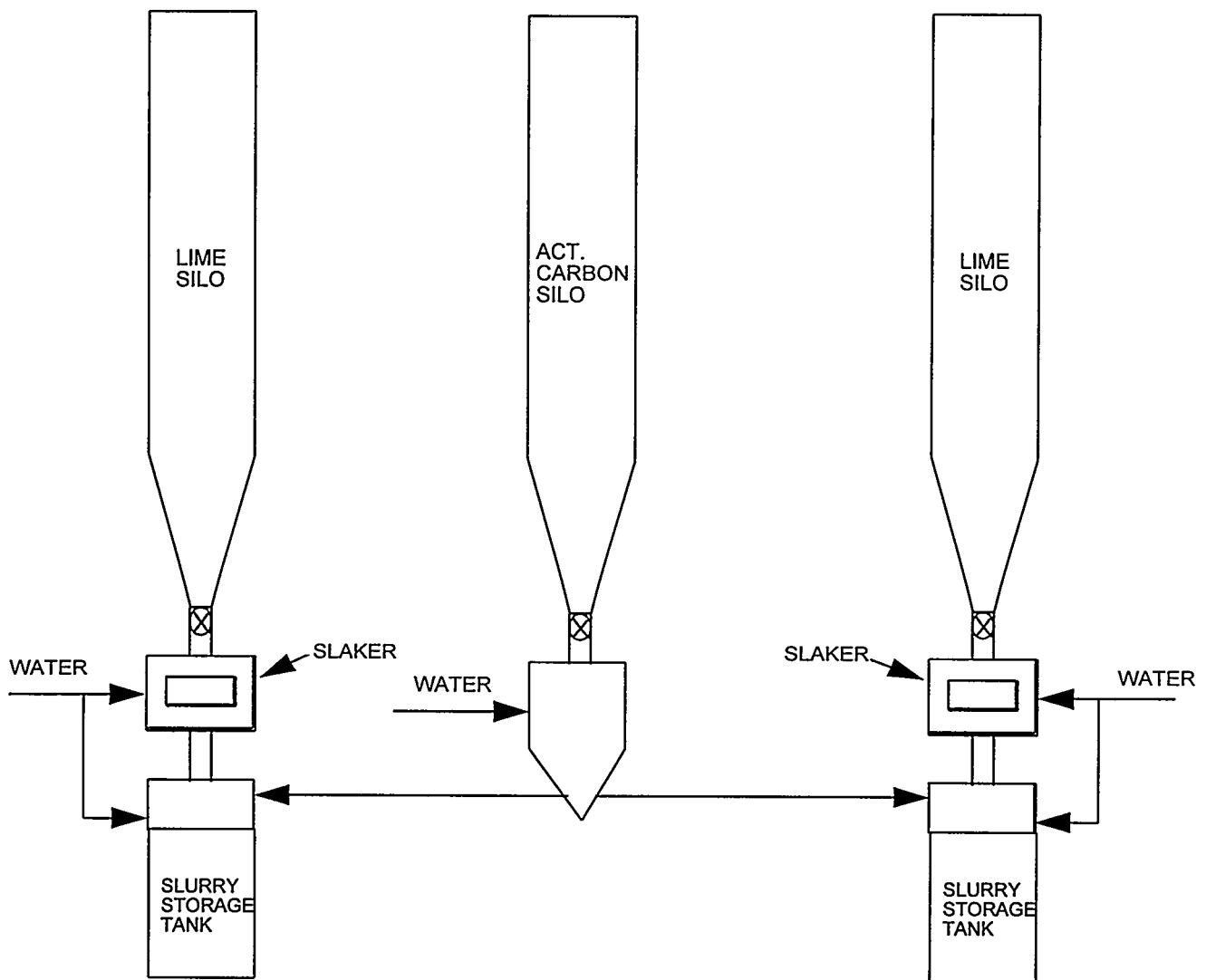


Figure #4
Slurry and Activated Carbon
Preparation

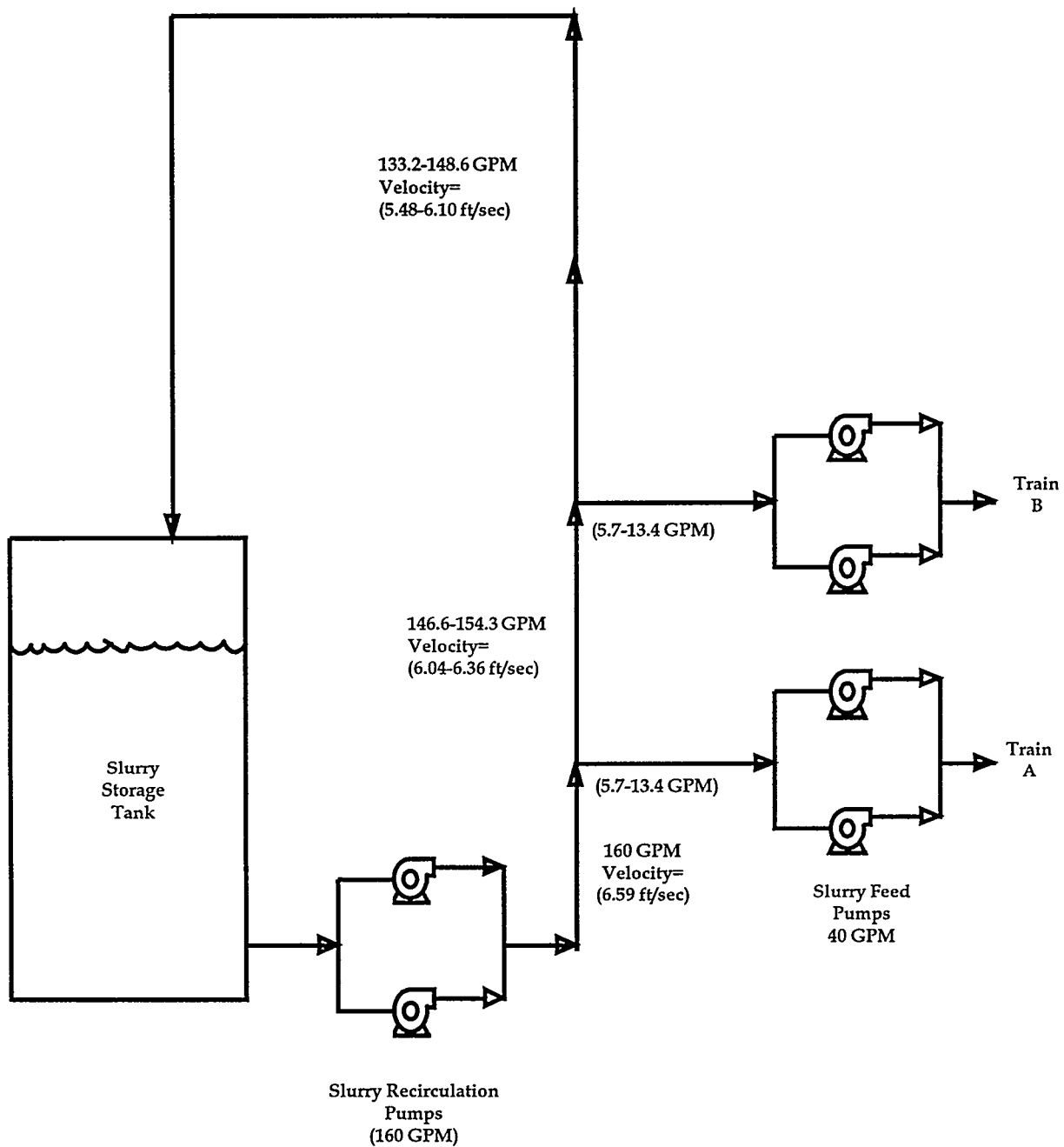


Figure #5
Slurry Recirculation

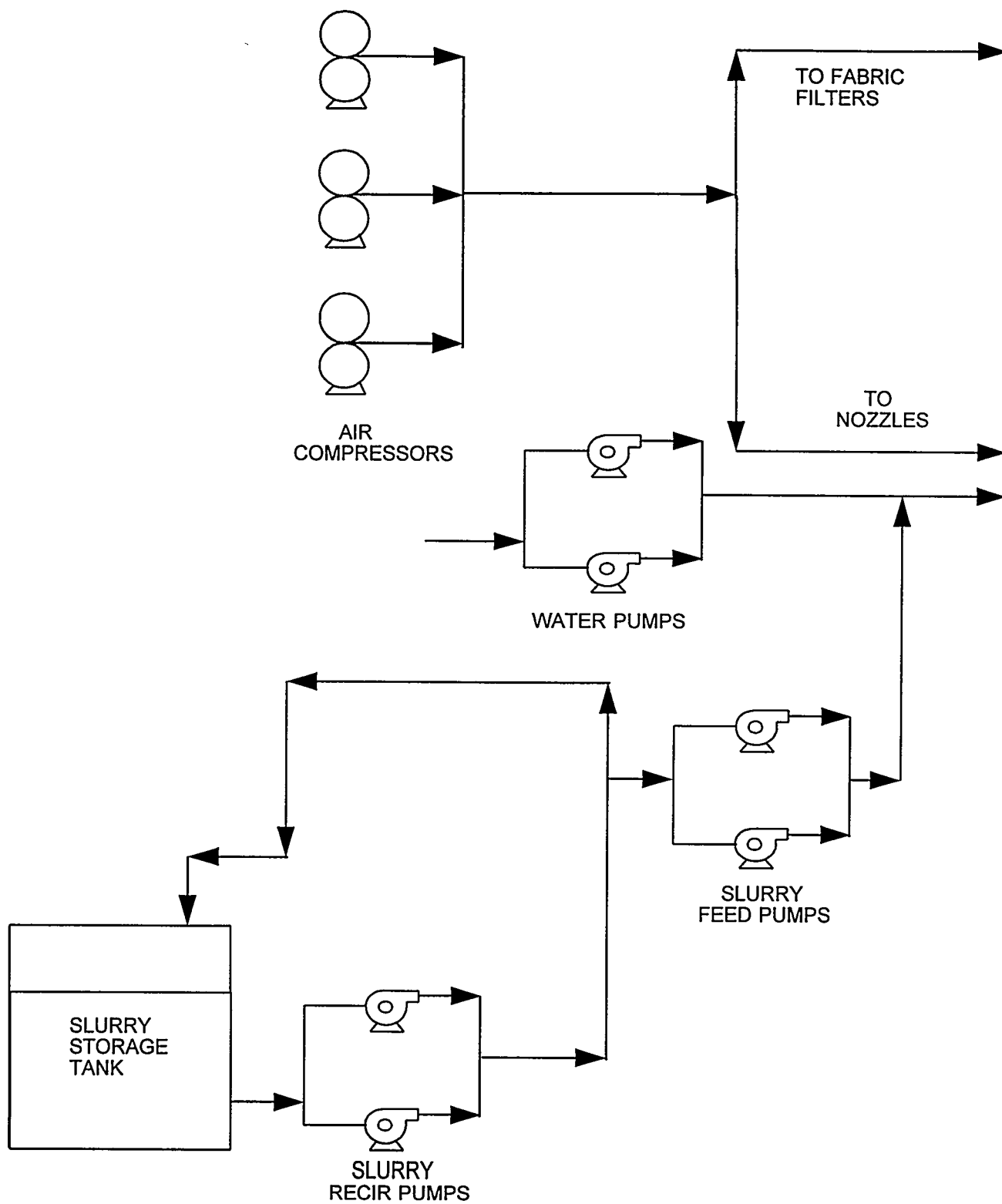


Figure #6
Slurry, Dilution Water & Compressed Air

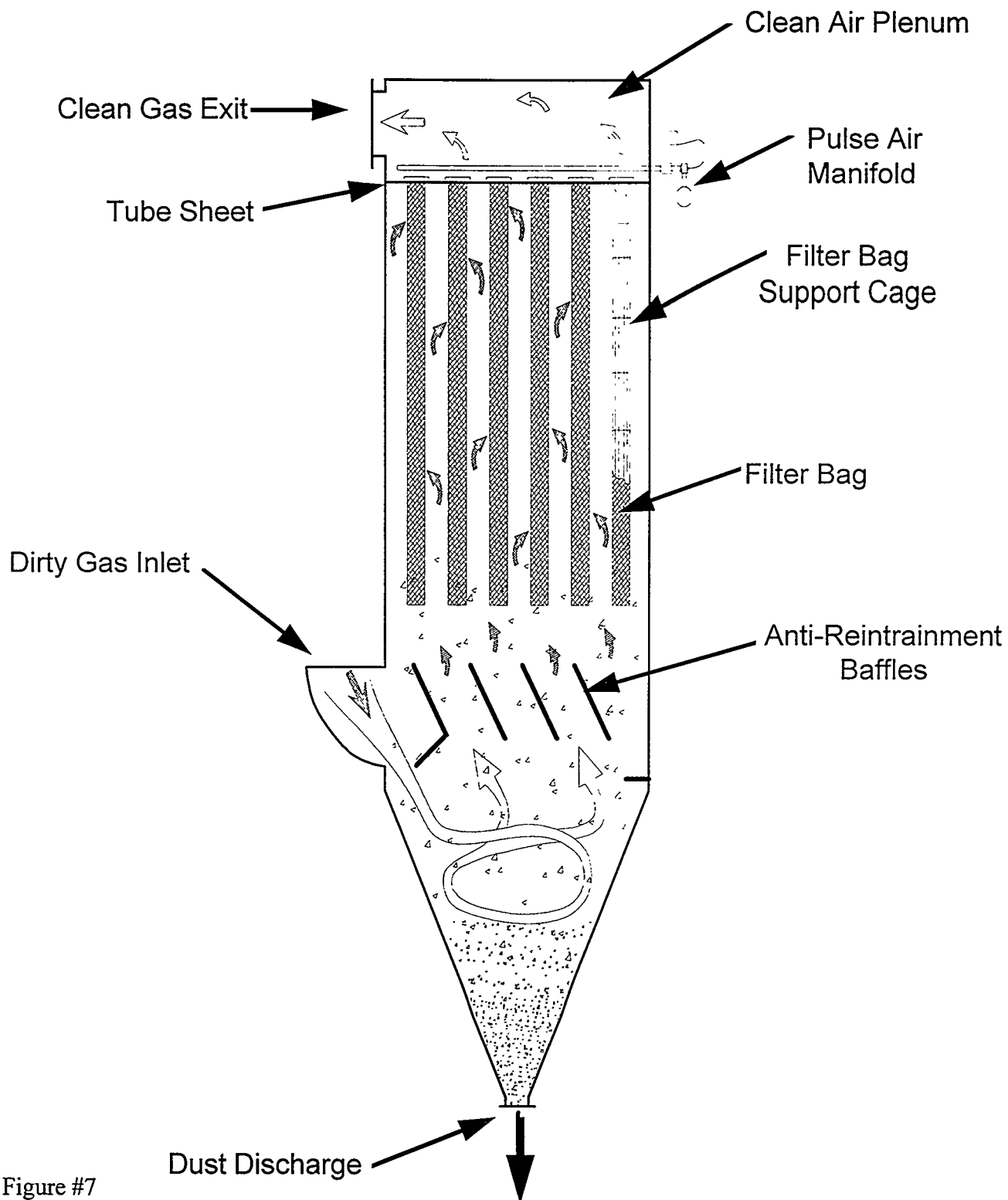


Figure #7
Typical Filtering Module

Air Pollution Control for Waste to Energy Plants -
What Do We Do Now ?

Mark R. Sankey
Research-Cottrell
US Highway 22 West at Station Road
Branchburg, NJ 08876-3599

Anthony Licata
Licata Energy & Environmental Consultants, Inc.
345 Concord Road
Yonkers, NY 10710-1848

INTRODUCTION

Recent regulations require owners and operators of many waste-to-energy facilities to upgrade their existing air pollution control equipment. While it makes sense for some of these to install systems which meet BACT (Best Available Control Technology) standards, for others such a route could be less than the best choice. For the purpose of this discussion we will consider BACT standards to be at least 90% SO₂ reduction and 95% HCl reduction. For SO₂, this is higher than required by new source performance standards (NSPS) as defined in December, 1995 and summarized in Table 1. An air pollution control system to meet BACT standards generally includes a spray dryer injecting lime slurry, addition of other reagents for control of mercury, etc., and use of a fabric filter. For many units, a less expensive upgrade which seeks only to meet the latest regulatory requirements might be optimum. In some instances, this could be the difference between a plant continuing in operation, or closing. Political uncertainties and the current economic climate make these decisions very difficult.

OVERVIEW OF THE SITUATION

Review of Regulations

After significant discussion and review, the latest federal regulations for waste-to-energy plants were promulgated in December, 1995. On the federal level guidelines were issued for existing municipal waste combustors. States have the authority to define their own requirements, but these must satisfy the guidelines as a minimum. A summary of these guidelines is included as Table 2. For new plants, the requirements are more stringent than the previously promulgated regulations. Actually, they represent a codification of typical existing permits. Spray dryers and baghouses will be the most commonly installed equipment for these with lime stoichiometry high enough to ensure the required removal rates of acid gases. The requirements for dioxins, furans, and heavy metals are generally attainable with such an equipment installation. The mercury emission specified is the same for all cases. Its evident that the developers of the guidelines sought to mitigate the financial hardship on smaller plants and those with Electrostatic Precipitators (ESPs) instead of fabric filters. One could also surmise that they did not believe the benefits of more thorough changes would justify the costs.

The most significant differences between the NSPS and existing plant guidelines are in the area of acid gas and dioxin/furan emissions. Recent litigation has brought more uncertainty to the situation. The lines of demarcation based on plant rather than unit size were successfully challenged in U.S. District Court. On March 21, 1997 the District Court granted EPA's motion to remand NSPS and Emission Guidelines for MWC greater than 250 tpd and vacate the standards for units 250 tpd or less. This ruling by the Court means that emission standards for large units remain in effect and EPA will have to redraft and promulgate the standard for small plants. The larger existing Municipal Waste Combustors (MWCs) will have to be in full compliance by December 19, 2000. While the compliance strategy for the larger existing units is now clear, it still makes sense to review equipment capabilities and potential modifications on the basis of the emission limits as shown in Table 1 and plan for upgrades now.

Equipment Capabilities

We have made some mention of the equipment typically used to achieve the performance levels referenced. As further background, we can consider typical performance levels guaranteed with use of ESPs as compared with fabric filters. Early in the development of acid gas removal systems for waste to energy plants, there were trends to use ESPs following a spray dryer. This was especially strong in Japan. Generally, these were applied where required removal rates were relatively low. Operating results from this market and elsewhere show that this equipment arrangement can perform above the requirements for small and large existing plants. Where fabric filters inherently have the ability to perform better than ESPs for collection of acid gas, there is potential for existing ESPs to be retained while maintaining acceptable performance. This is predicated on ESPs being of sufficient size. If an ESP is too small it may be sensible to increase the size or make other modifications rather than replace the unit with a fabric filter. Of course, the ESP must be capable of meeting the particulate emission limit as well as the maximum opacity of 10%. We will address modifications and other performance enhancements for ESPs in detail later.

Dry injection of lime or sodium based sorbents is used in some facilities for acid gas control. Generally this is followed by a fabric filter. For such existing installations classified as small units, no change should be required. For large units, the only necessary addition should be cooling equipment to bring the temperature to the level needed to optimize acid gas neutralization. This will usually mean installation of a water spray or quench tower. In duct quenching is not a reliable means of cooling in our opinion.

Some installations which only have ESPs may be able to achieve required performance with dry injection. Certainly higher amounts of lime are needed than with a fabric filter. Also operation at an optimal temperature is more critical. Since in most cases a quench tower is required, we would expect additions of spray dryers to be more common. Such a step also allows future upgrade of the ESP.

REVIEW OF LIME TECHNOLOGY

Technical Issues

For MWC air pollution control systems, lime is the principal sorbent used to control acid gas emissions. The authors have observed that many otherwise astute managers and administrators in the MWC industry are often not entirely aware of the unique economics, properties and reactions associated with the use of lime. We have seen numerous applications where quicklime was selected over other sorbents, most notably hydrated lime without any up-front assessment performed to fully analyze the technical and economical impacts of the selection. We considered it appropriate to review the technical aspects of the use of lime.

Calcium oxide (CaO) is called “pebble lime” or “quicklime”. CaO is not very reactive in absorbing acid gases at post combustion temperatures and conditions that exist in MWC facilities and has to be converted into the hydrate form to be reactive in scrubbing systems. The hydrated lime $[\text{Ca}(\text{OH})_2]$ has been demonstrated to remove acid gases in high temperature applications such as furnace injection. Hydrated lime is highly reactive and is made from CaO by adding controlled amounts of water in a hydrator to produce a powder. The resulting material has large reactive surface area with a mean particle size of 5 microns.

Pebble lime is slaked to form a slurry. CaO is converted to Ca(OH)_2 in the slaking process in which four parts of water are added to one part of CaO to form Ca(OH)_2 in a slurry that contains about 25% solids. The term slaking applies to the combining of varying proportions of excess water and quicklime, which yields a milk-of-lime, a lime slurry, or a viscous lime paste. This conversion requires two simultaneous steps that take place in the slaker. The first step converts the CaO into Ca(OH)_2 hydrate. The second step converts the hydrate to a slurry by mixing 3.96 lbs. of free water with one part hydrate (1.32 lbs) that results in a 25% solids slurry (5.28 lbs).

Hydrated lime can be introduced into the flue gas stream using several methods as follows:

- injection into the flue gas in a dry form;
- injection into the flue gas in a dry form after the gas has been conditioned by the addition of water which serves to increase the moisture content of the flue gas and to concurrently reduce the flue gas temperature; or
- injection into the flue gas as a wet slurry.

Quicklime is delivered to most sites as a “pebble” nominally 3/4" in diameter. In order to be reactive, quicklime has to be slaked and converted into a slurry form. Slaking is manpower intensive for most plants and is a high maintenance process. There are also capital costs associated with the purchase and replacement of equipment. Slaking is as much an art as it is a science.

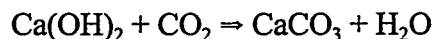
Many factors affect slaking including:

- reactivity of the lime
- lime quality
- particle size
- water quality and temperature
- distribution of water, and
- level of agitation

In order to analyze the cost differential between use of pebble and hydrated lime, we need to determine the relative usage. Please see Table 3 for details of this calculation.

A typical MWC would require either 12.9 lbs of hydrated lime or 10.5 lbs of pebble lime per ton of MSW burned to react with all of the SO_2 and HCl emitted. By ratio of the above, we can see that 23% more hydrated lime than quicklime is required to achieve the stoichiometric reduction of MWC acid gases. Both hydrated lime and quicklime sell for about the same unit price. However, when you purchase hydrated lime you are buying 32% water which reduces the actual calcium content. As you can see for the above, it is the Ca to SO_2 or HCl ratio that is important.

In actual applications, this theoretical balance never occurs. Due to the inability to provide perfect contact between all of the lime and the acid gas molecules, excess reagent is required in the process to achieve SO₂ and HCl emissions of less than 25 ppm. In addition, several secondary chemical reactions take place that also use some undefined portion of the lime. For example, lime will react with carbon dioxide in the flue gas as follows:



There is also a positive reaction that occurs. The presence of HCl in the flue gas actually improves the lime's capture of SO₂. This reaction has been discussed in numerous papers.

The ratio of the actual amount of lime used to the theoretical amount required is called the stoichiometric ratio. A typical MWC equipped with a spray dryer and an ESP will require about 35 lbs of pebble lime per ton of MSW while a MWC with a spray dryer baghouse will require about 20 to 25 lbs per ton to meet the current NSPS standards of 25 ppm of HCl (a 95.3% reduction) and 30 ppm of SO₂ (an 85.8% reduction). These values may vary for particular plants, depending on temperature and moisture conditions in the system. Based on the typical values cited, the stoichiometric ratio for a plant with an ESP would be:

$$35 \div 10.5 = 3.33$$

Typical air pollution system requirements developed by Dravo Lime's testing program to control acid gas emission to the NSPS requirements are as follows:

Technology	Hydrated Lime		Quick Lime	
	Lbs of Ca(OH) ₂ per ton of MSW	Stoichiometric Ratio	lbs of CaO per ton of MSW	Stoichiometric Ratio
Spray dryer/fabric filter	24	1.86	20	1.90
Spray dryer/ESP	35-40	2.71-3.10	30-35	2.85-3.33
Dry injection/ fabric filter	50	3.87	n/a	
Conditioned dry injection/fabric filter	24	1.86	n/a	

These results are shown to compare results of hydrated lime versus quicklime and do not necessarily reflect actual MWC plant operation.

Economics of Lime Technologies

As previously stated, in order to obtain equivalent levels of acid gas removal, it requires more hydrated lime than quicklime which results in an increased operating expense. Quicklime, however, requires more capital equipment, more operational and maintenance personnel, and a higher level of skill. As a rule of thumb, smaller plants or plants that require upgrading but have less than 20 years of expected life may find that a dry lime injection or conditioned dry injection of hydrated lime may be less expensive. The following analysis was made to compare operating cost for applying hydrated lime (conditioned dry injection) vs. Quicklime (lime slurry) (see Table 4).

The analysis in Table 4 was based on the following inputs:

- Three plant sizes were selected: 250 T/D, 500 T/D and 1,500 T/D. Each plant has an annual capacity factor of 85% and a 20 year life expectancy.
- The delivered price of both hydrated lime and quicklime is \$80.00 per ton.
- The quicklime (slaker and slurry system) requires one person about half time for operations and maintenance which results in a personnel cost of \$30.00 per hour inclusive of all overheads and benefits. Alternatively, the hydrated lime system requires about half as much personnel time resulting in a cost of \$15.00 per hour on the same basis.
- 23% more hydrated lime is required than quicklime to meet the emission standards. For this analysis, we used a factor of 25 lbs of quicklime per ton of MSW burned and 30.7 lbs of hydrated lime per ton of MSW burned.

SPRAY DRYER / FABRIC FILTER SYSTEMS

A spray dryer followed by a fabric filter has become the standard approach to air pollution control at MSW plants in the United States. As we have mentioned, this has resulted from the regulatory requirements and determination of lowest fixed cost. We felt this presentation would be incomplete without addressing the scenario of a backfit of such a system. Based on a 3 train installation, with total plant capacity in the range of 750 to 1000 tons per day (TPD) and supply of one common lime storage, preparation, and pumping system we reviewed recent budgetary pricing. For a refractory type furnace with high excess air usage, the result is a cost of about \$10,000/TPD of capacity. For a water walled furnace with lower excess air and thus lower gas flow rate, the cost is about 10% less or \$9,000/TPD. These costs are also based on use of a dual fluid nozzle atomization system including compressors. While these cost ratios include installation, costs for demolition and other site work have not been included.

Operating costs will vary somewhat depending on the acid concentrations in the flue gas resulting of course from the make up of the waste burned. Based on actual industry experience, pebble lime usage can vary from roughly 20 to 30 lbs./ton of waste burned. Actual usage can vary because the slurry feed rate can be varied based on actual flue gas concentrations. As well as SO₂ monitors which are commonly in use today, HCl monitors have proven reliable. Use of such a signal could add a measure to reagent savings. We estimate power usage for a complete spray dryer and fabric filter system to be about 10 kWh/ton of garbage burned. This includes power to run air compressors for slurry atomization.

In many cases there is not a need to replace the particulate collection device, but addition of a spray dryer is the best approach. With existing ESPs, this is an approach which can keep a plant in compliance, especially for units smaller than 250 TPD.

SPRAY DRYER BACKFITS

For a variety of circumstances including existing equipment, plant layout, desire for higher performance, and more stringent state regulations, plants may choose to add spray dryers to ESP or fabric filter systems. As we have mentioned, a quench tower can often do the job. Where some tower designs can only accommodate water spray, designs which could easily handle use of lime slurry in the future should be considered. Without getting sidetracked to detailed analysis and comparisons, rotary atomizer and dual fluid nozzle designs are available. Conversion of quench towers to spray dryers is favored with spray nozzles which have been used extensively for quenching. Upflow and downflow designs are also variations which owners will encounter when investigating spray dryers. These differences impact design, capital cost, and operating expenses and are worth understanding, but it is not our purpose to do that here.

As with any backfit, there are layout issues to be considered. Room for the basic tower diameter plus inlet and outlet ductwork must be available. A rule of thumb for layout requirements would start with calculation of the tower outlet gas flow at 285°F. Evaporated quench water must of course be included. Various tower designs and manufacturers use differing design velocities, but an upflow, dual fluid nozzle design would have velocity in the range of 5.5 to 6.5 feet per second. Inlet and outlet duct velocities of 60 feet per second are typical. For a unit capacity of 250 TPD, an upflow tower would be about 15 foot diameter.

Costs for backfits will vary with size and layout difficulties. There are situations where existing silos or other equipment can be reused and reduce costs. Availability of compressed air for dual fluid atomization is also an important factor. For a two unit plant with total capacity of 500 TPD, costs for a spray dryer backfit will range from \$5000 to \$6000/TPD of capacity. This covers installation, a complete pebble lime storage, slaking, and pumping system and compressors.

DRY INJECTION

Dry injection has many potential uses for upgrading pollution control systems. Related to acid gas removal, injection of dry lime has been demonstrated to provide acid gas removal at the levels now required for small plants. Sufficient moisture must be present, but this should not be any problem for MSW applications since proper temperatures for reaction are usually achieved with water spray cooling. For installations where this is not available, a quench chamber must be added. For future performance upgrade by addition of lime slurry, a tower design which would permit future use of slurry could be considered. This technology works best when followed by a fabric filter but, with proper gas conditioning it can also be effective with ESP's.

While past practice has followed a trend of using spray dryers with lime slurry produced by on-site slaking, our discussion of lime technology shows potential advantages of using dry lime injection. This is a current trend in Japan. The problems and costs associated with slaking and handling of slurry are avoided. It is well established that when operating at the same conditions of temperature and moisture upstream of a particulate collection device, acid gas removal levels are about the same whether using lime as slaked slurry from pebble lime, or lime as dry hydrated reagent injected into the gas stream. Experience indicates a slightly higher lime usage for dry injection than for spray drying with slurry. This increase is about 10 to 15%. We attribute this to the more favorable reaction environment when slurry is "drying" and the acid gas is exposed to the lime in a "wet" environment.

There are a variety of means available for injection. Some manufacturers use specially designed vessels to promote good mixing of reagent with the acid gas. In other cases, lime has simply been introduced through a pipe into the ductwork. The desired effects are rapid, intimate contact of acid and lime. Turbulent gas flow zones can be developed to produce this. Another important aspect is treatment time. The longer the contact period, the better the reaction. We expect that some reaction occurs in the baghouse inlet section as the gas is dispersed to the filter bag surface.

The filter cake is the final area where the reaction can occur. The longer the lime is available here for reaction, the better the utilization, and the lower the stoichiometric ratio and the operating cost. Here the term utilization refers to the extent the lime is used in reaction. Minimizing pressure drop through the cake and maintaining long cycles between cleaning help this process. Various types of cake modifiers have been used to facilitate this. Tesisorb is the name of one family of such materials. These can be fed to the system along with hydrated lime if convenient. The resulting thicker, yet more porous filter cake also provides a better bed for acid gas neutralization. Sizing fabric filters with appropriate air to cloth ratios is important. Generally, we use 2.5 net (including reverse air) for reverse air systems and 4.0 net for high pressure pulse jet systems. Net is defined as the condition with one fabric filter section off line.

Other additives can also be delivered to the system in this area. This can include activated carbon for mercury emission control or, as discussed below, Sorbalit. Some systems call for use of recycled ash which is also introduced dry.

RELATED CAPITAL COST SAVING TECHNOLOGIES

Key components of EPA's regulatory efforts for MWC's have been directed at controlling emissions of mercury and dioxins. There are a number of technologies that can reduce emissions of these pollutants, however, the predominant technology presently used employs activated carbon as the adsorbent medium. Carbon-based adsorption technologies include moving carbon bed filters; dry carbon injection, carbon slurry injection; and Sorbalit and Sorbalime.

Sorbalit/Sorbalime is a system for controlling emissions of acid gases, mercury, and organics in a single application. The sorbent component of the technology is produced by mixing lime, either calcium hydroxide (Sorbalit) or calcium-oxide (Sorbalime) with surface-activated substances such as activated carbon or lignite coke and sulfur-based components in a proprietary process. Sorbalit can be produced with carbon contents ranging from .5 to 65% depending on the technical and economic requirements of each facility.

Sorbalit/Sorbalime replaces the normal lime used at a plant either dry injection or milk-of-lime slurry. The key economic feature of Sorbalit/Sorbalime is that in most applications, no additional capital equipment is required while additional equipment is required for the injection of carbon in both a dry or slurry injection system. Field testing to date indicates that the amount of total carbon required by the Sorbalit process to meet regulatory standards is about half that needed by traditional carbon injection methods.

Conditioned Dry Inject and Fabric Filter Test Results

There are a number of MWC plants that were built in North America which employ a dry injection followed by a fabric filter. One such plant is the 440 T/D plant in Peel, Ontario, Canada which went online in 1992. This plant uses a quench tower to lower the boiler exit temperature from 260°C (500°F) to 160°C (320°F). The quench tower is followed by a dry lime system and a fabric filter. The Peel facility was meeting all of their existing permit conditions, however, they wanted to comply with Ontario's Guideline A-7 which is applicable to new facilities. In order to meet the A-7 Guideline, they would have to reduce their mercury emissions. The facility was also meeting the dioxin limits but was looking for additional margin and control.

A test program was conducted at the Peel facility where Sorbalit with a 4% carbon-based formulation replaced their normal hydrated lime. It was not possible to test the boiler outlet gases, so the test program was set up to measure the stack emissions comparing hydrated lime and Sorbalit. The test clearly indicates that Sorbalit reduced the Dioxin emissions by an order of magnitude and brought the mercury emissions into compliance with the proposed Ontario Guideline A-7. The summary of the test results will be found in Table 5.

Spray Dryer and ESP Test Results

The quicklime-based product, Sorbalime, was tested at a U.S. based MWC that was equipped with a spray dryer and an ESP. In this program, Sorbalime replaced the regular quicklime that the plant slaked for acid gas control. For this operation, no capital equipment was required and no changes were made to the plant operations. Prior tests at the facility had indicated that the spray dryer/ESP removed approximately 40% of the Hg emissions and 80% of the dioxin emissions. The Sorbalime test showed that existing spray dryer/ESPs can be upgraded to meet the EPA proposed standards without a major retrofit. The summary of the test results will be found in Table 6.

PRECIPITATOR UPGRADE APPROACHES

Rebuilds

If an ESP Owner intends to keep that unit in service, he needs to be sure it is in peak operating condition. A thorough structural and operational inspection should be made to determine any deficiencies. Some rebuilding or parts replacement may be needed.

Corrosion can be a serious problem for ESPs in MWC applications. Material and structural degradation is a significant cause leading to replacement of ESP internals. However, operational problems and need to enhance performance have also led Owners to consider some measure of rebuild. A fairly common practice in other industries is replacement of internals and casing repairs to deal with these sort of problems. Avoidance of corrosion requires elimination of inleakage, proper insulation systems and control of operating conditions. Where a quench chamber is upstream of an ESP, or fabric filter, it is imperative that complete evaporation be maintained.

Installation of rigid discharge electrodes can avoid shutdown of ESP sections due to breakage of wire electrodes or other similar high voltage system components. Such a replacement may require alteration of collecting electrode spacing, or use of different collecting surfaces. Interelectrode spacing, configuration of electrodes, and orientation of discharge electrodes with collecting surface profiles all affect electrical operation and orientation of discharge electrodes with collecting surface profiles all affect electrical operation and performance.

Rebuilds are a potential step in upgrade of an existing air pollution control system. If needed, effective collecting surface area can be increased depending on equipment arrangements. Rebuilds can also incorporate some of the technical advances.

Technology Advances

As with all pollution control equipment, precipitation has seen significant advancements in recent years. One area of changes is with controls. Again, as with other equipment, microprocessors have been applied to transformer-rectifier sets (high voltage power supply) controls. These regulate operation to ensure the maximum amount of usable power is available to the ESP. Electrical parameters are continuously monitored and the control automatically adjusts power to avoid wasteful sparks and arcs. Rapper controls have been similarly redesigned to incorporate state-of-the-art microprocessor components.

Changes to internal components have been focused on discharge electrode design and gas passage spacing, i.e. spacing between collecting surfaces. In certain applications, spacing has been increased to as much as 16 inches, thereby saving cost. The number of internal elements saved is proportional to the ratio of the spacing. Weight savings decreases load on supports and permits use of taller collecting surfaces increasing ESP capacity if necessary. For a given ESP casing on an MWC application, performance at wider spacings is as good or better than for ESPs at narrower spacing. Treatment time is the same in either case. This effect occurs due to greater electrical field strength in the wider spacing units which operate at proportionally higher voltage.

COHPAC

Based on use of a polishing collector downstream from an electrostatic precipitator, this technology named COHPAC (COncompact Hybrid PArticulate Collector) provides enhanced particulate collection. In MSW installations with existing ESPs it provides the benefit of a fabric filter step in the pollution control train without the need to completely abandon the ESP. The result will be increased collection of acid gas. The technology was developed by and is licensed from the Electric Power Research Institute (EPRI).

The first application of COHPAC technology added an entire baghouse with a length of ductwork downstream from an existing ESP. A more recent development uses the outlet field of an ESP as space for fabric filter bags. This approach is known as COHPAC II. The ESP internals in the outlet field are removed and gas flow modifications made for a very compact arrangement. The particular fabric filter technology used by Research-Cottrell is based on low pressure high volume cleaning. The cleaning system is the pulse jet type with cleaning air produced by positive displacement blowers. Bags are oval in cross section with a unique rotating air manifold.

The nature of this upgrade makes it suitable without regard to the original ESP manufacturer's design. However, dimensional requirements could hinder its viability in some otherwise promising situations. Certainly, where it does fit, arrangement and space requirements become immaterial.

Performance wise, we can expect acid gas removal rates for this technology range between those expected with ESPs versus those with fabric filters. With high air-to-cloth ratios that usually accompany COHPAC designs, its unreasonable to expect results as good as can be achieved with conventional fabric filter. Again, as with all of the techniques and modifications possible, this should be considered carefully based on the specific plant circumstances. The cost for a COHPAC II conversion of one outlet field of an existing ESP is about \$2,000 per ton per day of unit capacity.

Complete Conversion to Fabric Filter

There may be cases where Owners choose to replace an ESP with a fabric filter. This is often approached by using a long duct run to a location beyond ID fans or stack, to build a new unit. Another approach, again used by some power plants, is to use the ESP casing as the housing for the new fabric filters. When some ESP configurations may not be well suited for this, it warrants some consideration. An advantage here is real estate savings. Ash handling systems may also be reusable. A disadvantage is that the MWC must be offline while the conversion work is done. Overtime, shift work, and/or extended outage costs will result.

CONCLUSION

While the legislative and economic atmosphere leaves many uncertainties, waste to energy plants must plan to upgrade. Full blown additions of spray dryers and fabric filters are not always necessary to comply with current regulations. Consideration of various alternatives should be made before committing to a strategy. Awareness of these alternatives could keep an otherwise viable plant from closing.

Table 1. 1995 NSPS for new MWC's

Pollutant	Plant Capacity > 250 tpd	Plant Capacity > 39 tpd but < 250 tpd
Dioxins/furans	13 ng/dscm	13 ng/dscm
PM	24 mg/dscm	24 mg/dscm
Opacity	10%	10%
SO ₂	30 ppmv or 80% reduction	30 ppmv or 80% reduction
HCl	25 ppmv or 95% reduction	25 ppmv or 95% reduction
NOx	150 ppmv (180 ppmv first year of operation)	No control limit
Cd	0.020 mg/dscm	0.020 mg/dscm
Pb	0.20 mg/dscm	0.20 mg/dscm
Hg	0.080 mg/dscm or 85% reduction	0.080 mg/dscm or 85% reduction
Flyash/bottom ash fugitives	No visible emissions (exception for up to 5% of the time and for maintenance/repair)	No visible emissions (exception for up to 5% of the time and for maintenance/repair)

Table 2. 1995 Emissions Guidelines for Existing MWC's

Pollutant	Unit Capacity > 250 tpd ¹	Plant Capacity > 39 tpd but < 250 tpd ²
Dioxins/furans	30 ng/dscm (non-ESP) 60 ng/dscm (ESP)	125 ng/dscm
PM	27 mg/dscm	70 mg/dscm
Opacity	10%	10%
SO ₂	31 ppmv or 75% reduction	80 ppmv or 50% reduction
HCl	31 ppmv or 95% reduction	250 ppmv or 50% reduction
NOx	200-250 ppmv (Varies by MWC type, except none for mass burn refractory)	No control limit
Cd	0.040 mg/dscm	0.10 mg/dscm
Pb	0.49 mg/dscm	1.6 mg/dscm
Hg	0.080 mg/dscm or 85% reduction	0.080 mg/dscm or 85% reduction
Flyash/bottom ash fugitives	No visible emissions (exception for up to 5% of the time and for maintenance/repair)	No visible emissions (exception for up to 5% of the time and for maintenance/repair)

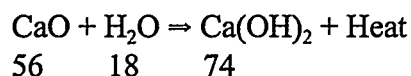
¹ U.S. EPA proposal - U.S. District Court - February 4, 1997

² U.S. EPA rule - December, 1996 Vacated by U.S. District Court

Table 3. Calculation of Comparative Usage Rates for Quicklime Versus Hydrated Lime

The theoretical reaction of the lime products (with their molecular weights) are as follows:

A. Hydrated lime and its production



1 lb of CaO yields 1.32 lbs of Ca(OH)₂

To clarify, capture ratio represents the theoretical amount of lime required to remove or capture acid gas on a weight (Lbs.) basis.

Thus, the stoichiometric, theoretically perfect, reaction of Ca(OH)₂ with acid gases requires:

1. 1.156 lbs of Ca(OH)₂ to capture 1.0 lbs of SO₂
2. 1.014 lbs of Ca(OH)₂ to capture 1.0 lbs of HCl

Without pollution controls, the average MWC facility has the potential to emit the following amounts of acid gases: [lbs/ton of municipal solid waste (MSW) burned]

SO₂ = 5.03 lbs/ton (Equivalent to 212 ppm_{dv} @ 7% O₂)

HCl = 7.03 lbs/ton (Equivalent to 532 ppm_{dv} @ 7% O₂)

Other acid gases such as HF and H₂SO₄ are also emitted in small amounts and are collected in the system but are not federally regulated in the U.S.

Table 3. Calculation of Comparative Usage Rates for Quicklime Versus Hydrated Lime. (Continued)

The characteristic stoichiometric requirement for $\text{Ca}(\text{OH})_2$ per ton of MSW is:

$\text{SO}_2 = 5.03 \text{ lbs SO}_2/\text{ton MSW} \times 1.156 \text{ lbs Ca}(\text{OH})_2/\text{lb SO}_2 =$	5.815
$\text{HCl} = 7.03 \text{ lbs HCl}/\text{ton MSW} \times 1.014 \text{ lbs Ca}(\text{OH})_2/\text{lb HCl} =$	7.128
TOTAL	12.943 (12.9) lb $\text{Ca}(\text{OH})_2/\text{ton MSW}$

B. Pebble lime (hydration process not included)

$\text{CaO} + \text{SO}_2 \Rightarrow \text{CaSO}_3$	Capture Ratio =	$56 \div 64 = 0.875$
56 64 120		
$\text{CaO} + \text{SO}_2 \Rightarrow \text{CaSO}_3$	Capture Ratio =	$56 \div 73 = 0.767$
56 73 111		

The stoichiometry of CaO with acid gases requires:

- 0.875 lbs of CaO to capture 1.0 lbs of SO_2
- 0.767 lbs of CaO to capture 1.0 lbs of HCl

The following is the stoichiometric reaction of CaO for typical MSW:

$\text{SO}_2 = 5.03 \text{ lbs SO}_2/\text{ton MSW} \times 0.875 \text{ lbs CaO}/\text{lb SO}_2 =$	4.401
$\text{HCl} = 7.03 \text{ lbs HCl}/\text{ton MSW} \times 0.767 \text{ lbs CaO}/\text{lb HCl} =$	5.392
TOTAL	9.793 lb CaO/ton MSW

Since CaO contains about 7% unreactive material and inerts that are lost in the slaking process, the usage is adjusted to compensate for impurities. Accordingly, the adjustment is made by the following computation:

$$1.07 \times 9.793 = 10.5 \text{ LB CaO/ton MSW}$$

Table 4. Cost Analysis

Plant design capacity - T/D		250	500	1,500
Plant operating capacity - T/Y		77,562	155,125	465,325
QUICKLIME ANALYSIS				
Annual Capital Cost ⁽¹⁾		\$8,000	\$10,000	\$15,000
Annual Replacement Cost		\$4,000	\$6,000	\$8,000
Labor (O & M) - \$/hr	\$30.00	\$134,400	\$134,000	\$134,400
Lime Cost - \$/Ton Lime	\$80.00	\$77,562	\$155,125	\$465,325
Quicklime Usage - lbs per ton MSW	25	970	1939	5817
Total Annual Cost		\$223,962	\$305,125	\$622,725
Unit Operating Cost - per ton MSW		\$2.89	\$1.97	\$1.34
DRY INJECTION ANALYSIS				
Annual Capital Cost		-	-	-
Capital Replacement Cost		\$4,000	\$6,000	\$8,000
Labor (O & M) - \$/hr	\$30.00	\$65,700	\$65,700	\$65,700
Lime Cost - \$/Ton Lime	\$80.00	\$95,246	\$190,494	\$571,419
Quicklime Usage - lbs per ton MSW	30.7	1191	2381	7143
Total Annual Cost		\$164,946	\$262,194	\$645,119
Unit Operating Cost - per ton MSW		\$2.13	\$1.69	\$1.39

Incremental capital costs above those required for the dry injection process.

Table 5. Peel Facility Test Results

Test ⁽¹⁾	Hg Stack Concentration $\mu\text{g}/\text{Rm}^3$ @ 11% O ₂ ² (@ 7% O ₂)	PCDD/PCDF - I-TEQ Stack Concentration ng/Rm^3 @ 11% O ₂ (@ 7% O ₂)
Hydrated Lime Only		
#1	127	0.1200
#2	172	0.0860
#3	217	0.1100
Average	172 (241.5)	0.1053 (0.1478)
Sorbalit		
#4	31	0.0180
#5	26	0.0087
#6	20	0.0027
#7	12	0.0023
#8	5	0.0010
Average	19 (26.6)	0.0065 (0.0091)
A-7 Guideline	57 (80)	0.14 (0.196)

Conditioned Dry Injection and Fabric Filter

²R = reference condition, 25°C

Table 6. Spray Dryer and ESP Test Results

Flue gas temperature - 295°F
 % C in Sorbalime 4%
 Average SO₂ emission during test - 22 ppm_{dv}
 All data corrected to 7% O₂

	Hg Emissions	Dioxin Emissions	
	μg/dscm	Total ng/dscm	I-TEQ ng/dscm
Inlet			
#1	219.3	692.3	17.2
#2	252.3	1172.4	21.4
#3	<u>209.9</u>	<u>3242.4</u>	<u>22.2</u>
Average	227.1	1702.3	20.3
Outlet			
#1	34.0	31.4	0.54
#2	36.8	64.1	1.14
#3	<u>22.7</u>	<u>32.9</u>	<u>0.6</u>
Average	31.1	42.8	0.76
EPA Guideline	80 μg/dscm	60 ng/dscm	
Average % removal	86.2%	95.51%	96.35%

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Heavy Metal Partitioning in a Municipal Solid Waste Incinerator

Lars Sørum
SINTEF Energy
Department of Thermal Energy and Hydropower
7034 Trondheim
Norway

Morten Fossum
SINTEF Energy
Department of Thermal Energy and Hydropower
7034 Trondheim
Norway

Egil Evensen
Trondheim Energy Company
Sluppenveien 6
7005 Trondheim
Norway

Johan E. Hustad
SINTEF Energy
Department of Thermal Energy and Hydropower
7034 Trondheim
Norway

INTRODUCTION

Waste Management in Norway

Norway has the following priorities for management of municipal solid waste (MSW)¹:

- 1) Reduce waste generation and toxic components in waste
- 2) Encourage re-use, recycling and energy recovery
- 3) Secure an environmentally safe management of residues

MSW consists of household waste and waste from the service and trade industry delivered to municipal waste treatment plants or recycling schemes. In 1995, a total of 2.7 million tons of MSW (1.26 million tons of household waste and 1.44 million tons of waste from service and trade industry) was handled as follows²: 68% was deposited on landfills, 18% was combusted, 13% recycled and 1% composted. Combustion of MSW is handled in five larger plants with energy recovery located in different cities in Norway. In addition, a new incinerator for MSW is planned. This incinerator will have to meet the new emission regulations given by the European Union which are more stringent than the present regulations. Hence, Norway is moving towards more stringent regulations, leading to an increased interest in the environmental aspects of MSW incinerators.

Heimdal Heating Central (HHC)

One of the largest MSW incinerators in Norway is situated in Trondheim and is owned and operated by Trondheim Energy Company (TEV). HHC consists of two lines each with a maximum capacity of 6.5 tonne/hour. The furnaces are moving grate units delivered by VonRoll, Switzerland. The flue gas cleaning system consists of an electrostatic precipitator (ESP) and a wet scrubber. The MSW incinerator is a base load energy production unit in a district heating system. In 1996, a total of 85600 tonne of MSW was incinerated in this plant with a heat production equivalent to 222 GWh. Figure 1 show a sketch of the incinerator. The MSW is delivered by trucks to a bunker for storage and mixing. The waste is collected from the bunker and into the feeding hopper by a waste crane. The waste is fed to the furnace by a dosing pusher. While the waste is transported through the furnace by a moving grate, primary air is supplied for combustion from below the grates and from the side walls. The side walls are cooled and insulated with refractory. Recirculated flue gas is injected into the flame above the grate before the flue gas enters the secondary combustion chamber. The flue gas first flows through a hot water generator and the ESP, which removes dust particles, before it enters the wet scrubber. In the wet scrubber, the flue gas pass through a quencher which reduces the temperature before it enters the wet scrubber where most of the pollutants in gas phase are removed. The water from the scrubber is first treated in a neutralization tank and then in a flocculation tank where particles are separated from the scrubber water. Then the scrubber water passes a sediment reactor where the solid phase is collected in the bottom. The solid phase is transported to a filter press where filter cakes are made. The water from the cleaning process is filtered in a sand filter and a ion exchanger system, before it goes to the drain. The clean flue gas is emitted through the 70 meter high stack. The bottom ash is deposited on a landfill, while the ESP dust and filter cakes are deposited in a landfill as hazardous waste.

Objective of the project

During 1995, TEV carried out an investigation program to examine the residues from the incinerator. Primary attention was on the heavy metals in the bottom ash, fly ash and the landfill leachate. The program was conducted in order to establish more information about characteristics of the residues and thus be able to undertake a sounder evaluation of the environmental aspects of the final treatment of these products. This program was supplementary to the emission analysis done periodically for the flue

gas and drain water. The objective of this work has been to establish knowledge about the partitioning of heavy metals through the incinerator and calculate the concentrations of heavy metal in the input MSW. A comparison of the results obtained from this study with other studies such as the WASTE Program (Burnaby)³ and Brunner/Mönch⁴ is of interest to see equalities and differences in the heavy metal partitioning through the incinerator and also the estimated heavy metal concentrations of the input MSW. All of the three different MSW incinerators (HHC, Burnaby, Brunner/ Mönch) have similar furnaces (moving grate), but different cleaning systems.

Heavy metal characteristics

Heavy metals are environmental toxics which accumulates in the environment. Heavy metals do not break down, but will remain in the environment forever. Cadmium, lead, mercury, vanadium, chromium, nickel, copper, zinc and arsenic are the most important heavy metals found in emissions from combustion of MSW. Cadmium, lead and mercury got most attention due to their relative toxicity^{5,6}. Some of the heavy metals, especially cadmium, can deposit in the soil and be absorbed by plants. Mercury can be transformed into methyl mercury in sediments and be accumulated in the food chain, especially through fresh water. Excessive levels of heavy metals can provoke a number of health effects. Excessive amounts of lead and mercury are especially dangerous with regards to damage to the nervous system and fetal life. Lead can also give cardiovascular diseases and anaemia. Excessive amounts of cadmium can damage the kidney after long term exposure and accumulating in the body^{6,7}. In order to reduce emissions of heavy metals and other pollutant emissions, the Norwegian government has signed several agreements, both national and international, which have the aim of reducing emissions in the future. For example: the Parliament report on national reduction of 70% of 13 selected environmental toxics, the North Sea Declaration states that the emission of 40 selected substances to both air and water shall be reduced and the Montreal Protocol include reduction of ozone destructive.

EXPERIMENTAL METHODS AND PROCEDURES

The experiments performed during this investigation were mainly conducted in 1995 and 1996. The input MSW has the average composition given in table 1⁹. The waste originates from the urban and rural areas in and around Trondheim municipality. The degree of material recovery of different components is estimated to⁹: paper 35%, food waste 22%, plastic/textiles/rubber 11%, glass 25%, metals 63% and other non-combustibles 50%. The total material recovery rate from MSW is estimated to 30%. In the sections below, a description of the sampling and experimental methods and procedures are explained.

Mass Balance

In this study the mass balance has been established for bottom ash, filter ash and filter cake. All of the values are mean values taken over a whole year and are on a dry basis.

All of the MSW delivered to the incinerator is weighed before dumped into the waste bunker. The weight of the waste is continuously recorded every year. The bottom ash, filter ash (ESP dust) and filter cakes are always weighed (on a wet basis) before sent to the landfill. However, the average moisture content has been determined for each of the different residues. All residues were expressed on a dry basis for the mass balance. The amount of flue gas has been calculated by measuring the flow through the stack with a pitot tube and micromanometer according to the Norwegian standard method (NS 4862). All of the moisture from the input waste was considered leaving with the flue gas.

Chemical Analysis

Chemical analysis of the different waste streams have been done according to different standard tests methods. The heavy metals presented in this investigation is mercury (Hg), zinc (Zn), chromium (Cr), cadmium (Cd), lead (Pb) and iron (Fe). Some of the residues and the flue gas has also been analysed for other heavy metals such as arsenic (As), nickel (Ni) and copper (Cu).

Bottom ash. For ten weeks samples were taken every Monday, Wednesday and Friday. The samples were taken from the bottom ash conveyor belt with a spade. Particles larger than 50 mm were sieved out and magnetic metals were removed with a magnet. Other easy visible pieces of metal was also picked out. The samples were air dried for 70 hours at 20°C before shipment to the laboratory, in order to enable crushing of the ash before analysis. Every sampling day six samples, each of approximately 2 kg, were taken with 1-1.5 hours intervals. The samples from one day were mixed and split into two parts and a sample of approximately 4 kg was sent to the laboratory for chemical analysis and another sample was analyzed for grain size distribution. The samples were sent to a certified laboratory in The Netherlands, Tauw Milieu bv, and the chemical analysis was done according to the standard test method ICP NPR 6425 for cadmium, chromium, lead and zinc; mercury was determined by the Cold Vapour-method NEN 5779. Full details of the chemical analysis of bottom ash is given in the report from Kummeneje¹⁰.

The amount of iron in the bottom ash was determined by sieving and magnet separation test in a pilot plant with a capacity of 36 tons/hour¹¹. Approximately six tons of bottom ash was handled in the sieving/magnet separation test. The bottom ash was first sieved on 50 mm sieve and this fraction was put through the magnet separator to determine the magnetic fraction. The rest fraction after sieving (<50 mm) was also separated for magnetic materials in the same system. The total amount of magnetic materials from the magnetic separation test was considered as iron.

Filter Ash. Samples of approximately 2 kg were taken once a week for three weeks. The samples were taken in the intermediate container below the conveyor belt from the filter ash bin. The samples were stored in plastic bags just above room temperature in order to prevent interaction with the surroundings before shipment to the laboratory. The laboratory, Tauw Milieu bv in The Netherlands, is certified for these chemical analysis. ICP-method NPR 6425 was used to determine the content of cadmium, chromium, iron, lead and zinc. The Cold Vapour-method NEN 5779 was used to determine the content of mercury. Full description of these chemical analysis of the filter ash is given in the report by Kummeneje¹².

Filter Cakes. Some samples of the filter cakes from the washing process were analyzed with Atom Absorption Spectrophotometry (AAS) to determine the content of lead, zinc and chromium¹³. Iron was estimated from values found in the literature. The content of mercury and cadmium was determined by measuring the difference in concentration in the water before and after the water cleaning process. For a whole year one sample was taken every day and all of the samples from one week were put together and analysed. The NS4768 and NS4781 methods were used to determine the content of mercury and cadmium in the samples.

Drain Water. The drain water has been analyzed for mercury, cadmium and lead according to Norwegian standard methods NS4768, NS4781 and NS4781. The amount of iron, zinc and chromium was estimated on the basis of values found in the literature.

Flue Gas. The Norwegian standard method NS 4863 was used to determine the content of lead, cadmium, mercury and chromium in the flue gas. The procedure is described in a SINTEF report¹⁴. The

content of iron and zinc was estimated on basis of values found in the literature. Four samples of the flue gas were taken for chemical analysis.

Sources of error in mass balances

In addition to the usual measurement inaccuracy's connected to every measurement done in this investigation, the closure of the mass balance also represent a source of error. Since the measurement inaccuracy's are given by the standardized measurement methods, those will not be commented on further. However, the mass balance closure need further explanation. The examination of the bottom ash, filter ash, filter cakes, drain water and flue gas has served different purposes. In addition to the determination of heavy metal balances and concentrations in input MSW, determination of heavy metal concentrations in residues and flue gas with regards to soil, water and air pollution has been one of TEV's objectives with these investigations. All of the measurements used in the mass balances has, therefore not been performed within the same period of time and with different sampling rates. However, this investigation has tried to give relatively long term mass balances and determined the concentrations of heavy metals in input MSW on basis of these findings. Short term investigations within the same time period has both the advantages and disadvantages of stable conditions with regards to operational parameters and composition of input MSW. The closure of the mass balances is therefore more likely to happen in investigations with parallel sampling of the residues and flue gas rather than sampling in series. However, the heavy metal balances and concentrations in input MSW is also a function of the variations in operational conditions and composition of input MSW. More extensive investigations with sampling in parallel would be very interesting and would provide a more complete picture of the mass balances and concentrations of heavy metals in input MSW. The cost of such comprehensive measurements is one of the major problems.

HEAVY METAL PARTITIONING THROUGH THE INCINERATOR

The results of the mass balance, heavy metal partitioning through the incinerator, heavy metal content in the residues and flue gas are presented in the sections below. Further, calculated heavy metal concentrations in the input MSW on the basis of the heavy metal content of the residues and flue gas are presented.

Mass Balance

The result of the mass balance is given in figure 2. The figure show that 83 % of the input MSW is converted to CO₂ and H₂O and is emitted as moist flue gas. The mass flux of bottom ash was found to be 16.5 % and the mass flux of filter ash was 0.37 %. The dust found in the filter cakes was almost negligible (0.02%). Brunner and Mönch⁴ found in their investigation a bottom ash portion of 20.5% and a flue gas portion of 77%. The flux of filter ash was the same as this study.

Heavy Metal Balance

Figure 3 and table 2 show the heavy metal balance between the different residues and flue gas for the incinerator.

Cadmium (Cd). Cadmium is a quite volatile metal in a combustion context with a boiling point of 767°C. Figure 3 show that 63% of the cadmium remain in the bottom ash, 24% is captured in the filter ash, 8% is emitted with the flue gas, 6% is captured in the scrubber (filter cakes) and virtually nothing is emitted via the drain water. In this study 37% of the cadmium was evaporated from the combustion process and entered the flue gas cleaning system. Several other studies on the evaporation of cadmium

from MSW incinerators have been done and they have shown quite different results. The Brunner and Mönch⁴ investigation stated that only 12% of the cadmium remained in the bottom ash, while the Burnaby project³ could report an even lower content of cadmium in the bottom ash (3.7%). A Swedish investigation¹⁵ of four different MSW incinerators found large variations in cadmium remaining in the bottom ash, varying from 13 to 83%. These large variations can originate from two different important parameters, namely combustion temperature and chlorine content in the waste. Cadmium has a boiling point which is close to the combustion temperature and the content of cadmium in the bottom ash will be dependent on the operating furnace temperature. The operating furnace temperature is a parameter which is strongly dependent on furnace construction, MSW composition and fuel/air ratio. Of these parameters the fuel/air ratio is the easiest to control. Two important factors in the evaporation of cadmium are: chlorine available to form cadmium-chloride and the chemical form of cadmium. With chlorine present, cadmium can form relatively volatile chlorides that will follow the hot flue gases¹⁶. When the temperature drops, volatile cadmium adsorbs on the relatively small particles which have the largest surface area. The emission of cadmium will therefore be highly dependent on the efficiency of the flue gas cleaning system and its ability to capture particle emissions.

Table 2 shows the heavy metal balance, the estimated heavy metal content in input MSW and concentrations of heavy metals for the different residues and the flue gas. The total yearly input of cadmium for the incinerator is 434 kg and 33 kg is leaving with the flue gas. The total efficiency of the flue gas cleaning system regarding cadmium is 80% (63% in ESP and 17% in scrubber) in this study. The Burnaby study³ which had a flue gas cleaning system consisting of a conditioning tower, reactor with lime injection and fabric filter showed an efficiency of 99.8% for cadmium. The Brunner and Mönch⁴ study which only had an electrostatic precipitator as flue gas cleaning system had an efficiency factor of 86% for cadmium.

Of the heavy metals in this investigation, cadmium is the one with the highest portion emitted through the stack. The calculated cadmium concentration in MSW was 5 mg/kg. The calculated cadmium concentration in MSW in the Burnaby project³ was 13.5 mg/kg while Brunner and Mönch⁴ reported 8.7 mg/kg. The city of Trondheim is currently implementing a source separation system where environmentally harmful waste such as electrical and electronic waste is separated and sent to a special landfill site for hazardous waste. A study has shown that electrical and electronic waste contributes with a large fraction of cadmium in MSW¹⁷. The effect of separating this fraction from the input MSW will be followed with great interest.

Chromium (Cr). Chromium with a boiling point of 2672°C can be regarded as a non-volatile heavy metal from a MSW combustion point of view. This is also shown by the results of the heavy metal balance for the combustion plant (table 2). Of the total input of 1829 kg/year to the incinerator, nothing is emitted through the stack. Approximately 2% is captured in the flue gas cleaning system the rest is left in the bottom ash. The Burnaby study reported that 93% of the chromium was left in the bottom ash. Only 0.06% was emitted with the flue gas, the rest was captured in the flue gas cleaning system. Calculated concentration of chromium in MSW is 21.1 mg/kg. The Burnaby project³ calculated the chromium concentration in MSW to 92.5 mg/kg.

Iron (Fe). Like chromium iron can be regarded as a non-volatile heavy metal in MSW combustion, with a boiling point of 2750°C. From the input of 764954 kg/year virtually nothing is emitted through stack or drain water, 0.4% is captured in the flue gas cleaning system while the rest is found in the bottom ash.

Brunner and Mönch⁴ found in their study 99% of the iron in the bottom ash and 1% in the filter ash, while 0.02% were stack emissions. Calculated iron concentration in MSW in this study was 8823 mg/kg.

Mercury (Hg). Mercury is the most volatile of the heavy metals with a boiling point of 357°C. The volatile behaviour of mercury was confirmed in this study with only 6% remaining in the bottom ash. Mercury content in the bottom ash between 0.2-19% has been found in other studies^{3,4,15}. Mercury differs from the other heavy metals by the fact that it is in gas-phase in a combustion plant¹⁶. Mercury is converted to a gaseous metal and gaseous chloride salt in the combustion process. The flue gas cleaning system had an efficiency of 95% for mercury. The wet scrubber captured 92% of the volatile mercury. Brunner/ Mönch⁴ had a mercury removal efficiency of 25% with electrostatic precipitator, while the Burnaby study³ had an efficiency of 40% where practically all captured mercury was found in the fabric filter. The calculated concentration of mercury in MSW in this study was 1.6 mg/kg, which is exactly the same concentration as a similar mercury balance study gave in 1994¹⁸. Other studies have indicated mercury concentrations in the range of 0.7 - 1.5 mg/kg^{3,4,19}. Given the volatile nature of mercury, emphasis should be put into removing mercury containing waste from the input MSW in order to reduce mercury emission to the environment. A study has shown that electrical and electronic waste contributes with a large fraction of mercury in MSW¹⁷. The potential for reduction of mercury entering the incinerator by removing the electrical and electronic waste fraction should therefore be considerable.

Lead (Pb). Lead, with a boiling point of 1750°C, should in combustion of MSW normally be considered as a non-volatile metal. However, studies have shown that small portions of chlorine in the waste will decrease the volatility temperature with several hundred degrees²⁰. From the total of 38061 kg/year input of lead to the incinerator, 94% is captured in the bottom ash, 5% is captured in the flue gas cleaning system and 0.2% is stack emission. Other studies have shown a large variation of lead in the bottom ash ranging from 58 to 89%^{3,4,15}. This and other studies have shown that most of the volatile part of lead is captured on ash particles and cleaned in the filter units. The calculated concentration of lead in MSW was 439 mg/kg. Other studies have reported values in the range of 160 to 430 mg/kg^{3,4,19}. As for cadmium and mercury, lead is also strongly represented in the older electronic and electrical waste fraction although not relatively as much as mercury and cadmium. The combination lead and PVC (resin PVC contains over 50% of chlorine²¹) is highly possible for the electronic and electrical waste fraction, giving an increase in the volatile release of lead in the combustion process.

Zinc (Zn). Zinc, with a boiling point of 907°C, is one of the more volatile metals in this investigation. Zinc is also the heavy metal with largest yearly stack emissions (76 kg/year). Most of the zinc was found in the bottom ash (86%), while most of the residual 14% is captured in the flue gas cleaning system. Only 0.1% is emitted through the stack. This study differ from other studies with a large portion of the zinc remaining in the bottom ash. Other studies^{3,4} have reported 42 and 51% of zinc in the bottom ash, but like this study most of the volatile fraction of zinc is captured in the ESP. The large variation in volatility can be ascribed to differences in combustion temperature due to the relatively low boiling point which is in the area of the combustion temperature. The calculated concentration of zinc in MSW was 1044 mg/kg while others have reported 1873 and 2000 mg/kg^{3,4}.

CONCLUSIONS

In this study most of the cadmium (63%), zinc (86%), lead (94%), chromium (98%) and iron (100%) was found in the bottom ash. The filter ash captured most of the volatile cadmium (24%), zinc (13%), lead (5%) and chromium (2%). The wet scrubber captured most of the mercury (87%). From these results it is evident that a large portion of the heavy metals are captured in the bottom ash compared to other studies, indicating a relatively low combustion temperature. The calculated concentrations of heavy metal in the input MSW was 1.6 mg/kg for mercury, 5 mg/kg for cadmium, 1044 mg/kg for zinc, 439 mg/kg for lead, 21.1 mg/kg for chromium and 8823 mg/kg of iron. Long term monitoring of the flue gas and residues seem to be a better and easier way to measure the content of heavy metals in MSW rather than sampling the input waste. Reduction in heavy metal emissions is expected after implementation of source separation of environmental harmful waste including electronic and electrical waste in 1997. The potential for reduction of mercury is confirmed by the relatively high concentration in MSW compared to other studies. The continuing work on identifying and separation of MSW fractions with large concentrations of heavy metals seem to be an important method to reduce heavy metal emissions further. Improved flue gas cleaning systems, furnace constructions and combustion control will also contribute to reduced emissions. This work has contributed to a better understanding of the behaviour of heavy metals in MSW combustion and given complementary understanding of the efficiency of various flue gas cleaning systems for different heavy metals.

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Table 1. Average composition of MSW delivered to HHC⁹.

COMPONENT	FRACTION [wt%]
Paper	30
Food wastes	17
Plastic, textiles, rubber, leather	6
Wood	8
Glass	7
Metal	12
Other combustibles	6
Other non-combustibles	14
Total	100

Table 2. Concentrations in residues, flue gas and waste and heavy metal balance.

	Cd	Cr	Fe	Hg	Pb	Zn
Concentration in residues, flue gas and waste						
Flue gas [mg/Nm ³ dry]@11%O ₂	0.057	0.00075	0	0.013	0.162	0.159
Bottom ash [mg/kg dry]	19	125	53250	0.62	2513	5464
Filter ash [mg/kg dry]	323	127	9833	8	5833	37667
Filtercake [mg/kg dry]	1331	10	2600	5805	7027	8567
Drain water [Tg/m ³]	1.3	0.9	0	3.6	48.1	100
Input MSW [mg/kg]	5	21.1	8823	1.6	439	1044
Heavy metal balance for the combustion plant						
Flue gas [kg/year]	32.7	0.44	0	7.2	91.8	76.3
Bottom ash [kg/year]	272	1788	761768	9	35950	78165
Filter ash [kg/year]	104	41	3154	3	1871	12083
Filtercakes [kg/year]	27.7	0.2	54.1	120.8	146.2	178.3
Drain water [kg/year]	0.02	0.02	0	0.06	0.83	1.7
Input MSW [kg/year]	434	1829	764954	139	38061	90515

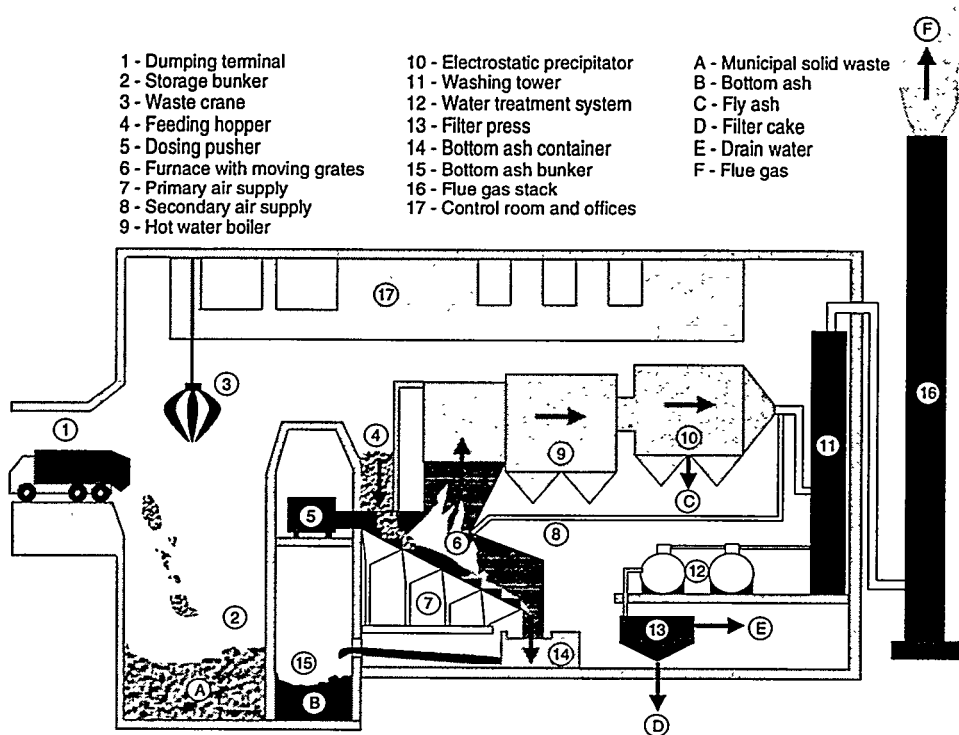


Figure 1. Sketch of the waste incinerator with major parts and mass fluxes indicated.

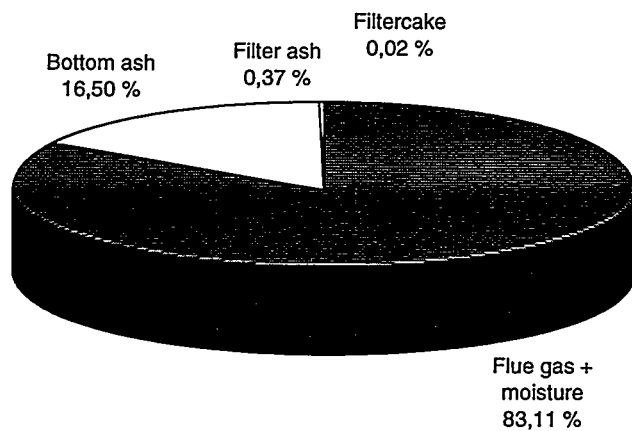


Figure 2. Overall mass balance for the MSW incinerator (dry basis).

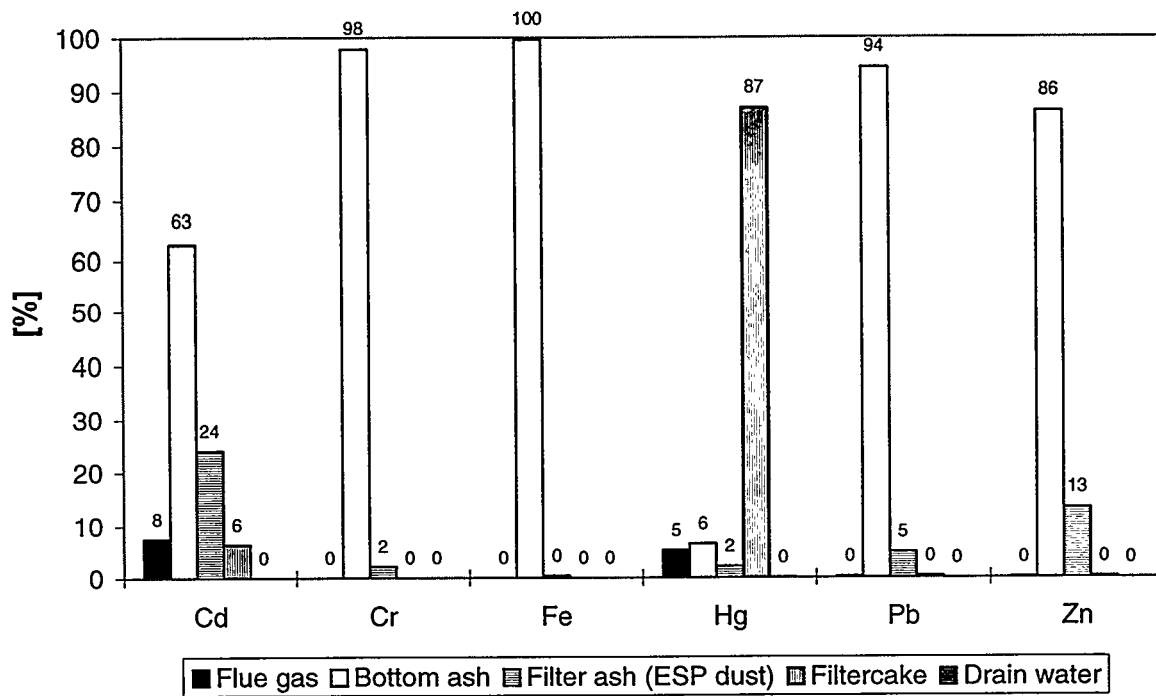


Figure 3. Heavy metal balances for the MSW incinerator.

TECHNICAL SESSION I

Implementation Issues

Using Life-Cycle Management to Evaluate Integrated Municipal Solid Waste Management Strategies

Keith A. Weitz and Subba R. Nishtala

Center for Environmental Analysis, Research Triangle Institute, 3040 Cornwallis Road, Research Triangle Park, NC, 27709, Ph: 919-541-6973, email: kaw@rti.org.

Morton A. Barlaz and Ranji Ranjithan

Department of Civil Engineering, North Carolina State University, Raleigh, NC, 27695, Ph: 919-515-7676, email: barlaz@unity.ncsu.edu.

Susan A. Thorneloe

Air Pollution Prevention and Control Division, National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Mail Drop 63, Research Triangle Park, NC, 27711, Ph: 919-541-2709, email: thorneloe.susan@epamail.epa.gov.

Introduction

Communities throughout the United States are struggling to develop efficient and cost-effective plans for managing their MSW. In the past, these plans primarily consisted of waste collection and disposal at a local landfill. Today's MSW management plans often include integrated systems that address all types of solid waste materials, solid waste sources, and waste management options [1].

Developing more efficient integrated MSW management plans necessarily involves complex decisions where tradeoffs between environment performance and cost and must be carefully analyzed. For instance, how does the cost and environmental performance of a MSW management system change if we include or exclude a specific material (e.g., glass, paper, plastic, metal) from our recycling program? And should we recycle newsprint if we are interested in waste-to-energy combustion? To better evaluate the tradeoffs involved with these types of questions, the entire life cycle of MSW must be considered. As shown in Figure 1, the life cycle of MSW starts with the production of products from virgin and/or recycled materials. Eventually, these products are discarded to the MSW stream and may be managed through a variety of options such as recycling, combustion, composting, and landfilling. Materials that are recovered and recycled are incorporated into new products and will eventually reenter the MSW stream. By taking a life-cycle perspective, it is possible to capture tradeoffs and transfers of environmental burdens from one waste management operation to another, or from one life-cycle stage to another, and analyze multiple system design issues concurrently [2,3,4].

The Research Triangle Institute (RTI) is continuing work under a multi-year cooperative agreement with the U.S. Environmental Protection Agency (EPA), through funding from EPA

and the U.S. Department of Energy (DOE), to conduct a life-cycle study of integrated MSW management. The final outputs of this research include a database containing life-cycle inventory (LCI) and cost data and a computer-based decision support tool to help solid waste planners evaluate the environmental burdens and costs associated with integrated MSW management systems. RTI's research team currently includes life-cycle assessment and MSW experts from North Carolina State University, University of Wisconsin-Madison, and Franklin Associates, Ltd. Groups of internal EPA and DOE advisors and external stakeholders are also active participants in this unique forum which brings together experts from industry, federal government agencies, local governments, academia, and environmental advocacy organizations.

Overview of Key System Considerations

Figure 1 highlights the major components of our defined system. The system definition also includes specifications for the types of waste components, waste management upstream processing units, and waste generating sources. Because the waste management stage is the primary focus of this research, it is defined in greatest detail.

In general, all unit operations that have a bearing on the LCI are being evaluated. In cases where some portion of the MSW is recycled, the energy and resources expended and emissions generated in separating, transporting, and converting the recyclables to a new product are considered. These are then compared and netted out from the energy, resources, and emissions for manufacturing the same product from virgin materials. For example, the total amount of energy required to recover the recyclable from the waste stream and convert it to a new product is included in the LCI and termed E_r . Similarly, the amount of energy required to produce a corresponding amount of the same product from virgin material is calculated and termed E_v . The net amount of energy (E_n) saved (or expended) to recycle a material is then calculated as the difference between E_r and E_v ($E_n = E_r - E_v$). Similar calculations are performed for all LCI parameters involved in the recycling and remanufacturing processes.

In operations where energy is recovered (e.g., combustion of MSW or Refuse-Derived Fuel (RDF), combustion of landfill gas), an energy offset is calculated. The methodology used for energy recovery is the same as that described above for remanufacturing. However, an assumption is made that any net energy "saved" offsets electricity generated from fossil fuel (coal, oil, or natural gas) and not from alternative sources (e.g., hydro, nuclear, and geothermal). The rationale for this assumption is that, because the alternative sources are "cleaner," they will be operating at capacity and any energy "saved" will reduce the reliance on electricity generation from "dirtier" sources.

Numerous pieces of capital equipment from refuse collection vehicles, through balers, to major equipment at paper mills are also important parts of the system. In theory, resources associated with the fabrication of capital equipment, as well as the construction of a new facility, should be considered as part of the LCI [2, 4]. This may be particularly relevant in evaluation of MSW management strategies which suggest the construction of a new facility, such as a material

recovery facility (MRF), or the purchase of new refuse collection vehicles. Although theoretically correct, the inclusion of these resources introduces additional complexity which may not be necessary. Thus, the amortized purchase price of a facility or a piece of equipment is being used as a screen to evaluate the importance of its inclusion in the LCI. Where the amortized capital cost of a piece of equipment is low relative to the non-labor cost to operate it, an assumption is made that the resources involved in fabrication of the equipment are insignificant.

In the waste treatment and disposal end of the system, the energy associated with the treatment of liquid and solid wastes is also considered. For example, if biological oxygen demand (BOD) is treated in an aerobic biological wastewater treatment facility, then energy is consumed to supply adequate oxygen for waste treatment. Similarly, if a solid waste is produced which requires burial, energy will be consumed in the transport of that waste to a landfill and its burial in the landfill. These and similar parameters are included in the study.

It is important to recognize that the system boundary for cost analysis differs from that used for the LCI. The cost analysis focuses only on the cost of MSW management as experienced by the public sector. Thus, the cost analysis includes the cost of waste collection, transfer stations, MRFs, composting facilities, combustion, RDF plants, and landfills. In addition, where a waste is produced as part of a waste management facility, the cost of waste treatment is included in the cost analysis of that facility. For example, we include the cost of leachate treatment in our cost analysis of landfills. Costs associated with remanufacturing are not included because they are assumed to be reflected in the price paid to a community for recyclables or electricity (as generated through combustion of MSW or landfill gas).

Overview of Allocation Procedures

A major challenge in this research is allocating LCI data to the individual components of MSW. Existing allocation schemes are based on simplistic mass- or volume-based schemes. For this research, we are investigating and developing more accurate allocation procedures. A summary of the key assumptions, allocation procedures, key issues, and improvement needs related to the allocation of LCI data for each major unit operation are presented in Table 1.

Conclusions

The issues presented in this paper convey a sense of the complex relationships of environmental burdens and costs between different waste management operations. As data for upstream raw materials acquisition and manufacturing for MSW components are obtained and added, this complexity will be extended throughout the entire life cycle. However, such a life-cycle perspective is critical for making accurate and efficient decisions about the environmental burdens and costs of integrated MSW management systems.

The value of life-cycle thinking and more formal life-cycle assessment for evaluating integrated MSW management systems has also been recognized by many other countries, including Canada, France, Germany, the Netherlands, Sweden, and the United Kingdom, all of whom have studies underway in this area. We are continuing research in the context of this international initiative to advance the application of life-cycle concepts to integrated MSW management in the United States.

Finally, it should be recognized that environmental LCI and cost data only present two components of a very complex system design problem and they must be combined with additional decision making factors to formulate a solution. Additional factors facing solid waste planners might include political pressures, social pressures, aesthetics, and level of available technology. Striking a balance between environmental, cost, and these additional decision making factors is crucial to the development of successful integrated MSW management strategies.

Acknowledgments

The information contained in this paper has been developed as part of ongoing research funded through an interagency agreement between the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Energy (DOE) under EPA Cooperative Agreement No. CR823052 with the Research Triangle Institute (RTI). Use of the methods or results presented in this paper does not imply EPA or DOE policy and are not intended to be used to make judgments about which material, product, or waste management practice is environmentally preferable.

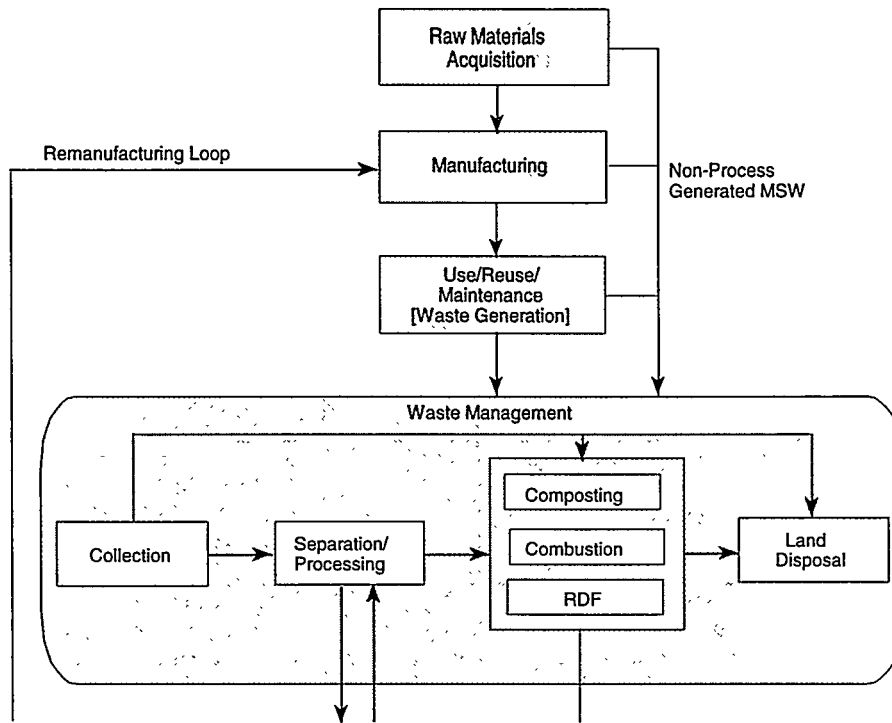
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Table 1. Summary of Existing and Proposed LCI Allocation Procedures

Major Operations	Key Assumptions	Key Design Characteristics	Existing Allocation	Proposed Allocation
Upstream	Closed-loop recycling, and products made from virgin versus recycled material are identical.	Energy grid structure can be specified by user. A typical process design will be used to estimate LCI data.	Mass	None. Primarily dependent on the allocation method used by developer of data.
Collection	Data on population, generation and, capture rate, etc. are input by the user.	Given data for a site, fuel used, and associated emissions are calculated.	Mass	Allocation procedures for collected materials are being evaluated on a volume basis.
MRF	Data on facility cost, labor cost, and productivity are input by the user.	MRF design depends on the collection type and the recyclables mix.	Mass	Allocation procedures are based on the specific equipment (e.g., baler) that is used to process recyclables.
Composting	Data on site conditions are input by the user to derive retention time, cost, and emissions.	Aerated windrow composting design is assumed.	Mass	Allocation procedures are currently being developed through laboratory testing and factorial analysis.
Combustion	Combustion with generation of electricity is assumed from a new facility that meets recent regulations.	Generic cost and design data are used, no detailed design is available.	Mass	Allocation of metal emissions is based on specific components of waste, allocation of other air emissions is based on ultimate analysis of waste components.
Landfill	Data specified by the user are used in designing the landfill.	Landfill designs with or without gas control and leachate collection can be considered.	Mass (organics only)	Allocation procedures are being developed based on analyses of waste components and leachate quality.

Figure 1. Life Cycle of Integrated Solid Waste Management



Life Cycle Assessment of the Environmental Emissions of
Waste-to-Energy Facilities

Jacques Besnainou
Ecobalance, Inc.
15204 Omega Drive, Suite 220
Rockville, MD 20850

Anne Landfield
Ecobalance, Inc.
15204 Omega Drive, Suite 220
Rockville, MD 20850

INTRODUCTION

Over the past ten years, environmental issues have become an increasing priority for both government and industry alike. In the U.S. as well as in Europe, the emphasis has gradually shifted from a site specific focus to a product specific focus. For this reason, tools are needed to scientifically assess the overall environmental performance of products and/or industrial systems. **Life Cycle Assessment (LCA)** belongs to that category of tools, and is used to perform this study.

In numerous industrial countries, LCA is now recognized, and is rapidly becoming the tool of preference, to successfully provide quantitative and scientific analyses of the environmental impacts of industrial systems. By providing an unbiased analysis of entire systems, LCA has shown that the reality behind widely held beliefs regarding “green” issues, such as reusable vs. one way products, and “natural” vs. synthetic products, were far more complex than expected, and sometimes not as “green” as assumed.

This paper describes the modeling and assumptions of an LCA, commissioned by the Integrated Waste Services Association (IWSA), that summarizes the environmental emissions of waste-to-energy facilities, and compares them to the environmental emissions generated by major combustible energy sources of the northeast part of the United States (NE). The geographical boundary for this study is, therefore, the NE US.

General Principle of Life Cycle Assessment

LCA is an analytical tool used to comprehensively quantify (with further option to interpret) the material and energy flows (flows to and from the environment, including air emissions, water effluents, solid waste, and the consumption/depletion of energy and other resources), over the entire life cycle of a product or process. The life cycle is meant to be studied comprehensively, including production and extraction of raw materials, intermediate products manufacturing, transportation, distribution, use, and final disposal. The general principle for extending system boundaries is illustrated in Figure 1.

All flows within the system are normalized to a unit summarizing the *function* of the system. This allows for the comparison of different industrial systems performing the same function. Once this shared function is defined, a unit has to be chosen in order to compare the systems on the same quantitative basis. The concept of the *function* is presented in the example of comparing milk bottles of different packaging materials (glass, plastic, etc.). The *function* of the comparison would be: *packaging of milk*. The *functional unit* would be: *the packaging of one gallon of milk*.

APPLICATION TO THIS STUDY: FUNCTIONAL UNIT AND SYSTEM BOUNDARIES

The Life Cycle Starting Point for MSW

In the Life Cycle approach, it is necessary to study the environmental and resource consequences of a product or process comprehensively. In the case of waste-to-energy, the commonly accepted starting is the generation of waste at the point of collection¹.

Functional Analysis

WTE is a process that performs two functions: MSW is being disposed of, and it is being reused in a beneficial way as a fuel source to generate electricity. In an LCA, when an additional function is introduced, it must be meaningfully compared in all of the options. Although the disposal of MSW is considered a meaningful function, it will not be studied in this LCA: following LCA reasoning, the function of disposing MSW in the WTE option would also have to be presented for all of the comparisons. However, the study of an alternate means of disposal on the other electricity options would entail the analysis of processes of landfilling, recycling, etc., and studying these large and complex processes would go beyond the scope of this study.

As a result, the remaining main function considered in this study is the production of electricity, comparing each electricity option on a per unit of electricity generated.

Figure 2 presents the three electricity comparisons in this study: the production of electricity from a waste-to-energy facility vs. the production of electricity from the major combustible sources electricity: coal, fuel oil, and natural gas.

Figure 2 shows each comparison as having only one function (F1): producing electricity. Producing electricity, however, is not the only function that is associated with WTE. An additional function of WTE is recycling steel scraps. The WTE process recovers ferrous material from MSW and sends it off site to be recycled into usable steel (secondary steel), which displaces the production and use of steel from natural resources (primary steel).

Since none of the combustible electricity sources perform this same function, the production of primary steel must be subtracted out of only the WTE system. Figure 3 presents the two systems which contain the processes of each option and their respective functions. Note: only coal combustion is shown here, although WTE is compared to fuel oil and natural gas in the same way.

The Functional Unit Precisely Defined

The functional unit that will meaningfully compare the function of energy is a defined quantity of electricity produced, and has been chosen as 1 kilowatt-hour (kWh).

MODELING

This section describes all of the components modeled in the LCA. The entire waste-to-energy system and a general overview of the NE electricity grid contributors are discussed. Due to limited space in this paper, the detailed descriptions for modeling NE electricity grid components are not included. All data are modeled in Ecobalance's LCA software, TEAM^{TM2}.

Waste-To-Energy System

The waste-to-energy system includes the transportation of MSW to the waste-to-energy facility, combustion of MSW, including air emissions and water effluent control, disposal of the waste-to-energy ash residue, and production of steel with recovered ferrous materials.

Transportation of MSW to Waste-to-Energy Facility. Municipal solid waste is processed from the surrounding residential, commercial, and industrial facilities. The service area is assumed to be 50 miles in diameter with the average hauling distance of 25 miles. Approximately two-thirds of the waste stream is delivered by transfer trailer and one-third by roll-off containers and packer trucks. They return empty from the facility.

Residential MSW is typically collected with a 20- to 30- cubic yard packer truck. Since packer truck utilization is normally about 80 percent with a packing density of 750 pounds per cubic yard, a packer truck collects approximately 7.5 short tons of MSW per load. The average consumption of diesel oil per load is 13 gal/load which implies a fuel consumption of 1.8 gal per short ton of MSW³. Transfer trailers and roll-off containers will be modeled from Ecobalance's database, DEAM^{TM4}, on standard heavy-duty diesel-powered trucks.

Air emissions generated from the collection vehicles are based on measured air emissions of a diesel oil heavy-duty truck⁵, however, actual air emissions may be higher than considered, due to the high stop-start frequency.

Waste-to-Energy Facility. In order to use a representative waste-to-energy facility as a fair comparison to other NE electricity grid contributors, a typical facility was defined to produce average facility parameters. Figure 4 presents the five different areas of the waste-to-energy process for which typical data were obtained.

General Characteristics of the Waste-to-Energy Facility. The size of the waste-to-energy facility is assumed to be a 1500 ton-per-day (TPD), 5000 Btu/lb. refuse throughput. The facility has an annualized capacity factor of 92%, so it combusts an average of 1380 TPD of MSW. The facility consists of two 750 TPD mass burn waterwall furnaces, multi-pass boilers. Superheated steam is generated and used to drive a condensing steam turbine and generator set to produce electricity.

The facility includes an enclosed tipping hall for waste deliveries and a refuse storage bunker which holds up to 5000 short tons of MSW. Each boiler generates steam at 850 psig, 850°F, and operates continuously 24 hours per day, seven days per week, with the exception of power outages. The steam system includes a turbine generator, a water-cooled condenser, a wet cooling tower, condensate pumps, a low pressure heater, a deaerator, feedwater pumps, a boiler with an economizer, generating banks and superheater sections, and all ancillary equipment required to generate steam at the specified condition. Net power produced is 37.5 Megawatts (MW). 600 kilowatt-hours of electricity are produced per short ton of MSW combusted⁶.

Auxiliary Burners. Auxiliary burners are provided for startup, shutdowns and any upset conditions. No auxiliary fuel is combusted other than for these conditions. The auxiliary fuel is assumed to be fuel oil, and on average 0.6 gallons per short ton of MSW fired is used for combustion (less than 1% of total heat release).

Water Systems. City water is demineralized in the water treatment system, and sulfuric acid (35% solution H₂SO₄) and caustic soda (50% solution NaOH) are used to regenerate the treatment system. In

addition, small quantities of other chemicals are used for water treatment. The demineralized water is used for boiler makeup, and it is assumed that all process waste water is reused in the facility.

MSW Handling On-Site. Trucks carrying MSW enter the site, proceed to the weigh scales and remote scalehouse and continue on to the tipping floor. On the floor they back into bays to discharge their load into the refuse bunker. The trucks leave the tipping area and proceed to the facility scales to be weighed out before exiting the facility grounds.

Ancillary Materials. Besides MSW and the fuel oil used periodically in the auxiliary burners, there are additional materials that are consumed during the waste-to-energy process. The materials added to emissions control operations include powdered activated carbon (1.0 pounds per short ton of MSW), pebble lime (25 pounds per short ton of MSW), and aqueous ammonia (0.5 gallons per short ton of MSW). Materials used to regenerate the water treatment system are caustic soda (0.006 pounds per short ton of MSW), and sulfuric acid (0.004 pounds per short ton of MSW).

Air Emissions. The waste-to-energy facility contains emissions control equipment that complies with EPA's emissions guidelines. These include a selective non-catalytic reduction (SNCR) NO_x control system, an activated dry carbon injection system, a lime-based spray dryer absorber system, and a fabric filter.

This facility uses technology that meets the Maximum Achievable Control Technology (MACT), as defined by the U.S. Environmental Protection Agency (EPA) for waste-to-energy facilities⁷ for electricity production in the NE US. Table 1 presents average values for actual WTE emissions as reported by the U.S. EPA⁸, per short ton of MSW combusted.

A fraction of the 2080 pounds of CO₂ emitted per short ton of MSW combusted comes from burning biomass. Paper and paperboard make up 25% of total MSW directed to WTE plants, yard trimmings make up 18%, and wood makes up 4%⁹. Organic carbon content by weight of biomass is assumed to be 41%¹⁰

Ash and Ferrous Scrap Management. After combustion of MSW, bottom ash falls off the grate into a quench basin and is combined with grate siftings. The bottom ash is conveyed to a ferrous recovery system. Fly ash and spent salts of reaction are conditioned with water and combined with the bottom ash for disposal. All ash handling occurs in buildings and enclosures so that no significant fugitive emissions occur. Ash and ferrous materials are stored separately in a grade level storage building, and then are sent to be disposed of or recycled in the ash residue monofill and the scrap metal recycling facility, respectively.

Ash Residue Monofill. The amount of combined fly ash residue and bottom ash that is generated at the facility is assumed to be 500 pounds per short ton of MSW. Ash is transported 50 miles to a double-lined monofill in payloads of 22.5 short tons. The typical truck used to transport ash residue is a tandem truck, filled based on weight of the material. Besides the emissions due to truck and transport of the material, it is assumed that no significant fugitive emissions come from the ash due to ash wetting, indoor loading, and covered transport.

The ash residue monofill is double-lined, consisting of a 24-inch clay layer and a 60-mils geosynthetic layer. Leachate from the landfill (40 pounds per short ton of MSW) is collected and discharged to a treatment works plant.

Scrap Metal Recycling Facility. Forty pounds of clean ferrous scrap metal per short ton of MSW are hauled fifty miles to a scrap metal recycling facility. Ferrous material is transported 50 miles to a scrap recycler in payloads of 22.5 short tons.

From an LCA modeling perspective,

- the burdens of the recycling of 40 pounds of ferrous scrap (secondary steel from an electric arc furnace) are added to the waste-to-energy system; and
- the burdens of producing that quantity of steel from primary means are subtracted out of the waste-to-energy system. This is because, since steel is being recycled and used for secondary steel production, the same quantity of steel that would have been produced by primary means is offset.

Electricity from Combustible Sources of Electricity

The combustible sources of electricity that are compared to waste-to-energy electricity production are coal, fuel oil, and natural gas.

Electricity from coal. The coal important to this study is eastern bituminous, since the vast majority of coal burned in the northeast is eastern bituminous coal. Modeling electricity production from coal includes materials, energy consumed, and emissions due to bituminous coal mining, preparation, transportation to facilities, combustion, emissions control technology such as flue gas desulfurization, and management of coal combustion byproducts at a landfill or storage pond.

Emissions due to coal combustion are figured for each type of firing configuration since firing configurations have different combustion requirements (coal burning temperatures, firing methods, and emissions control equipment, etc.) and emit varying amounts of pollutants.

Electricity from fuel oil

Heavy fuel oil, or residual oil, is the fuel oil used in power utilities. This type of oil is produced from the residue remaining after the lighter fractions of oils, such as gasoline, kerosene, and distillate oils have been removed from the crude oil. In general, the combustion of residual oils generates large quantities of ash, NO_x, and SO_x.

Modeled in this report includes energy, raw materials consumed, and emissions due to mining crude oil (including onshore production, offshore production, and thermal enhanced recovery methods), refining crude oil, and transportation from the mining site to the power generation plant.

Petroleum Administration for Defense Districts¹¹ (PADD's) were originally defined during WWII for purposes of administering oil allocation. The PADD region in the NE US that contains MACC and NPCC is PADD region I. Over 97% of the crude oil in PADD Region I comes from foreign crude oil sources. Therefore, transportation will take into account foreign oil brought into the US. It is assumed that foreign oil precombustion processes require the same energy and have the same environmental impacts as domestic oil processes, so figures for domestic oil precombustion processes are used in the model.

Electricity from natural gas. Raw natural gas is a mixture of hydrocarbons, N₂, CO₂, sulfur compounds, and water. It may have any range of compounds from mostly methane to inert gases, such as nitrogen, carbon dioxide, and helium, and smaller amounts of ethane, propane, and butane. Natural gas may be mined onshore, offshore, and in conjunction with petroleum processes.

Modeling natural gas includes taking into account the energy, raw materials, and emissions due to mining and cleaning natural gas, pipeline transportation, and combustion.

Modeling Software: TEAM™

All of the modeling for this LCA is performed on TEAM™, the LCA modeling tool developed and used by Ecobalance for the last 5 years. This tool, developed in C++, efficiently performs complex Life Cycle Assessments, and models material and chemical flows through extended industrial process networks. This model contains an extensive database called DEAM™ of the basic Life Cycle Inventory of commodity materials, transportation means, energy sources and disposal options. This model strictly follows the LCA methodological framework developed by Society of Environmental Toxicology and Chemistry and adopted by the U.S. EPA. It also follows the recommendations developed in the ISO 14000 forum.

DISCUSSION ON WATER EFFLUENTS

Water effluents are not being taken into account for any of the electricity options for the following reasons:

Pre-electricity production: Water effluents coming from pre-electricity production processes are considered negligible for this study since the only effluents coming from precombustion are those from mining the fuels that are used to transport materials and refinery processes. Over the entire life cycle, these quantities are considered negligible.

Electricity Production: Water used during combustion of MSW includes demineralized water used for boiler makeup, for treatment of fumes, and for slag cooling. It is assumed that most of the water is recycled in the facility, so water effluents generated as a result of MSW combustion are negligible. The same applies for other combustible fuels.

Post-combustion waste management: The monofill that holds MSW ash residue is lined, and leachate is collected and transported to an offsite waste water treatment plant (WWTP). This collection of leachate is considered standard practice for typical waste-to-energy facilities in the U.S. Water discharged from the WWTP is considered safe enough to be released into the environment.

Leachate from coal combustion byproduct (CCB) monofills in the U.S. is generally not collected and taken off-site, so it is very difficult to quantify its actual amount per specified quantity of coal combusted. In terms of environmental impacts, leachate generated from coal ash at a monofill depends upon local conditions, such as precipitation, the leachability of the fly ash, and origin of the coal.

RESULTS

The results of this study will be presented at the conference. The comparisons between the electricity options are made to comparatively assess different impacts each option makes on the environment. Following is a brief overview of what the results will show.

Direct Comparison: Waste-to-Energy vs. Coal, Fuel Oil and Natural Gas

A direct comparison will be made between electricity produced from waste-to-energy and electricity produced by each of the combustible fuels. Actual quantities for each flow are directly compared. Examples of flows are as follows:

- **Raw materials** extracted from the earth and consumed: coal, natural gas, oil, uranium, and limestone;
- **Air pollutants** emitted: particulate matter, CO₂, NO_x, SO_x, and CO;
- **Energy** consumed: total renewable and non-renewable and feedstock and fuel energy.

Impact Analyses

Acidification potential, global warming potential, and natural resource depletion for each electricity option will be presented at the conference.

Acidification Potential. Potential acidic deposition (onto soil, vegetation, and water) can be expressed as potential H⁺ equivalents. Potentially acidifying emissions of SO₂, NO_x and NH_x can be aggregated on the basis of their potential to form H⁺, and the resulting value is the acidification potential.

Global Warming Potential. The "greenhouse effect" refers to the ability of some atmospheric gases to retain heat which is radiating from the earth. Global Warming Potentials (GWPs) have been calculated to compare the emission of different greenhouse gases. The emissions accounted for in this assessment are CO₂, N₂O, and CH₄, the pollutants recognized to potentially contribute to global warming.

Natural Resources Depletion Index. Resource depletion can be defined as the decreasing availability of natural resources. Resources considered in this impact are fossil and mineral resources, excluding biotic resources and associated impacts such as species extinction and loss of biodiversity. The fossil and mineral resources taken into account for this study are: coal, iron, natural gas, oil, and uranium. It is important to recognize that what is addressed in this index is the fact that some resources are depleted, not the fact that their extraction from the environment will generate impacts (e.g., methane emissions from coal mining).

TABLES

Table 1. MACT emissions limits and Waste-to-Energy facility emissions per short ton of MSW.

Pollutant ^{note 1}	MACT Rule (per dry std. m ³)	WTE Facility Emissions (lb./short ton MSW)
SO _x	7.9 ppm	0.19
NO _x	136 ppm ^{note 2}	2.4
CO	40 ppmv ^{note 3}	0.42
Particulate Matter	4.8 mg	0.099
HCl	9.7 ppm	0.13
Pb	0.006 mg	5.4*10 ⁻⁵
Hg	0.022 mg	1.9*10 ⁻⁴
Cd	0.00098 mg	8.8*10 ⁻⁶
PCDD/PCDF	3.3 ng	3.0*10 ⁻⁸
CO ₂ ^{note 4}	Unregulated	2080
CH ₄	Unregulated	0.003
N ₂ O	Unregulated	0.008

1 All pollutants are assumed to have O₂ at 7%.

2 Emissions from Mass Burn/Water Wall Furnace type of boiler, 200 ppm NO_x.

3 Emissions from Mass Burn Waterwall, 100 ppmv CO.

4 The emissions values chosen for unregulated emissions such as CO₂ (2080 lb./short ton of MSW), methane (0.003 lb./short ton of MSW) and N₂O (0.008 lb./short ton of MSW), were supplied by IWSA engineers.

FIGURES

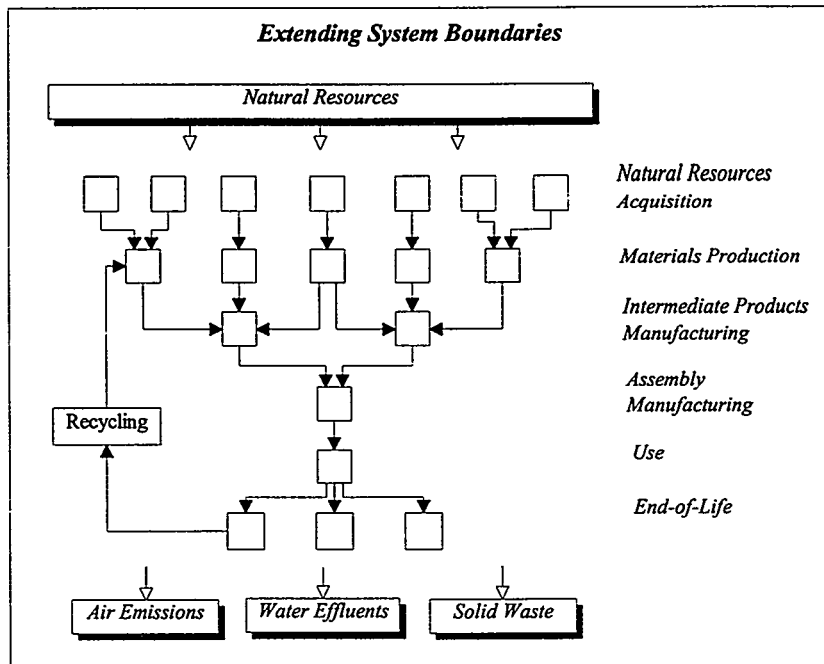


Figure 1 Extending system boundaries.

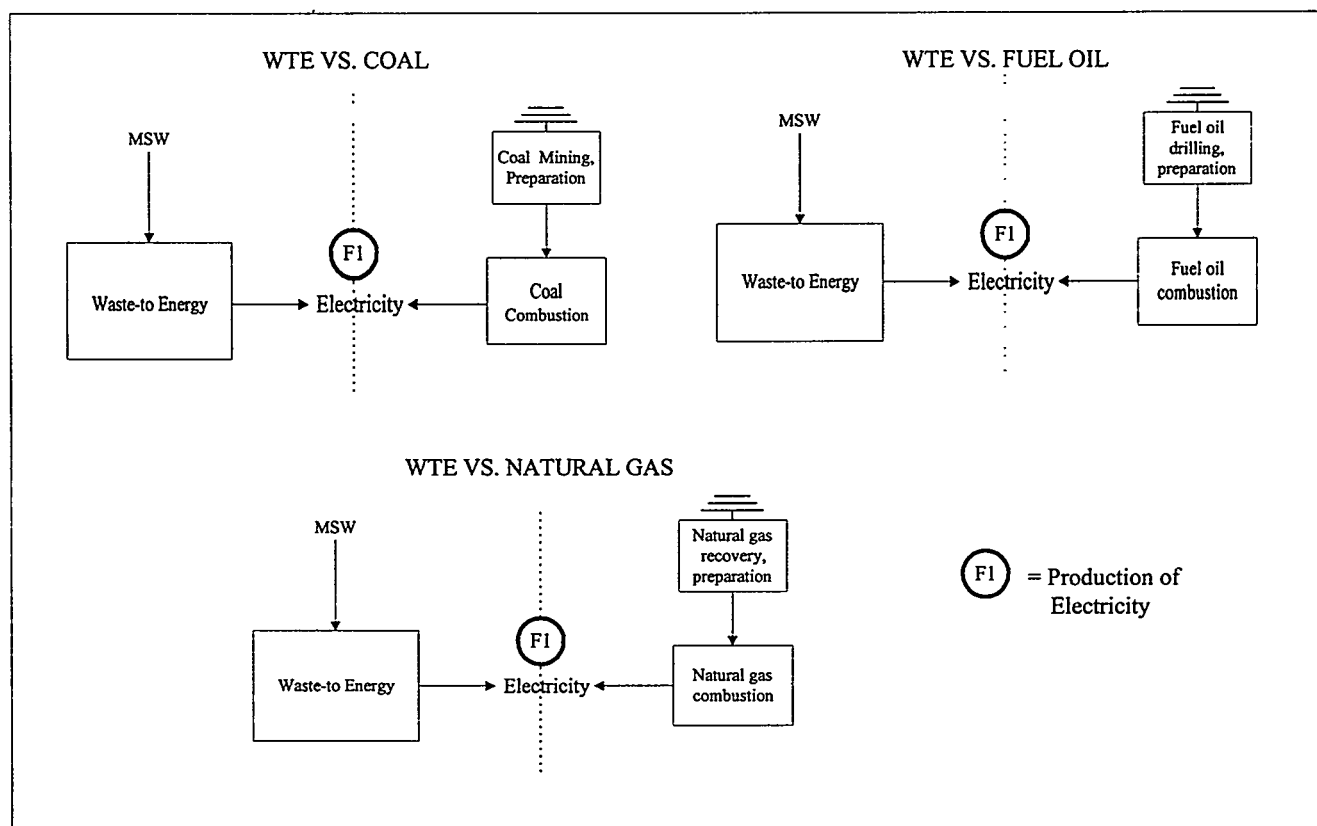


Figure 2 Production of electricity by a waste-to-energy facility and the combustible electricity sources.

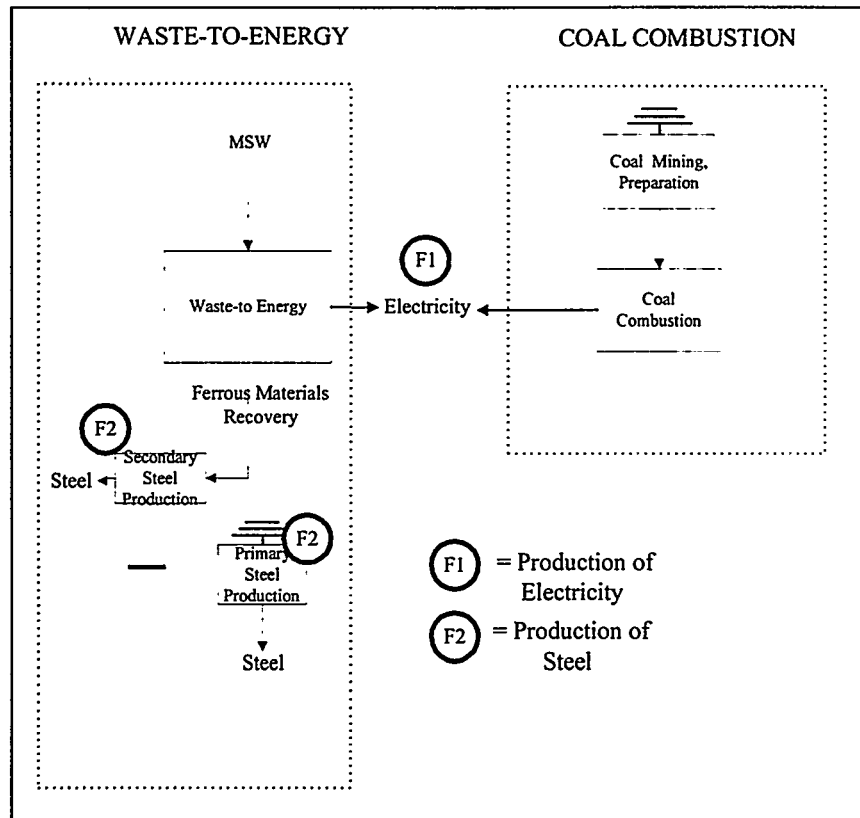


Figure 3 System boundaries for WTE vs. the combustible source of electricity.

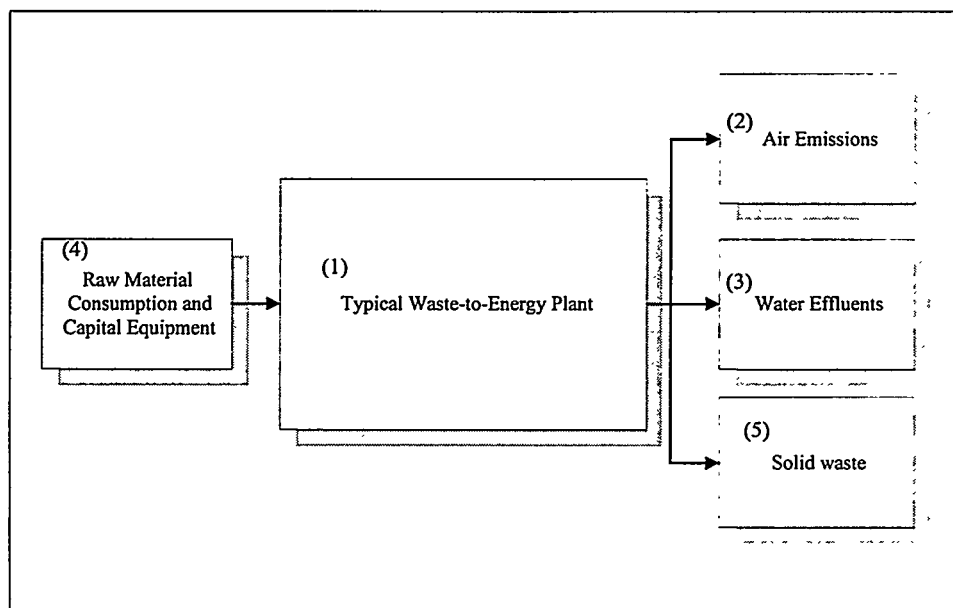


Figure 4 Schematic of the waste-to-energy facility.

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⁶ IWSA, May 1996. 1996 IWSA Municipal Waste Combustion Directory.

⁷ 60 Federal Register, p. 65387, December 19, 1995.

⁸ US EPA Docket A-90-45, items IV-B-13, II-B-39, and IV-B-015.

⁹ Derived from data provided in Franklin Associates, September 1994. "Summary: The Role of Recycling in Integrated Solid Waste Management to the Year 2000", Table 5.

¹⁰ Carbon content percentage for paper and paperboard products from an unpublished LCA report by Ecobalance for American Forest and Paper Association on unbleached paper products, 1995.

¹¹ EIA Petroleum Supply Annual 1993, Vol. 1. 1993 data was used because that was the latest year for which information used to calculate transportation distances could be found (see Section 3.3.2).

Permitting and Siting Success Using the “I-Site” Approach

Timothy J. Coco
COCO+CO.
20 Park Plaza, Suite 431
Boston, MA 02116

INTRODUCTION

Growth in the waste-to-energy industry has fallen considerably since its hey day in the mid-1980s.

Depending on the perspectives of various interests, many explanations for this decline are given. These include the effects of recycling mandates, lack of energy markets and citizen environmental concerns.

Two obstacles to successful siting—energy surpluses and overly ambitious recycling mandates—are being cleared away. Deregulation of the electric power industry promises to create new, competitive energy markets. Utilities are making plans to exit the so-called “merchant function,” thus creating new opportunities for independent power producers and aggregators. Unreliable recycling markets present new demands for disposal capacity.

There appears, then, to be only one remaining hurdle that must be overcome for the industry to take advantage of the potential opportunities ahead. Not surprisingly, it is community perception. Driven by a fear of the unknown, the public—including news reporters and local politicians—challenges disposal methods they don’t understand. And their protests persist even though these projects actually lessen many environmental threats. Fueling opponents are some personal injury lawyers and special interest groups that secure economic opportunity from the debate.

Each victory by waste-to-energy opponents has the effect of rocking investor and lender confidence, employee morale and customer and prospect resolve. Regulators and elected officials take cues from the public and either kill plans outright or impose expensive and unnecessary conditions that have the same effect. These individual battlefield victories by opponents makes their winning the war much more likely. One needs to look no further than the moribund nuclear power industry to see these results.

How can the waste-to-energy industry take advantage of new market opportunities, win permits with a minimum of delay, limit costly conditions, reduce unfounded objections and contain legal costs? The answer is letting down the traditional corporate guard and fully “involving” all constituent audiences in the siting process. The success of the involvement in siting—or the “I-Site”—approach also relies heavily on the adoption of a new, yet common sense, communications model. These conclusions are

based on a comparison of siting successes and failures over the last 15 years, including lessons learned from other industries.

INVOLVEMENT AND COORDINATION

At the forefront of the I-Site approach is defining and coordinating messages to all of the constituent audiences. These audiences may include:

- Neighbors
- Elected officials
- Appointed officials (board of health, fire department, conservation commissions, zoning, etc.)
- Investors and lenders
- Employees
- Vendors and contractors
- Customers and prospects (host communities, purchasers of energy or disposal capacity, etc.)
- Business groups (chambers of commerce)
- Environmental and health organizations

None of these groups can be taken for granted.

Coordination of messages and targets is especially important today because a wide variety of information sources ensures all constituents will have access to data. Sometimes, these audiences receive information not directed to them, creating confusion and misunderstanding when taken out of context. Communicating concessions to host communities, for example, may alarm investors. Informing investors or lenders of cost-saving initiatives may concern employees or regulators. Each stakeholder's reaction depends on his or her vested interests, and these may appear at odds with other constituents. Traditionally, responsibility for dealing with each constituent often falls upon as many different people, departments or outside agencies—placing at risk controls that would otherwise consider the ramifications for other audiences.

Most progressive companies now realize the industrial assembly line model is out-dated because it fragments what should be a single process—that of delivering a product to consumers. Similarly, what should be a single process—communication aimed at reaching sitting goals—has become artificially fragmented. The market conditions and customs of a century ago dictated separate and uncoordinated advertising, public relations and marketing efforts. Today, though, these present barriers to your success. Working independently, each department or outside vendor will interpret the plan differently and put their own “spin” on the message. This serves to dilute—if not completely undermine—messages aimed at others. The end result: audiences feel betrayed.

Companies must reassemble into a unified entity all marketing, government affairs, community relations, investor relations, advertising and internal communications efforts. Existing departments, individuals or outside vendors must be brought under a central command to ensure communications becomes a single process. This may require reorganizing departments so that sales and marketing, government affairs, investor relations, corporate communications, community relations, advertising, etc. are brought under one roof.

If you rely on outside vendors for any company communications, make sure they wholeheartedly endorse this philosophy and have skills in all areas—from advertising to the do’s and don’t of writing a press release. Watch for any biases or limitations they may have that might result in them using inappropriate communications vehicles. Re-engineering guru Michael Hammer says, “You cannot reengineer a process in isolation. Everything must be on the table. Any attempt to set limits, to preserve a piece of the old system, will doom your efforts to failure.” Ironically, communicators frequently talk about re-engineering on behalf of their companies or clients while their departments or agencies have been largely overlooked as candidates for change.

PLAN A PROACTIVE PROGRAM

No matter what you’ve been told by proponents about overwhelming support for the project, plan a proactive program—and the earlier the better. A proactive approach helps developer’s build credibility,

demonstrate an image of cooperation and nothing to hide. If you don't tell the story early and often, audiences will be blindsighted by legal notices or what they hear from so-called environmental "experts." They may even misinterpret what they are seeing out their kitchen windows. Steam may be mistaken for smoky pollutants, for example.

Those charged with coordination of the communications program often must assume the roles of devil's advocate and detective in their organizations. They should ask questions about potential "nuisance" concerns such as noise, odor, truck traffic and so on. When a potential problem area is discovered, find out what mitigating measures will be employed. This information should then be incorporated into the siting program.

KEEP MESSAGES AUDIENCE-CENTERED

All attention must be focused on the target audience. In practice, this means substituting complex jargon with easy-to-understand language. Further, your audience wants to know "what's in it for me"—WII-FM. Let them know what benefits they can expect, such as:

- Permanent and temporary jobs
- An improved environment (replaces older facility or landfill)
- Community royalties (PILOTs) or increased tax revenues
- Reduced tipping fees
- Other community involvement (cite past experiences with schools, Chambers, etc.)

Put yourself in the place of opponents. Of what are they afraid? Are there concerns valid? What can be done to mitigate these issues? Balance humane understanding with business goals. Learning from Union Carbide's Bhopal catastrophe, company spokesman Robert M. Berzok said recently, executives must "make an emotional connection" with audiences.

Take this a giant step forward, ask neighbors to get “involved.” Contrary to what your general counsel says, invite them to call or write with questions or comments. The nature of the legal profession is one of tight-lipped caution. Developers must find a middle ground between project attorneys and communicators. Most importantly, “listen” to what each audience has to say. Neighbors may not only have some good ideas, they may become supporters.

Health risk assessments are widely misunderstood. Be prepared to explain the inherently conservative nature of such studies and give constituents everyday equivalents. Driving in traffic, eating certain foods and other daily life needs expose humans to risks far greater than those being studied. During one lengthy and heated debate over the findings of a “worst case” health risk assessments, some project opponents clamored for a recess—for a cigarette break. Use opportunities such as these to compare relative risks.

If opponents argue that they choose to take certain risks, sensitively point out the risks from other disposal alternatives.

After the permits are granted, continue to inform all audiences. Tell neighbors and officials what they may see and hear during other project phases, such as:

- Site preparation (traffic, noise, relocation of buildings or utilities, etc.)
- Construction (pile driving, etc.)
- Start-up (steam blows)
- Commercial operation (traffic, noise, odor)

When talking with reporters, be sure to avoid use of technical jargon and, again, tell the facts loud, clear and often. In every conversation, emphasize your main points over and over. This is important because invalid arguments you thought you previously addressed have a way of re-entering the debate. When a problem occurs or a mistake is made, remember the truth is never too complicated to explain. There is a reason for everything, explain yours. If you don’t tell your side of the story, someone else will. If you

don't have the answers yet, tell the reporter as much and promise to get back to them. Follow through on your promise as quickly as possible.

TIMING IS EVERYTHING

For best results, an orderly and well-timed flow of information is critical. In all cases, start by telling all employees. This remains true during any crisis—such as an accident or set back—that might take place. Be sure notifications are made through usual and customary channels. Project opponents look for inconsistencies in notification procedures as evidence of management flaws. Further, placing all employees on the same page helps prevent sending out mixed messages. If you don't have an employee notification procedure, create one.

Next, notify key political leaders, neighbors and the media—in that order and as soon as possible. If political leaders hear from you first, there is much less likelihood they will grandstand later. Ask them to withhold public comment until neighbors are notified of siting plans, progress or unforeseen events. They not only should understand this courtesy to their constituents, but will appreciate not being thrown in the middle.

Try to talk to key neighbors and community leaders in person. If it is impossible to talk to every neighbor, deliver or send personalized letters to all who might be impacted. If neighbors hear from the press first, they are much more likely to make misinformed comments and that may position them forever.

When delivering notifications, be sure not to put them in mail boxes. Such actions not only violate postal service rules (and could result in your communications being confiscated), it gives opponents additional weaponry.

Last in this timeline is the local media. If you are lucky enough not to receive a call from them first, proactively deliver your press release and facts to reporters and be prepared to answer their questions. If

the reporter reaches you first, explain candidly that you have already begun notifying officials and neighbors. This open and honest approach demonstrates you have nothing to hide.

It is vital that a reporter always reach someone at your company. There is only one thing worse than the words “unavailable for comment” appearing in print. And that is the words “no comment.” The former sends the message that you may be hiding something and the latter confirms it. Additionally, never talk “off the record” with reporters. Even if the reporter invites an off the record response, you can bet your comments will be published if the editor hears about them.

Designate a contact person who can answer questions. Since some reporters may have early deadlines before your office opens, make sure they have a way of reaching someone during these hours. That may mean giving out a home telephone number. Make sure the company receptionist or secretary understands the importance of media calls and directs them to you or your designee. If you use voice mail, get in the habit of checking it often.

After these core groups are notified, create and take advantage of opportunities to share information with local business and economic development officials, neighborhood groups and influential people in the community. Arrange to speak before service clubs and the Chamber of Commerce. Continue to emphasize your key points.

At all times, remember to put yourself in the place of other constituents and consider their reactions to the planned message. They will want to know what you are doing to mitigate problems.

CONCLUSION

In summary, developers often either overestimate the public’s ability to understand complex jargon or underestimate the impact of so-called “experts” who join opposition groups. Further, waste-to-energy developers frequently omit project details that seem too complicated to explain. However, executives who *pro-actively* and fully involve the public in an exchange of easily understood terms achieve success

at the lowest cost. Successful public involvement means *interactive* communication—not only distributing information, but listening to comments and responding accordingly.

Further, the timing and types of notices to employees, supporters, politicians, neighbors and the media is much more critical than some would believe. Vital to success is a global view that gauges the impact of these communications on unintended audiences.

Giving reporters information clearly, concisely and in appropriate news style is critical. A company must tell its side of the story or someone else will. And, the story must be told loud, clear and often.

These findings appear to be supported by a 1994 study, *Waste-to-Energy in the United States: A Social and Economic Assessment*, organized by Oak Ridge National Laboratory (ORNL) researchers. The study concluded that “financial barriers were not the predominant reason for WTE project cancellations, and those barriers are not likely to be highly problematic in the coming decade. The case study portion of the study identified numerous complexities that community leaders and decision makers must address when considering WTE. After a WTE project has been initiated, the decision to proceed with or abandon the project appears to depend largely on the dynamics of the decision-making process and the interactions among concerned parties.”

The emerging competitive electricity marketplace has the potential to create new opportunities for the waste-to-energy industry. However, a bright future will only be realized if the industry learns from its past mistakes and considers communications a single process that is well coordinated and audience-centered.

EVENING PLENARY SESSION

***Assessment of Emission and Ash
Management Regulations - A Global
Report***

**Assessment of Emission and Ash Management Regulations
The European Perspective**

Kjell Nilsson
ISWA WG on Thermal Treatment
Åkervägen 20
S-245 62 Hjärup
Sweden

INTRODUCTION

To reduce the impact on the environment, the emission requirements on waste incineration have increased rapidly in Europe during the last 10 years. Priority has been laid on the reduction of gas emissions. It is important to state that the regulatory requirements on air emissions differ a lot between the European countries. The Directives, approved by the European Community, EC, in 1989 are still being implemented. But, the EC member states are free to impose more stringent requirements than the EC Directive and some countries in the Central Europe: the Netherlands, Germany, Austria and Switzerland have done so. The situation during 1989-1992 could be characterized as a race between these countries in tightening the emission standards. The most conspicuous are the extremely strict requirements introduced in the Netherlands in 1989. Those standards have confused and worried the operators and other parties in other European countries because of the risk that it might serve as a model for a new EC Directive.

The misgivings soon turned out to be justified as the EC Commission started the preparation of a revised directive for waste incineration. The last draft proposal was presented in 1994. It is strongly influenced by the strict standards of the Central European countries, but not as far-reaching as the Dutch regulation. Anyhow, objections were raised by several countries to the frequent tightening up of the emission standards claiming that the financial consequences are unacceptable. The new EC Directive is still in the pipeline, but there is no fixed time for the approval.

Efficient gas control does not mean that the harmful compounds disappear. They are to also found in the residues from the gas cleaning. In Europe, we can observe a growing concern about the environmental consequences of ash disposal, especially the long term risk of leachate discharges. An increasing number of countries will no longer accept land disposal unless the residues are properly treated. The very strict standards on gas emissions in many countries will probably be followed by as strict requirements on the control of residues.

This paper reports on the emission and ash management regulatory requirements for waste incineration in Europe and reviews the level of emission controls, current technologies and enforcement practices. The development of emission standards in different European countries during the last 10-15 years is illustrated as background for the now actual situation. The proposed European Directive is discussed and compared with the American regulations under the Clean Air Act. The adopted objectives and strategies are discussed and other means of control exemplified.

GAS EMISSIONS

Emission standards (1, 2, 3, 4)

The emission standards for waste incineration in the European Community, EC, and in some of the memberstates are presented in **table 1**. The presentation does not comprise the complete conditions. The table is meant to illustrate the essential features of the different regulations. The consideration of more sophisticated discrepancies is not within the scope of this paper, but it is important to observe that the standards have different reference conditions in different countries. The following list comprises the most important differences.

- The average values must be met as over varying time periods, from 1/2 hour to 1 month.
- The values are related to differing O₂- or CO₂- levels.
- The sampling and analysis methods (hence what is actually measured) are different.
- There are differences regarding standard status: whether it is target values or limit values and the

- measures and penalties that a transgression will lead to.
- The times for the given standards to be fulfilled are different.
- Whether they are valid for existing plants or only the new ones.
- The figures in the table are valid for big plants, for the small ones there are normally other, less strict requirements.

The selection of standards in the table is meant to illustrate the stepwise development of the standardised requirements on air emissions from waste incineration in Europe and reflect the different priorities concerning pollutants in the mentioned countries.

The background to the rapidly increased emission requirements in Europe during the last 10 years is to be found further back in the growing awareness of the threatening pollution of our society and its impact on the human health and the environment. But, the starting point for strongly sharpened requirements on waste incineration came with the Swedish standards of 1986, focusing on dioxins and mercury. The preparatory work for this regulation started in 1984-85 as a result of public concern in Sweden about dioxins and the uncertainty concerning the impact of dioxins on the human health. Dioxin had been detected in mothers milk and waste incineration was pointed out as one of the main sources of the emissions. The course of events in Sweden attracted special attention internationally since the Swedish Environmental Protection Board declared a temporary moratorium on the construction of new incineration facilities waiting for the result of a thorough investigation. In 1986 the result of the effort was published in the report "Energy from Waste". The overall conclusion of the study was that it is possible to reduce the emissions to the levels acceptable to human health and the environment by the implementing improved operation and gas cleaning. Consequently the moratorium for new plants was lifted in 1986. Dioxins and mercury were singled out as critical pollutants, whose high toxicity, resistance and accumulation in the eco systems required very strict control. The emission standards set down in 1986 as a consequence of the investigation were at that time much more strict regarding these two pollutants than in any other country. Total dust emissions were also strictly regulated because of the high correlation with the emissions of several hazardous pollutants as cadmium, lead etc. The acids were not prioritized, since the emissions of those compounds from waste incinerators were evaluated as being of minor importance to health and the environment. It is interesting to observe that the Swedish authorities have not followed the Netherlands and Germany regarding the later, fundamentally tightened standards for especially acids in those countries. The reason is most likely the study of 1986.

While Sweden in 1986 pointed out dioxins and mercury as critical pollutants, Germany gave during the early 80's special attention to acids like HCl, HF and SO₂. At the end of the 80's, the real revolution concerning emission requirements came when other countries in Europe combined the two priorities into very strict requirements on all pollutants. In 1989, the Netherlands introduced extremely strict requirements and Austria was close behind. Germany took up the challenge by new stricter guidelines and so did Switzerland.

The European Community, EC, approved a directive on waste incineration in 1989, closely following the older, less strict standards of 1986 from Germany, without specified requirements on dioxins and with moderate requirements on mercury. As a consequence of the tightened standards in the Netherlands, Germany and other Central European countries, EC started the preparation of a revised directive for waste incineration in the beginning of the 90's. The first draft editions were targets for strong criticism but gradually the proposal became much more balanced. The last draft directive was presented in August 1994. It is practically identical with the German Standards of 1990. There are still a few substantial objections, but as a whole the proposal seems to be acceptable. The most important objection, and that is

a fundamental one, is the lack of a scientific risk assessment and a cost/benefit analysis as a basis for the emission requirements.

Since EC presented the proposal on tightened Waste Incineration Directives in 1994, we have not experienced any new official initiative in this field from the Commission. They are said to work on a cost/benefit analysis, for the new standards. That must be understood as a response to the critical reactions to the proposal. In December 1996 the European Council of Ministers adopted a Resolution on an updated Community Strategy for Waste Management. In that paper the Council "invites the Commission to consider the scope for the amendment of Community legislation in relation to the incineration of waste with energy recovery". That opens up for a prompt accomplishment of the revised European Directive, most likely very close to the draft proposal. Everything seems to indicate that most countries will approve the new Directive unchanged, but some countries will remain with their stricter requirements.

Glancing at the table, the Dutch standards seems to be fairly close to the draft EC standard. But there is a fundamental difference in the measuring period for the plants to comply with the requirements: 1 versus 24 hours. The difference is obvious when comparing the short-period requirements for the two standards. Apart from that the most salient discrepancy is the maximum emission level of 70 mg/m³ (see table 1) in the Dutch standards. As the low level has an obvious impact on the gas treatment cost, it has stressed the debate concerning the reasonableness of the figure. It is said that a cost analysis has been conducted in the Netherlands, but so far I have not heard about any changes of their standards.

Based on later evaluations it is questioned if the very strict requirement on dioxins (0.1 ng/m³) introduced by Sweden 1986 is scientifically justified.

Indirect measures on emission reduction (2, 4)

The European standards according to the draft EEC Directives or national regulations normally include operational measures in excess of the emission limits with the intention to achieve low emissions. Here are some examples on that type of measures:

- the oxygen level may not fall below 6%
- the combustion temperatures must always be at least 850°C
- the residence time at 850°C must exceed 2 seconds
- auxiliary burners must be installed and operated in the start-up phase

There has been a strong opposition from the operators to this type of restrictions, not least in Sweden. There are experiences telling us that auxiliary burners sometimes may lead to deterioration instead of improvement. For some types of incinerators it is not obvious that an oxygen level of at least 6%, a lowest temperature of 850°C or a minimum residence time is relevant. There is an obvious risk that this type of regulation puts a negative influence on the technical development and the optimization of plant operation.

Comments to the draft EC Directive (2, 4)

As mentioned above, the draft proposal of 1994 to a new EC Directive on waste incineration has caused substantial opposition to arise from several operators and other experts. The following list illustrates subjects of discussion in connection with official regulations.

- The frequent change of standards - the new proposal coming up before the previous has been implemented - leads to poor operation and increased costs. The standards must be long term, permanent, to make it possible to operate plants economically and technically optimal.
- The emission requirements must be based on consequence analysis regarding impact on the environment compared with cost expenditures. The margin effects of increased requirements must be carefully considered. Expenditures should correspond to environmental benefits.
- The emission standards should be based on accurate considerations of the alternatives for energy production and waste treatment. If the requirements are more strict than for the alternatives, the net result will be an unfavourable use of the society resources. There is also an obvious risk that incineration will be replaced by other methods, which may give more pollution to the environment while consuming a higher quantity of fossile fuels.
- The principle of BAT (Best Available Technology) is unrealistic since it does not consider the financial consequences. It means as well frequent changes, leading to unstable operating conditions and uncertainty, not to say action paralysis. BAT must be combined with cost restrictions, which means growing into the principle of BATNEC (Best Available Technology, No Excessive Costs).
- There are no reason at all to put standardized requirements on operating conditions, like process temperatures and auxiliary burners, in addition to the emission requirements. That holds back the technical development and limits the possibility to optimize the plant operation.
- Too frequent measuring of emissions are unwarranted. No expert can honestly conclude that there are acute toxicity or acidification risks at modern waste incinerators. It is only the long term average emissions, that are of interest. The frequency and type of measuring must be adapted to that fact.

Comparison of European and American Standards (4)

In april 1996, the ISWA Working Group on Thermal Treatment organized a specialized seminar in Copenhagen addressing "European requirements and its consequences". That session developed a comparison between the proposed EC Directive and the corresponding USA standard, according to the Clean Air Act (CAA). Coincidentally, the two documents were promulgated at about the same time. Since then, the administrative handling of the two standards has been different. The USA standard has been approved but so far not the European.

There are significant differences between the two directives. The American one focuses entirely on air quality standards. The European is more far-reaching, addressing as well pollution standards for emissions to soil, surface- and groundwater. A comparison between the two directives is no simple task. First of all they must be normalized regarding equivalent units. The EC Directive is referred to 11 % oxygen content, 0°C (32°F) and a pressure of 101,3 kilopascals (29,92 inches of mercury) whereas the US CAA Standards is referred to 7 % oxygen, 68°F (20°C) and the same pressure. The EEC Directive is based on the metric system where the US CAA Standards are based on the English system of weights and concentration (i.e. parts per million, grains per dry standard cubic foot etc.). The measurement periods, on which the emission values are based as average values, differ significantly between the two standards.

The European and the American standards are compared in **Table 2** with the American values converted to the European equivalent units. The differences in sampling methods and averaging periods has been ignored. The conclusion is that the two standards are fairly close numerically to each other, but can be very different in actual stringency.

Comments to adopted objectives and strategies (4)

It stands to reason that the reduction of emissions from waste incinerators, as from other emitting activities, is to protect the human health and the environment. To stipulate the acceptable level of

emission a risk assessment has to be accomplished. The European countries and EC have so far in general assumed an unresponsive attitude towards scientifically based risk assessments. The chosen approach is "technology oriented", which means that it is based on the principle that the best available technology (BAT) must be put into practice regardless of what is required to protect health and environment. The economic consequences and the requirements on competing waste treatment and energy production alternatives are not considered.

Here we find an interesting comparison between Europe and America, reflecting differences in the approach to the problem. The US Clean Air Act Standards have a more "objective oriented" approach, aiming at what is necessary for the protection of human health and the environment. That means the same assessment undependant of type of emittent and consequently equality between different waste treatment and energy production options. The result of the European approach is very rigorous restrictions for waste incinerators compared with other waste treatment and energy production alternatives. It is of course technically possible to apply gas control technology at waste incinerators capable of meeting every demand including unmeasurable emission. But it leads to very high investment and operation costs as well as reduced reliability as a consequence of increasingly complex technology.

Other means of control

There are other means of administrative control besides air emission standards that have influence on the emissions from waste incineration. Here are a few examples from Europe.

- Requirements on separate collection of hazardous wastes as batteries and chemical residues makes the feeded waste fuel cleaner and helps to reduce the pollution of the exhaust emissions. According to studies in Sweden, such measures have reduced the mercury load with the waste fuels heavily and thereby substantially contributed to the reduced mercury emissions. Another similar measure is the ban on the use of cadmium in some European countries.
- Taxes and other economic means of control has been put into practice in some countries. In France a tax of 150 FF_r (about 25 US dollar) per ton gas is imposed for HCl, SO_x and NO_x with further taxes being planned for particulates and organic compounds. Another example is the Swedish charge system on emission of nitrogen oxides from energy producing units, undependant type of fuel. The system is as a whole a zero-sum game, favourising low emissions. The charge is 40 SEK (about 5 US dollar) per kg NO_x-emission with a refund proportional to produced amount of energy. That means incentive for continous improvements and technological development as long as it is inside the scope of the fee level.
- According to the applied solid waste management hierarchy, landfilling has the lowest priority. But recycling and recovery, not just modern energy-from-waste plants, have difficulties in competing financially with landfilling, especially with the very strict requirements in the Central European countries. A growing number of countries have inaugurated taxes or governmental charges on landfilling in order to support recycling and recovery. But the cost gap is too big to be bridged over by these loadings. Another means of cost equalization being introduced in several countries is the ban on landfilling of waste without pretreatment. Such a restrictions make incineration of unusable, unrecyclable organics a necessity independant the cost levels. But that type of restriction involves a risk that cost/benefit assessments of emissions reductions will be ignored.

AIR POLLUTION CONTROL

Control technologies and enforcement practices (2, 3, 4, 5, 6, 7, 8, 9, 10)

Since long time ago, at least since the beginning of the seventieth decade, it has been obvious that waste

incineration plants must have gas cleaning equipment to avoid adverse impacts on the public health and the environment. The measures were at that time concentrated on dust reduction, normally by means of electrostatic precipitators. A changed attitude came with the eighties and a better understanding of the impact on the environment from all type of emissions. It started with acid gasses and different types of wet scrubbers were tested and introduced, especially in Germany. But the real break-through came with the Swedish alarm about dioxins in 1984-85. The Swedish investigation during 1985-86 represented in my opinion the ideal model for a target directed achievement. It was organized as an extensive, cooperative joint effort of regulatory authorities, plant operators and other experts. Everyone realized the gravity of the situation and was devoted to solution of the problem. That created a breeding ground for realistic conclusions about impact on human health and environment, required reduction of emissions, technological solutions and economic considerations. The importance of waste as fuel and energy supplier was emphasized and expressed through the title of the report: "Energy from waste". As a follow-up of the investigation, essential development was performed in Sweden during the rest of the eighties, not only about gas cleaning equipment, but as the other factors affecting the emissions: the quality of waste as fuel, the combustion process and the energy production. A typical design used cyclone or electrostatic precipitator for primary cleaning followed by dry scrubber and bag filter for emission polishing. The result was rapid and impressive, which is shown in table 3 as a summary for the total number of incineration plants in Sweden.

The introduction of the even more strict standards in the Netherlands in 1989 raised a question whether it was possible to find gas cleaning systems capable of coping with those standards, at least if the economic consequences are considered. Anyhow, a new market opened for the manufacturers of gas cleaning equipment. The air pollution control systems became multistep, chemical factories.

A system for air pollution control capable of meeting the strict requirements of today can be designed in many different ways. The gas cleaning equipment must be an integrated part of the total plant, which means influence from such factors as fuel quality, combustion process, energy recovery, handling of residues, reliability and flexibility. In some countries in central Europe, as Germany and the Netherlands the systems for gas cleaning have become very complex and expensive during the nineties. A total net waste treatment cost of 1000 SEK/ton (about 130 US dollars) is not exceptional. A typical layout is as follows:

- dust removal by electrostatic precipitators, cyclones and fabric filters
- two stage wet flue gas cleaning with acid and basic stage
- deNO_x stage with non-catalytic (SNCR) and/or catalytic (SCR) reduction system
- active carbon filter or catalytic oxidation.

It is obvious that the implementation of such a complex system threatens the reliability and safety of the plant operation, at least during a transitional period. It is also obvious that it is possible to apply technology capable of achieving these and even stricter standards as long as the economic factor is neglected. The question remains: is this a necessary measure and the right priority to maximize protection of human health and environment.

In other countries, as in Scandinavia, there has been a more pragmatic, cost-benefit characterized approach. The Swedish attitude has its origin in the investigation in the middle of the eighties. The chosen systems, dominated by dry scrubbers and bag filters, makes it possible to meet the now valid EC Standard and as well the dominating fraction of the proposed new Standard. A normal net waste treatment cost is about 300 SEK/ton waste (about 40 US dollars), significantly lower than in the Central

Europe. The difference reflects the very high additional costs that must be paid for a questioned benefit to the environment.

In this paper it is not possible to address technical descriptions on different systems and equipment for emission control. I do not think it is necessary either since the manufacturers serve the international market. I will mention one project, because it has a new technology under development in the SYSAV waste-to-energy plant in Malmö. A full size installation of a high dust (front end) catalyst has been in operation at the plant since 1996 to reduce NO_x. Before that a selective non-catalytic reduction with urea injection has been in operation since several years ago resulting in a NO_x-emission of about 100 mg/Nm³. It is well known that catalytic reduction of NO_x with ammonia is very efficient if the catalyst is located after a fabric filter at the tail end. The problem is that this is a very expensive solution. A catalyst capable to stand the conditions in the high dust position of a waste incineration plant would be much more cost effective. The full scale prototype in Malmö, which has been in operation since autumn 1995, was prepared by a 2-years promising test in a pilot plant. The full scale operation has so far been in accordance with the expectations with a further NO_x-reduction of 40-50 % compared to the original SNCR installation.

THE HANDLING OF RESIDUES

The new challenge (11, 12)

As a result of efficient measures to reduce the gas emissions the hazardous pollutants are to be found concentrated in the residues: bottom ash (slag), fly ash (in this paper including boiler ash) and other gas cleaning products. The predominant ash management practice in Europe has been and is still disposal in landfills. But there is a growing concern about the environmental consequences of ash disposal, especially the long term risk of leachate emissions. Here we have a new challenge in taking care of the residues from the waste incinerators. Though the development of the residue management in Europe has been evolving for several years, the work is still in its start-up phase. The reason for that is the number of difficulties associated with the problem.

The ash residues produced in Europe makes a considerable amount to handle. The around 30 million tons of waste incinerated in Europe yearly will result in about 7-8 million tons of residues. Bottom ash is the dominating part, accounting for 80 to 95 % of the total, which means around 6-7 million tons. The rest is gas cleaning residues, around 1 million tons yearly. In Europe the bottom ash, the fly ash and the other gas cleaning products are normally managed separately.

The main objective of the handling of residues from waste incineration is, as for emission control, to protect human health and the environment. But there is as well another objective, attracting increased interest: the recovery of the residues. To meet both objectives the management of waste incineration residues in Europe gives priority to and even demands recycling. Economically and environmentally viable residue management alternatives are under development to meet the objectives. That means normally use of treated residues in construction, e.g. in roads. But there are other options as well. The residues contain concentrated substances from the waste and represents obviously a source of metallic raw material. The wet gas cleaning products are sources for the extraction of hydrogen chloride, sodium chloride and gypsum. Extraction of these valuables makes it possible to close resource cycles.

The residue management in Europe is generally aiming at

- reduced amount of residues,
- reduced content of hazardous pollutants in the residues

- maximized recycling of residues.

The quality of the waste, the type of incinerator and the efficiency of operation is of the utmost importance for the possibility to comply with these objectives. It is normally a good strategy to design a waste incineration plant so that the toxic elements are concentrated in the fly ash and the gas cleaning products, leaving the bottom ash as "clean" as possible. An optimized operation will ensure minimal amounts of trace metals as cadmium and mercury, low content of organic constituents and high concentrations of stable mineral phases in the bottom ash. We have here an example on how important it is to look upon the total system of an incineration plant in order to optimize the total result, based on the prerequisite in the specific case concerning feeded waste, energy market, emission requirements, use of recycled slag, ash deposition etc. Several operators, manufacturers and other experts in Europe are acting in that direction.

Impact and regulations (11, 13)

As the dominating ash management practice in Europe still is landfilling the regulations for landfill disposal is of vital importance for the requirements on waste incineration residues. There are so far no approved EC Directive on landfilling, but a proposal is under final preparation. Current regulations are consequently national and differ a lot. An example of well developed landfill regulation is the German "TA Siedlungsabfall" which defines two different landfill classes with different demands on ash quality. Fly ash is classified as "hazardous waste" and consequently has the most demanding landfill requirements, normally in separate cells. As a consequence of a growing concern an increasing number of European countries will no more accept disposal unless the residues are properly treated.

For bottom ash the situation is different since the content of harmful pollutants are significantly lower than with the fly ash and there are obvious recycling options. The different countries have approved their own standards for the utilisation of slag, but these are stepwise being brought closer to each other as a result of exchanged experiences and extensive cooperation. In due time an EC standard will be approved but the memberstates will still have the possibility to require stricter standards. The requirements are under frequent alterations, based on new knowledge from research and development.

In the Central European countries (Germany, the Netherlands, France) the requirements have reached a quite strict level, considering especially the burnout and the leaching properties of the slag. The burnout is normally expressed by the loss on ignition (LOI) and/or the total organic carbon (TOC). Typical requirements are (weight percent):

- Loss on ignition less than 3 %
- TOC less than 1 %

The slag quality must comply with requirements on the maximum limits according to leaching tests (primarily trace elements and unorganic salts). As the limit values and the test methods are not harmonised for the different countries, a comparison is very difficult. As an example parts of the German standards according to "LAGA Merkblatt" is shown in table 4. The document is continuously revised.

Storage of the wet slag before use is normally a standardised requirement in order to transfer the strongly alcalic hydroxids into carbonates, thereby lowering the pH-value to 9.5 or lower, which also reduces the solubility of lead.

The treatment of residues (11, 12, 13, 14))

To develop treatment practices and management options for waste incineration residues it is necessary to thoroughly consider the physical and chemical characteristics of the materia. Those residues are

heterogeneous materials, whose properties vary over time in response to waste feed as well as plant design and operating conditions of incinerator and air emission control equipment. In general the ash residues from a waste incineration plant amounts to about 15-35 % of the weight of the waste fed. Bottom ash (slag) is the dominating part, accounting for 80-95 % of the total solid residues. That means about 150-300 kg per ton waste. Typical ranges of gas cleaning residues produced per ton of feeded waste are 20-50 kg (dry process, including fly ash), 15-40 kg (semi-dry process including fly ash) and 1-3 kg (wet condensing process exclusive of the fly ash). The amount of fly ash precollected in the wet condensing process is 10-30 kg/ton waste. Wet condensing processes also produce 0,3-0,5 m³ of saline wastewater per ton waste.

To meet the requirements on proper treatment of the residues various treatment methods are being considered and several equipment manufacturers in Europe are currently developing methods and systems to meet the requirements. There are several commercial ash treatment plants in operation or under construction and many examples on test and demonstration projects. The methods and systems of interest are in different levels of technical development and validation. A few methods can be viewed as nearly established technologies but as to the rest there are still a considerable amount of improvement work to be done. The efficiency of the different methods are questioned and has to be confirmed, especially when speaking about the long term liability of deposited treated residues. Anyhow there are methods promising a long term stable and harmless product, which sets aside the need of controlled deposition and opens up for reuse.

An obvious problem with most of the ash treatment methods is the very high investment and operation costs. Added to the heavy economic burden of very strict gas emission control these costs can turn aside the construction of urgent new incineration plants in favour of landfilling or other inferior waste treatment alternatives. That should be an impelling force for the development of cheaper ash treatment and gas cleaning alternatives. Here we face an important challenge for the manufacturers and contractors. In my opinion, deposition in landfills or longterm storage (for instance in German salt mines) should be accepted as an alternative to advanced treatment practices if the storage site conditions can meet strict requirements.

The available treatment processes under development and implementation can be classified as follows:

- Separation
- Stabilization
- Solidification
- Thermal treatment

The most widespread form of separation in Europe, in commercial operation since the early eighties, is the screening and sorting of bottom ashes for the recycling of metals, especially ferrous, and the use of the screened ash in construction. This has been done to varying degrees for many years in different countries.

Ash stabilization and solidification are often combined. The dominant solidification agent is cement, often a tailor-made compound. Removal of soluble salts such as calcium chloride before stabilization and solidification is sometimes necessary to meet longterm stability requirements. A promising process for stabilization without solidification seems to be adding soluble phosphates, which form low solubility phosphate minerals.

Thermal treatment involves melting or sintering of the residues at high temperatures of 1200 to 1500 °C to transform the ash into a harmless and very stable glass (vitrification). Dioxins and other organic compounds are also destroyed. Thermal treatment is the most expensive of the actual methods involving high energy consumption and exotic technology. The need of further development is obvious.

Liquid discharges from wet scrubbers have been traditionally discharged to the sewers after treatment and that is still the case for some plants. But, there is increasing pressure to eliminate such discharges. One possibility is to use dry or semidry scrubbers. In Germany, there is the general opinion that these methods are not able to comply with the strict requirements on acids. Another method put into practice in Germany, is vaporization of the scrubber blow-down to make the plant a zero-discharge facility. Filter cakes from wet scrubbing systems are normally disposed of in special landfills.

Utilisation of residues (11, 12, 13)

The bottom ash has been utilised in some countries in Europe for more than 20 years for civil engineering purposes, particularly as subbase at parking lots, bicycling paths and residential as well as major roads (paved and unpaved). As a subbase material, the bottom ash usually substitutes gravel, which is a limited resource in many countries in Europe. Therefore, there is an incentive for utilization of bottom ash from a natural resource conservation as well as an economic point of view. An important limiting factor for recycling of residues from waste incineration is the difficulties to guaranty an acceptable longterm quality of the utilized residues and a low longterm impact on the environment.

In Germany, France, the Netherlands, Denmark and Switzerland a considerable part of the produced slags and minor parts of the fly ash are recycled, **table 5** . Other countries report lower levels of recycling of different reasons.

Raw slag from a waste incineration plant can normally not be utilized without treatment. Two treatment steps are in general required:

- Storage of the wet slag (maturing process, normally a formal requirement).
- Mechanical treatment - especially sieving and multistage magnetic separation, which sometimes may be followed by a washing step.

The quenching of bottom ash in water involves some negative effects for recycling since several metals are oxidized and the iron scrap contaminated by calciumproducts. Methods for dry discharge has been introduced in Europe in order to eliminate these disadvantages.

The data on treatment practices and utilization options for slags available in different reports are often very difficult to compare and evaluate because of the discrepancies. The reason to that is the different sampling and analytical methods, misinterpretation of reported data and other mistakes.

A typical result of the treatment of waste incineration slags in Europe is as follows (weight percent):

- 80-85 % secondary construction material
- 10 % secondary raw material, mainly ferrous metal
- 5-10 % coarse fraction for disposal or returned to processing

The fly ash and other gas cleaning products are of less interest as construction materials, mainly due to the higher contents of toxic inorganic (heavy metals) and organic (dioxins and furanes) compounds or water soluble salts. These residues can be utilized only after further conditioning or more sophisticated treatment. In the Netherlands fly ash is used as aggregate in asphalt and concrete. An interesting possibility practiced in Germany, requiring less treatment, is the use of such residues to fill underground salt mines. The extraction of high graded hydrochloric acid, gypsum etc for recycling is so far of less importance in Europe.

CONCLUSIONS

There is no doubt that the turbulence around the very restrictive requirements on waste incineration in Europe has given rise to impressive technical and operational progress. The operators have been much more target-directed and the contractors and manufacturers have met the increased demand for advanced equipment and methods. Waste incinerators complying with the new, strict emission standards are close to the zero-level of emissions. The rapid progress confirms that a drastic change in conditions sometimes is a driving force for the development.

The problem is that the costs associated with the measures have exploded. The new strict standards have in general been adopted politically with inadequate consequence considerations. They are obviously not based on a scientific risk assessment concerning the impact on the human health and the environment. The environmental gains compared to the additional costs and operation difficulties have not been satisfactorily analyzed. That is of course a very serious consequence since there is an evident risk of mismanagement of society's resources and the environment. Waste incineration runs the risk of being replaced by other, less favourable waste treatment methods not because it is bad, but because it costs too much to comply with the low benefit regulations.

It must be admitted that risk assessment in this case is difficult because of a lack of basic knowledge. The stringent requirements can be justified politically as being a precautionary measure. Today we have reached the level of knowledge and experience where we should try to define the point of reasonable emission levels and the prudent cost/benefit ratios for the emission control. That gives the opportunity to issue reasonable standards and offer the market stable long-term conditions.

The approach on waste incineration in Europe, not to say worldwide, seems to be based on the belief among the political decision makers that waste incineration is an extremely harmful **destruction** method, which must be hedged by very rigorous restrictions compared with most other activities in the society. The created atmosphere has a strong influence on public opinion and strengthens the negative attitude. The specific requirements on waste incineration stresses the public opinion that waste incinerators are very harmful. For the just acceptance of waste incineration and therefrom following fair requirements, it is in my opinion of utmost importance that the method be widely recognised as the environmentally friendly **energy production method** it really is.

It is possible that the future may bring such a changed attitude. The search for new energy sources, based on renewable fuels, is one possibility. Municipal and industrial wastes are to a large degree biofuels, which can reduce the need of fossile fuels. A broader adoption of the energy-from-waste concept is hopefully the key to a revised, more positive approach to waste incineration in Europe. Looking at the situation in the Nordic countries, where waste incinerators have been synonymous with energy production for many years gives at least a small hope for such an alteration in public attitude. Another balancing pressure is a better understanding of the problem with landfills, as being resource destructive and long-term risks to human health and the environment. The new waste management legislation under implementation in many countries bans deposition of waste without pretreatment, which opens up the arena for incineration.

Based on facts, the prospects for waste incineration with energy recovery should be very favourable.

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Table 1. European emission standards for waste incinerators

Pollutant (mg/m3)	Sweden 1986 1)	Germany 1986	Germany 1990 2)	EC 1989 3)	the Netherlands 1989 4)	EC (draft dir.) 1994 5)	1994 5)
HCl	100	50	10	50	10	10	60
HF	-	2	1	2	1	1	4
SO ₂	-	100	50	300	40	50	200
NO ₂	-	500	200	-	70	200	400
TOC	-	20	10	20	10	10	20
CO	100	100	50	100	50	50	100
Dust	20	30	10	30	5	10	30
Cd + Hg	Hg=0.08(0.03)	0.2	0.05+0.05	0.2	0.05+0.05	0.05+0.05	0.05+0.05
PCDD+PCDF (ngTEQ/m3)	0.1	-	0.1	-	0.1	0.1	0.1
Related to dry gas	10%CO ₂	11%O ₂	11%O ₂	11%O ₂	11%O ₂	11%O ₂	11%O ₂
Sample average	1 month	24 hours	24 hours	1 month	1 hour	24 hour	0.5 hour
(with some exceptions)							

1) According to ENA 1986. Sweden has later adapted the EC Directive of 1989 regarding stricter requirements.

2) According to 17. Decree to BImSchG, Dec 1, 1990.

3) According to Directives 89/369 and 89/429, Dec 1, 1990.

4) According to BLA, Aug 15, 1990.

5) According to Draft Directive Incineration of waste, Aug.1994 (GH016).

Table 2. Comparison of European and American Standards (converted into European equivalents)

Pollutant mg/m3	European standard EEC draft Directive	American Standard	American State Standards
HCl	10	28 or 95 % removal	28 or 95 % removal
HF	1	-	2
SO ₂	50	61 or 80 % removal	61 or 85 % removal
NO ₂	200	219	205
NH ₃	10	-	11
TOC	10	-	15
CO	50	175	79
Dust	10	17	17
Cd	0.05	0.026	
Hg	0.05	0.10 or 85 % removal	
PCDD + PCDF (ng TEQ/m3)	0.1	(0.13)	

Table 3. Total reduction of air emissions from the Swedish waste incinerators 1985-1994

Pollutant		1985	1994	Reduction
HCl	ton/year	8400	290	96 %
SO ₂	ton/year	3400	820	76 %
NO ₂	ton/year	3400	1600	53 %
Dust	ton/year	420	40	90 %
Hg	kg/year	3300	100	97 %
Cd	kg/year	400	15	96 %
Pb	kg/year	25000	300	99 %
PCDD + PCDF	g/year	90	2	98 %
Basic data				Increase
Number of plants		21	21	
Waste load	Mton/year	1.53	1.68	10%
Energy prod.	TWh/year	3.4	4.3	25%

Table 4. German standards and outlines for deposition and utilization of slags.

Compound	Unit	Deposition by TA Siedlungsabfall		Utilization LAGA Merkblatt
		Class 1	Class 2	
<i>Unburnt, organic</i>				
LOI	weight %	3	5	3
TOC	weight %	1	3	1
<i>Elutant by DIN 38414</i>				
pH		5.5-13	5.5-13	7-13
TOC	mg/kg	200	1000	-
Pb	mg/kg	2	10	1
Cd	mg/kg	0.5	1	0.05
Cr(6)	mg/kg	0.5	1	0.5
Cu	mg/kg	10	50	5
Ni	mg/kg	2	10	0.4
Hg	mg/kg	0.05	0.2	0.01
Zn	mg/kg	20	50	3
Chloride	mg/kg	-	-	2500
Nitrate	mg/kg	-	-	5000

Table 5. Utilisation of bottom ash in some European countries

Country	Amount utilized	Applications
Germany	About 50 % or 1.5 Mtons/year 1)	Road construction (ptimarily as granular base).
France	About 50 % or 1.2 Mtons/year	Road construction
the Netherlands	About 90 % or 1 Mtons/year	Road construction, embankments, noise and wind barriers. Aggregate in asphalt and concrete
Denmark	About 90 % or 0.4 Mtons/year	Construction works (roads, parking lots, bicycle roads etc)
Sweden	Limited, under developement	Construction works (roads, parking lots, etc)

1) 1 M ton = 1,000,000 kg

Incineration of Municipal Waste and Measures against Dioxin in Japan

Toru Sanbongi, Kentaro Doi
Waste Management Division,
Ministry of Health and Welfare
1-2-2 Kasumigaseki, Chiyoda-ku,
Tokyo, Japan

Introduction

It was in 1983 that dioxin was detected from fly ash emitted from municipal solid waste(MSW) incinerators in Japan. Since then, the Ministry of Health and Welfare has executed numerous researches on the generation mechanism and control of dioxin. Based upon the results of the researches, the Ministry entrusted a group of experts to conduct a study on measures to be taken against dioxin, and finally issued "the Guidelines for the Prevention of Dioxin Generation from MSW Incinerators" in December 1990. In June 1996, "The Conference for examining the measures to reduce dioxin in connection with waste disposal" was established ; and in January 1997, the Guidelines was amended

The present situation of MSW management in Japan

(1) Measures currently implemented in Japan

In Japan, we are reducing the volume of waste and promoting recycling along with incineration of combustible waste; in addition, we are promoting "recyclic treatment of waste " which involves the use of heat generated from incineration.

The Ministry of Health and Welfare has been pursuing an initiative through a project which subsidizes the waste disposal facilities established by municipalities with public funds. In 1994, the project for creating a recycled waste treatment infrastructure was started, in order to subsidize incineration facilities, which supply other facilities with electric power by power generators of their own, as well as RDF (refuse derived fuel) facilities and facilities related to recycling.

In "The 5-year Plan for Establishing Waste Disposal Facilities(8th)" started in 1996, the target for project by the year 2000 is given based on the assumption that the annual growth rate of waste volume per capita is 0.5%.

Moreover, under the Law for Promotion of Separate Collection and Recycling of Containers and Packages that will actually come into force in April 1997, recycling of containers and packages, which accounts for about 60% of the total volume of municipal waste, will be promoted by classifying the role of individuals as follows: (1) Consumers shall cooperate with separate collection of MSW; (2) Municipalities shall collect containers and packages by type; and (3)

Enterprises shall recycle containers and packages collected by municipalities by themselves or subcontract such operations to designated recycling corporations.

(2) Volume of waste and the situations of waste disposal

The total volume of municipal waste was 50.3 million tons in a year (up 0.2% from the previous year) and the daily volume of waste per capita was 1,103 g, both of which have leveled off in the last few years, as shown in Fig. 1.

The rate of intermediate treatment, which accounted for 85.6%(Fig.2), has been increasing steadily year by year. This shows that as the waste treatment facilities have been established, intermediate treatment has been actively implemented. On the other hand, the volume of waste directly landfilled was 7.12 million tons, accounting for 14.4%, which decreased from the previous year(Fig.3).

The volume of recycled waste through separate collection in each municipality totaled 2.2 million tons, showing an increase from the previous year. The volume of recycable waste collected by local residents' organizations was 1.92 million tons. Fig. 4 shows the rate of recycling through resource recovery and group collection in each municipality was 8.0%, increasing year by year.

(3) Waste disposal facilities

As Fig. 5 shows, the number of incineration facilities in 1993 was 1,854, remaining at the same level over the past few years. Table 1 shows a change in the number of facilities according to the type of incinerator. There were 433 continuous type incinerators, 324 semi-continuous type incinerators, 866 mechanical-grate batch type incinerators, and 231 fixed-grate batch type incinerators. Those numbers have hardly changed over the past few years.

There were 2,321 final disposal facilities with residual volume at 149.31 million m³, showing a tendency to decrease(Fig.6).

In order to obtain understanding and cooperation from residents, it is essential to carry out

any assessment. In a growing number of cases, it has become necessary to improve the environment around disposal facilities as well as facilities themselves.

Forming part of such efforts is the building of parks and green zones, swimming pools utilizing heat generated by incineration plants, tropical plant gardens, welfare for the elderly, rehabilitation facilities and city halls and supply of hot water and area-wide air conditioning.

(4) Significance of incineration as a method of intermediate disposal

The basic rule in waste disposal is to reduce waste through resource recovery and recycling, then treat waste with considerations for sanitary and environmental preservation. Since Japan is narrow country, it is difficult to keep sufficient landfill sites, it is common practice in Japan to incinerate waste then conduct final disposal with environmental considerations. Intermediate disposal is an effective and important process where waste can be reduced in terms of weight and volume, stabilized and made harmless. In particular, waste in terms of weight can be reduced to about 1/6 or 1/7 through incineration, thereby contributing significantly to environmental preservation in our daily life. Therefore, about 3/4 of the total waste is currently disposed through incineration.

(5) Use of heat from waste incineration

Heat generated by waste incineration plants is used in various ways; power generation, air conditioning and hot water supply, hot water swimming pools, hot water and energy supply to social welfare facilities like facilities for elderly, and energy supply to local air conditioning. Surplus heat is most widely used for air conditioning and water supply to facilities.

Waste power generation is an effective way of using surplus generated by waste incineration plants. Under the system, thermal energy from high-temperature exhaust gas generated from waste incineration is collected by boilers, which generate steam to rotate facilities.

It is at Nishiyodo Plant of Osaka City in 1965 that surplus heat was first used for power generation. The national government has since promoted power generation by surplus heat. For example, it has extended subsidies to local governments which have built facilities to use surplus

heat when they built new waste incineration plants or renewed existing plants.

As of the end of fiscal 1994, power was produced at 135 waste incineration plants. Total power generation capacity stood at some 450,000 kW, equivalent to the power consumption of about 1.2 million households or Yokohama City. Moreover, 50 to 60 incineration plants sell excess power to electric power companies, accounting for 40% of the plants with power generation (Fig. 7 and Fig. 8)

Guidelines for preventing dioxin generation in MSW treatment

(1) Background

There seems to be diverse sources of dioxin (and the like), as it is generated during combustion of materials. In Japan, the volume of dioxin generated at incineration facilities accounts for 80% to 90% of total dioxin. Therefore, it is imperative that dioxin generated at incineration facilities be reduced.

The Ministry of Health and Welfare set out "Guidelines for preventing dioxin generation" (hereinafter referred to as "Old Guidelines") in 1990 to guide local governments. In response to a suggestion from the public welfare study group to use 10pg-TEQ/kg/day instead of TDI currently used, "The Conference for examining the measures to reduce dioxin in connection with waste disposal" was established in June 1996; and in January 1997, "Guidelines for preventing dioxin generation in connection with municipal waste disposal" (hereinafter referred to as "New Guidelines") were established.

(2) The salient points of the guidelines

New Guidelines, not only to reduce generated dioxin but also to prevent the generation itself as much as possible, aim at adopting the best available technology to prevent adverse effects on our health. In order to reduce dioxin at MSW incinerators established by municipalities, the New Guidelines require the following measures:

[1] Promotion of recycling and Reduction of waste. It is important to reduce the amount of waste to be incinerated by restricting waste discharge and promoting recycling.

[2] Measures adopted against emitted gas.

(i) New incinerators. Incinerators which will be constructed in the future, in principle, must be continuous type incinerators. By setting the standard of dioxin density at 0.1ng-TEQ/Nm^3 , which is at the same level as western developed countries, the New Guidelines show some measures to achieve this standard.

The measures include homogenization of waste content, stabilization of operation load, good combustion practice, low temperature at the entrance of dust collectors, and exhaust gas disposal using advanced technology such as activated carbon absorption.

(ii) Existing incinerators. Measures will be adopted at the following two stages:

○ From the viewpoints of adverse effects on human health, the standard for judging whether emergency measures are necessary or not is given as 80ng-TEQ/Nm^3 , based on TDI at 10pg-TEQ/kg/day . Emergency measures should be implemented immediately at the facilities where the emission density exceeds 80ng-TEQ/Nm^3 . The measures include appropriate combustion management, changing from intermittent operation to continuous operation, improvement of facilities (such as changing from electric precipitators to fabric filter dust collectors), and suspension of operations or closure of facilities.

○ From the viewpoint of adopting the best available technology, even when the emission density is less than 80ng-TEQ/Nm^3 , permanent measures will be adopted systematically, with an aim towards achieving the following standards through the similar measures adopted for new incinerators. Under the Old Guidelines standards for existing incinerators are: 0.5ng-TEQ/Nm^3 for continuous type incinerators, 1ng-TEQ/Nm^3 for semi-continuous type incinerators, and 5ng-TEQ/Nm^3 for intermittent operation incinerators.

[3] Broader-based waste disposal. As combustion in small-scale intermittent running incinerators is unstable, it is difficult to adopt measures against dioxin. Therefore, neighboring municipalities work in cooperation to put them together for combustion in large-scaled continuous type incinerators. In order to actualize this, each local government will establish the broader-based project for waste disposal; and based on the project, each municipality will promote broader-based waste disposal regardless of the municipal boundaries.

[4] Disposal of bottom ash and fly ash. In order to reduce dioxin from bottom ash and fly ash, the decomposition treatment, such as melting solidification method, should be promoted.

[5] Measures adopted at landfill sites. The measures, such as soil capping, and reduction of the SS of leachate from disposal facilities, will be implemented at final disposal facilities in order to prevent scattering of bottom ash and fly ash which may contain dioxin.

[6] Follow-up measures. In order to steadily, promote above-mentioned measures it is indispensable to adopt follow-up measures as well. In each municipality, density of dioxin generated at incineration facilities must be measured on a regular basis (once a year in principle), the results of the measurement must be announced publicly, and the measures adopt must be constantly reviewed.

The Ministry of Health and Welfare will provide guidance to local governments in promoting the measures to be adopted against dioxin based on the New Guidelines.

Measures adopted against dioxin, and waste disposal system in the future

(1) Broader-based waste disposal

Each municipality has responsibility for municipal waste disposal. Therefore, in general, disposal of waste was performed within each jurisdiction. However, due to the transition to recyclic waste treatment and the advanced technology in waste disposal, it is also necessary to discuss the broader-based waste disposal. In particular, in local areas, when pursuing the following measures such as (1) the promotion of recycling, (2) the promotion of incineration and the maximum utilization of the residual heat, and (3) the implementation of measures against dioxin.

In short, we are now entering a period of revolution of the waste disposal system. Therefore, as shown in Fig. 9, measures adopted against dioxin are closely related to the waste disposal system as a whole in the future.

(i) Promotion of recycling. Compared to the current situation where facilities are located in

different areas, a broader-based system will facilitate recycling, as recyclable material can be collected at one place. This leads to a reduction in the volume of waste to be incinerated. Moreover, based on the Law for promotion of recycling of containers and packages, collection by type will be actively implemented; thus, it would be possible to recycle containers and packages on a broader basis.

(ii) Promotion of incineration and the maximum utilization of the residual heat.

Combustible waste excluding material recycle waste should be incinerated as much as possible, thereby reducing the volume of waste for final disposal. The utilization of the residual heat results in the continuous operation of incinerators; in addition, thermal recycling enhances the conservation of primary fuel. This will eventually reduce the generation of greenhouse gases.

(iii) Measures adopted against dioxin. The New Guidelines state that incineration facilities, which will be constructed in the future, must be continuous type incinerators to reduce the quantity of dioxin. In order to employ continuous type incinerators, a certain volume of waste, in other words, a certain scale of population is required. Therefore, in a sparsely populated area, a broader-based system is necessary.

(2) Considerations for broader-based waste disposal

When broader-based waste disposal is carried out, a high cost as well as the measures beyond municipal boundaries will be often required. Therefore, each municipality must include the measures against dioxin in their respective waste disposal projects, adjust the measures between neighboring municipalities, and promote broader-based efforts toward systematically solving dioxin problems. For a well-balanced broader-based waste disposal, prefectural governments are required to adjust the measures between municipalities.

When examining broader-based waste disposal, it is necessary to consider the following matters: a scale for the broader-based waste disposal, timing for implementation, selection of a site where incineration facilities will be established, a combination with other facilities, preparation of various elements for implementation, effects of broader-based waste disposal and evaluation, and the methods for implementation.

(3) Broader-based waste disposal using RDF

When waste is disposed as proper RDF, it has a more stabilized quality than waste itself, thereby facilitating combustion control. Moreover, as RDF can be stored in a stable form over a relatively long period, RDF produced at each RDF facility can be collected at one place, used as fuel, and incinerated.

Therefore, because of these characteristics, the introduction of RDF facilities is highly recommended in the following cases:

- (i) The case in which the transportation of waste is problematic since incineration facilities are located far away as a result of broader-based waste disposal;
- (ii) The case in which the geographically condition make the implementation of broader-based incineration unfeasible (such as a solitary island); and
- (iii) The case in which the utilization of RDF is widely promoted.

(4) Follow-up measures

In order to implement the above-mentioned measures steadily, follow-up measures must be adopted on a continuous basis. For this purpose, municipalities and prefectural governments must make concerted efforts; as a nation, it is necessary to review the state subsidy for waste disposal facilities with focusing on recycling, broader-based waste disposal, and disposal employing advanced technology.

Conclusion

In 1996, total discharge of dioxin from municipal waste incinerators is estimated about 4300g-TEQ/year. By taking measures against existing incinerators, constructing new full-continuous type incinerators, putting small-scaled facilities together, introducing RDF plants ,etc. It is possible to reduce most of discharge as Fig.10. Since it is said that discharge of dioxin from municipal waste incinerators occupies 80~90% of total, we expect that total concentration of dioxin in environment and our daily intake of dioxin will be greatly reduced.

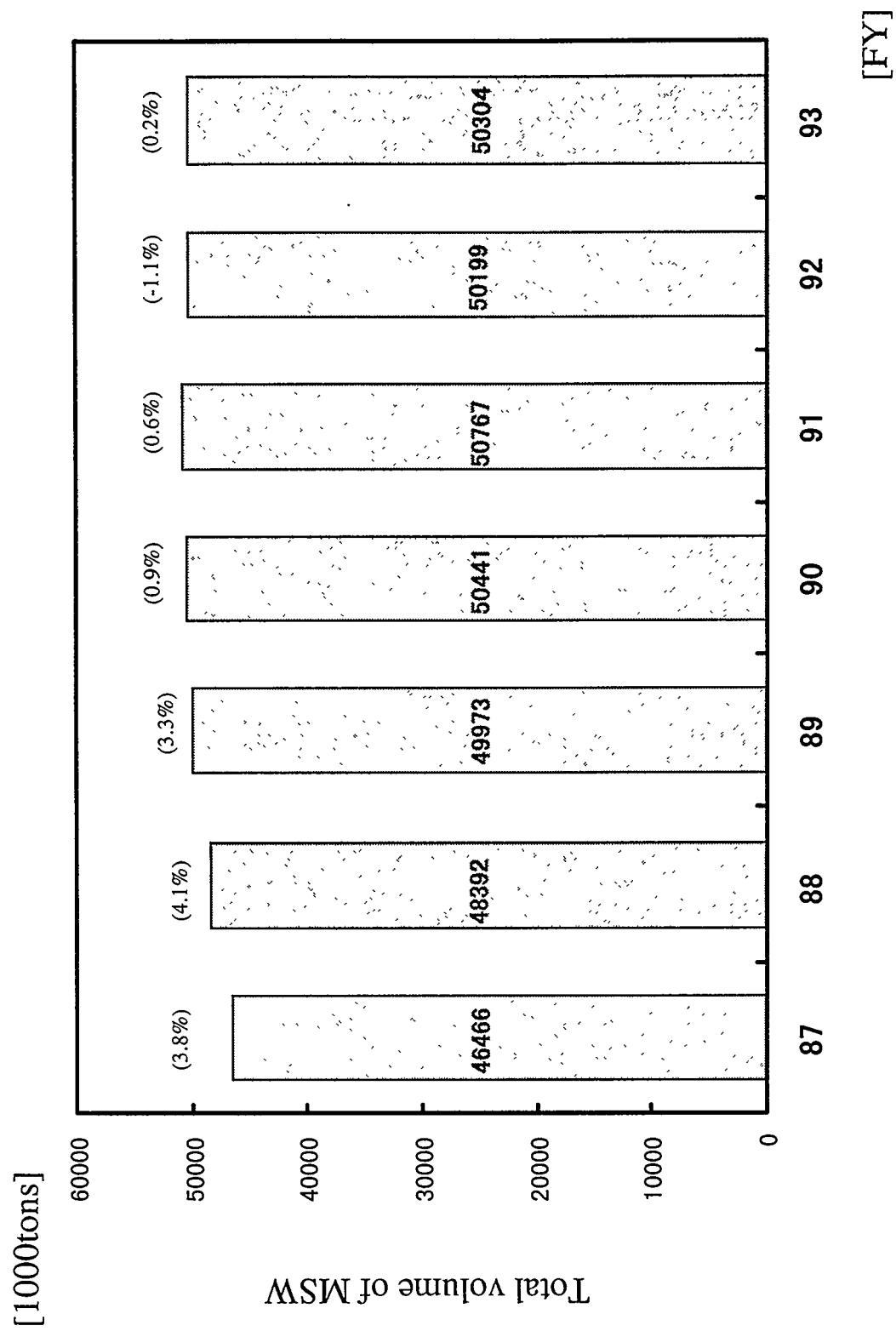


Figure 1. Change in total volume of MSW

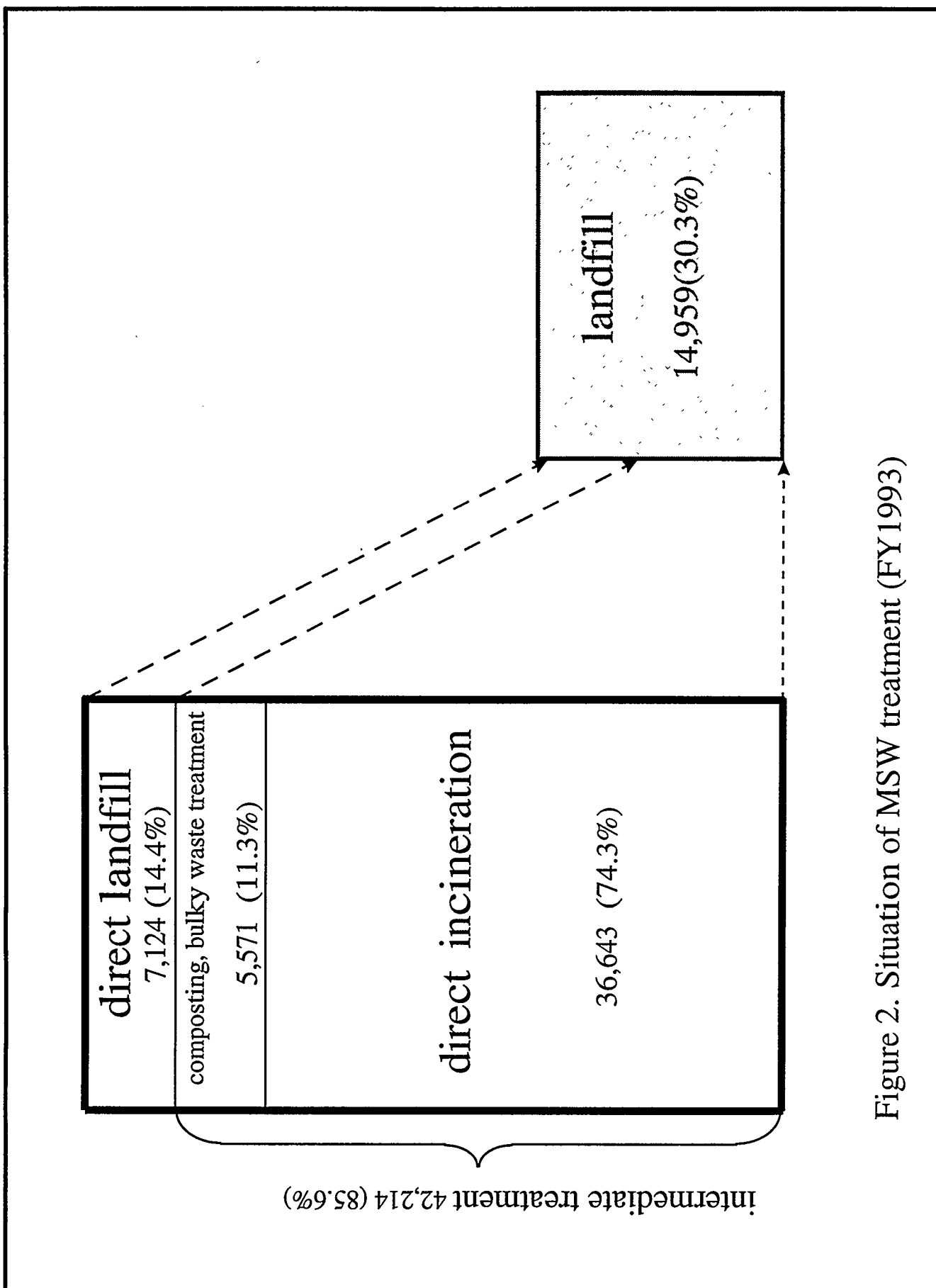


Figure 2. Situation of MSW treatment (FY 1993)

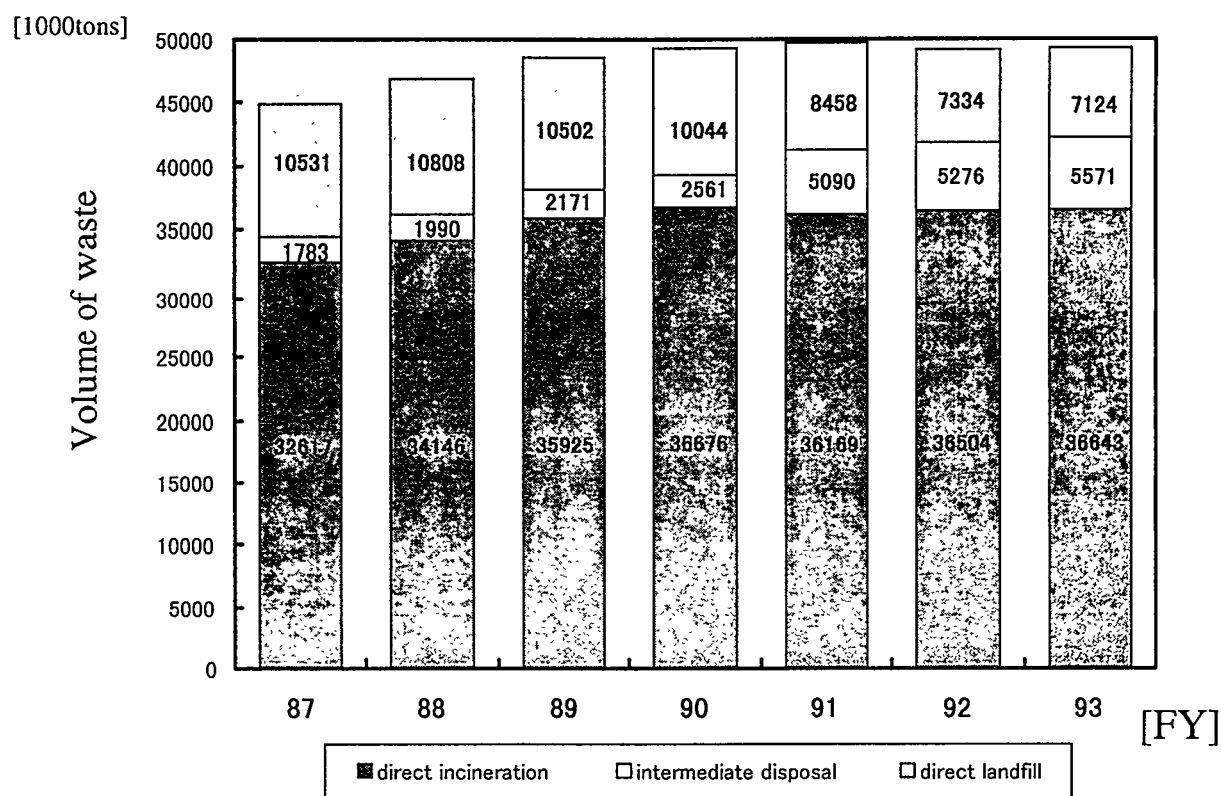


Figure 3. Change in method of waste treatment

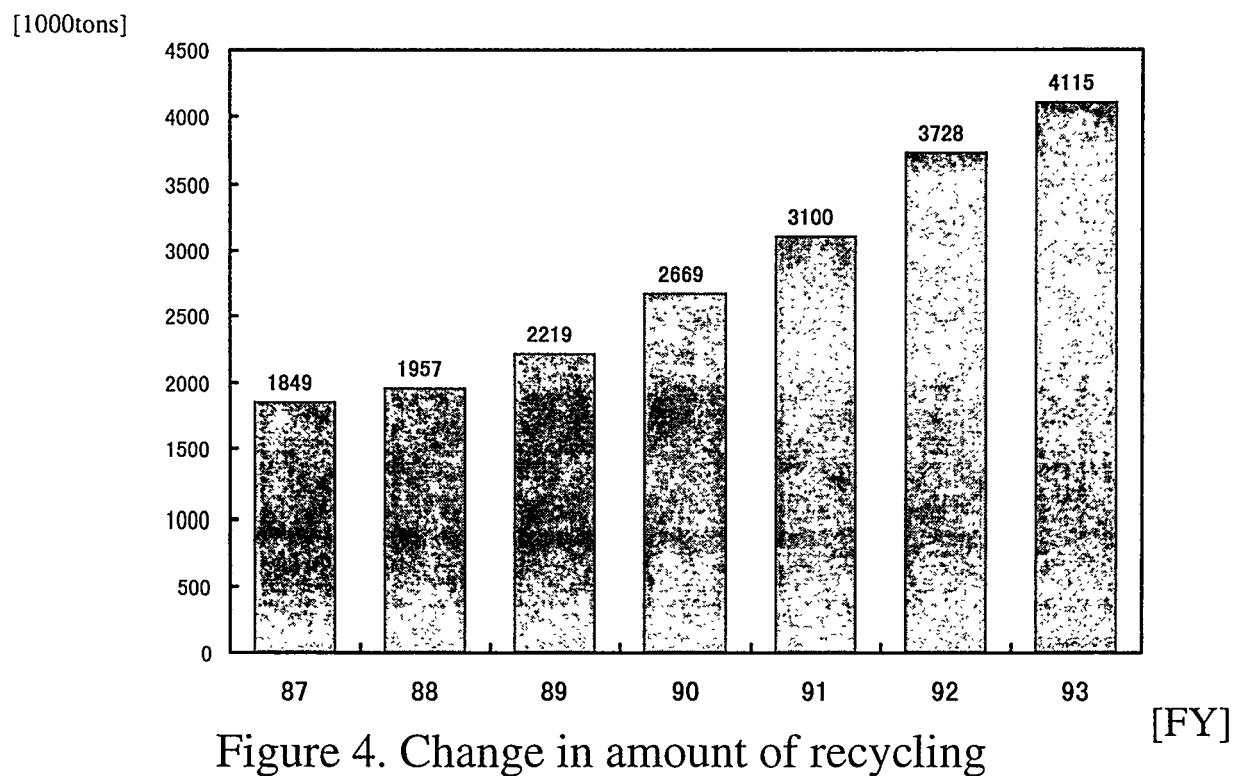


Figure 4. Change in amount of recycling

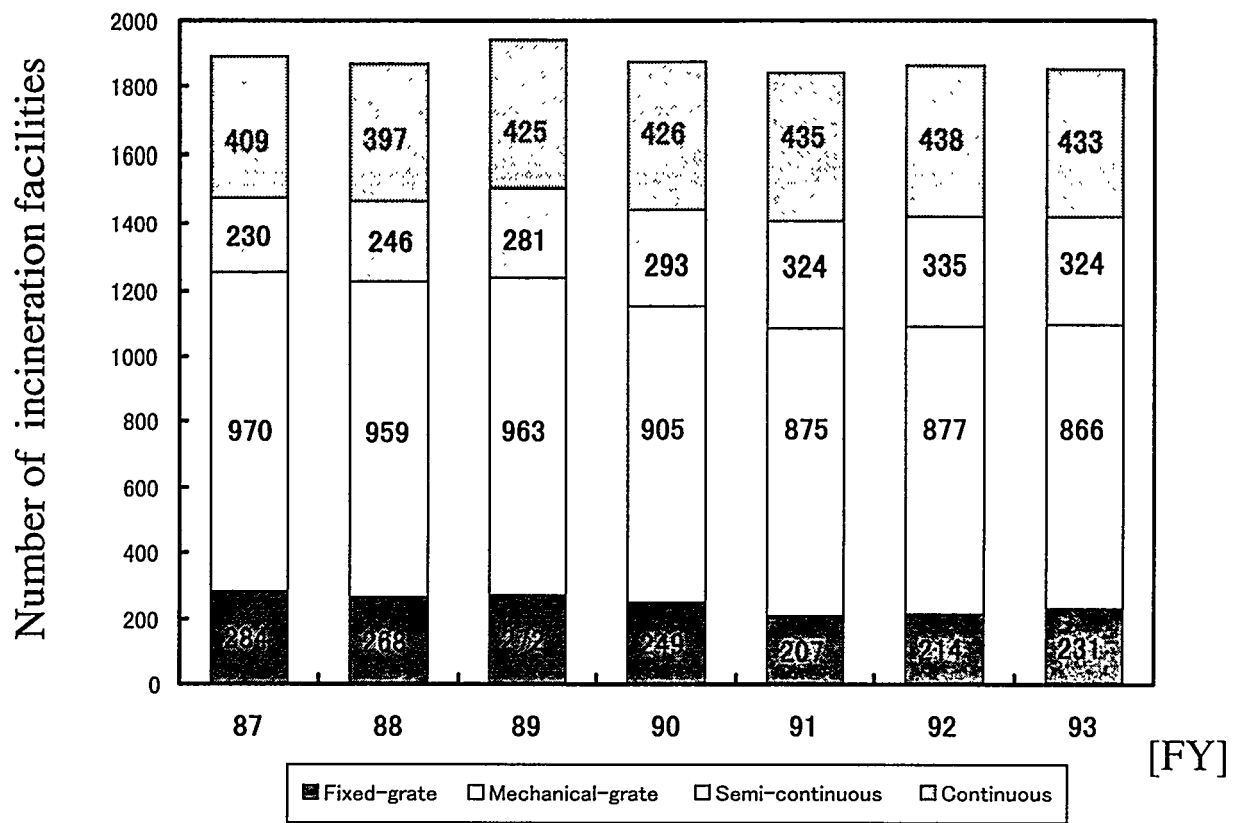


Figure 5. Change in number of incineration facilities

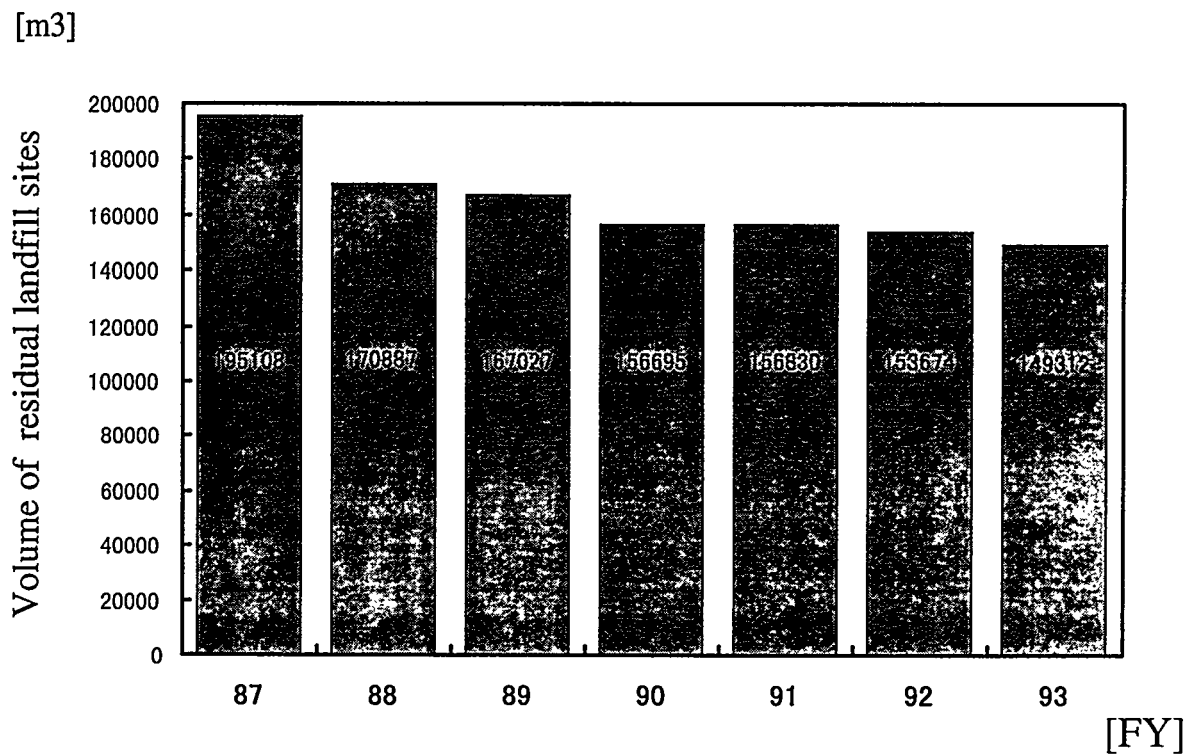


Figure6. Change in residual volume of landfill sites

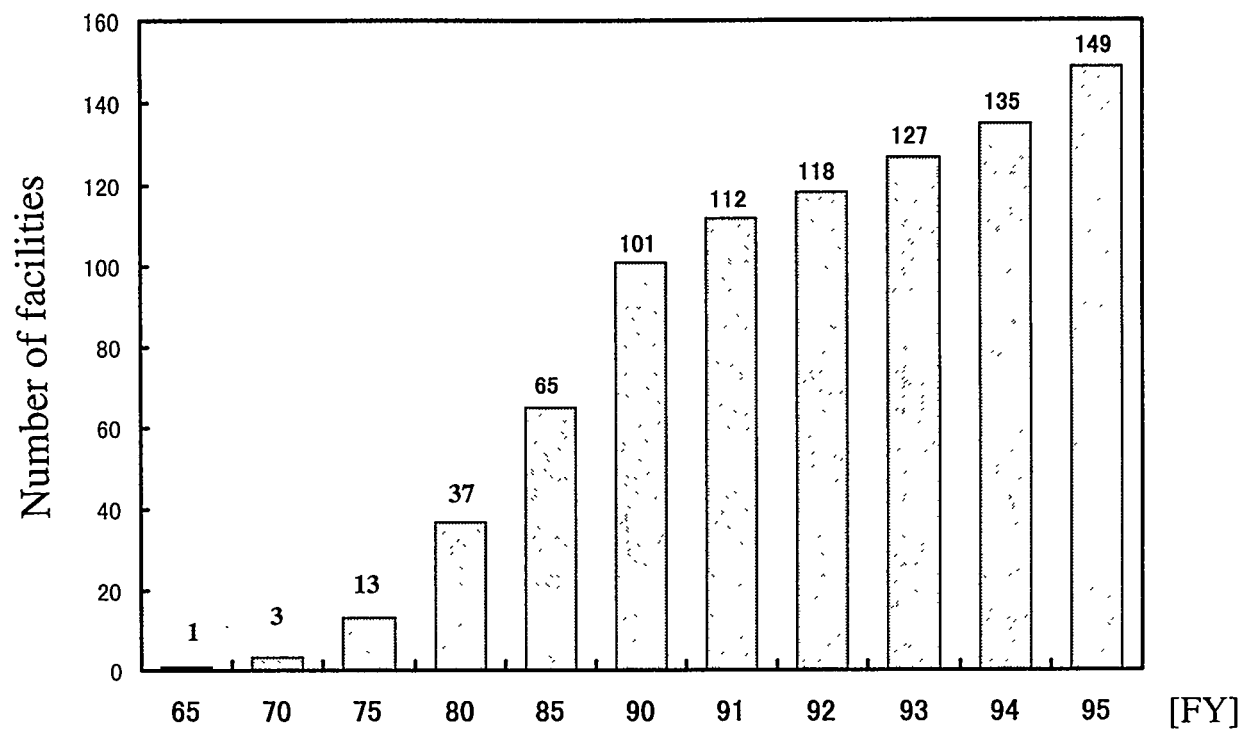


Figure 7. Change in number of facilities with Power Generation Equipment

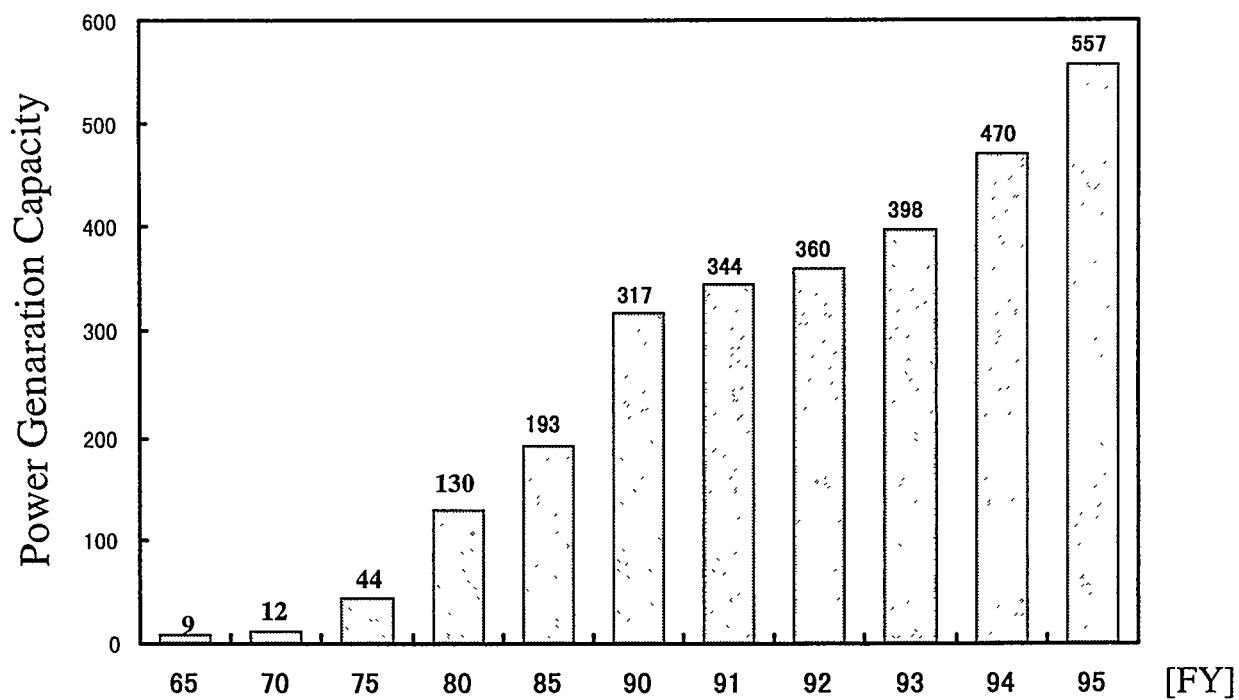
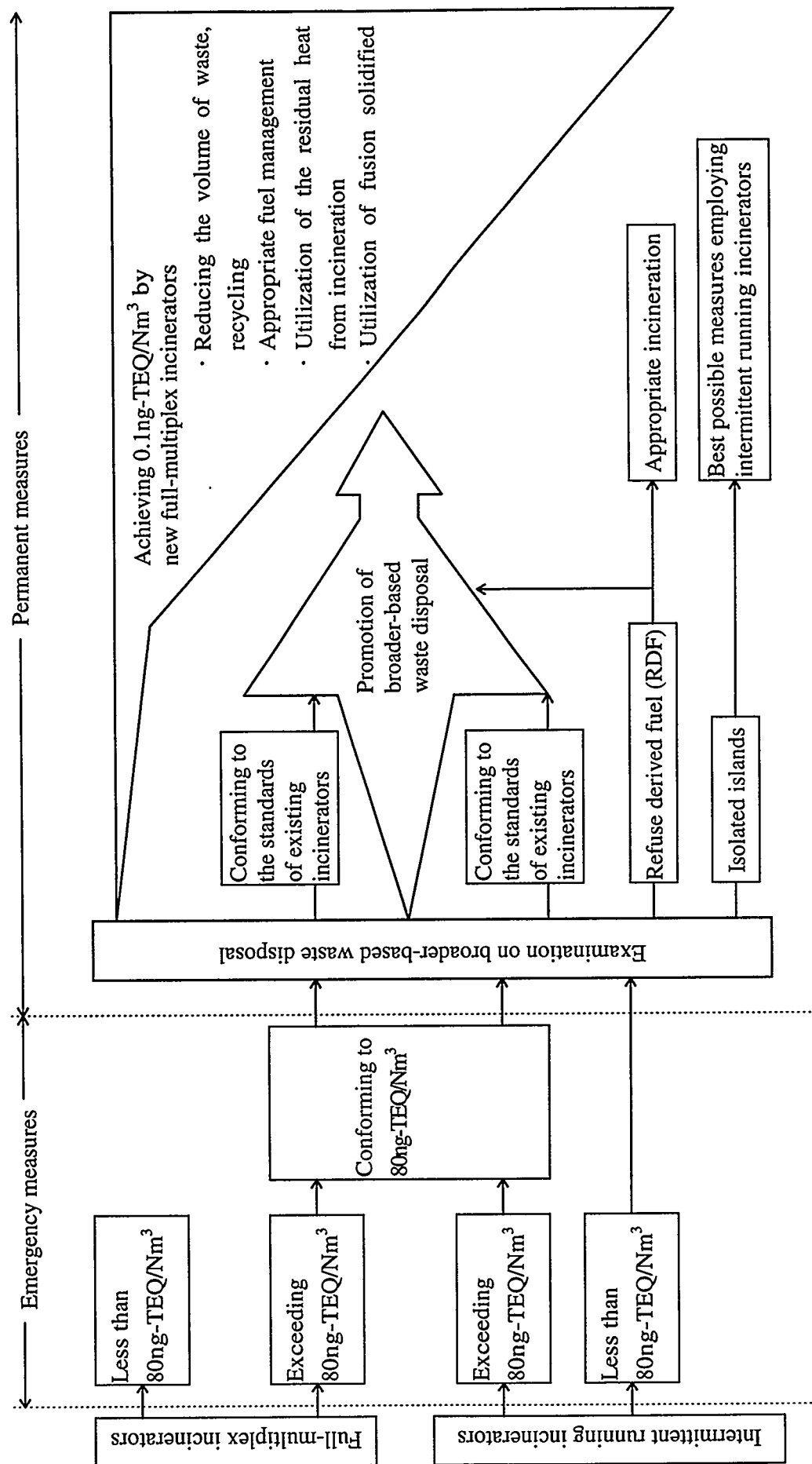


Figure 8. Change in Power Generation Capacity of waste incineration facilities

Fig. 9 Waste disposal system in the future (Promotion of measures to be adopted against dioxin at incineration facilities)



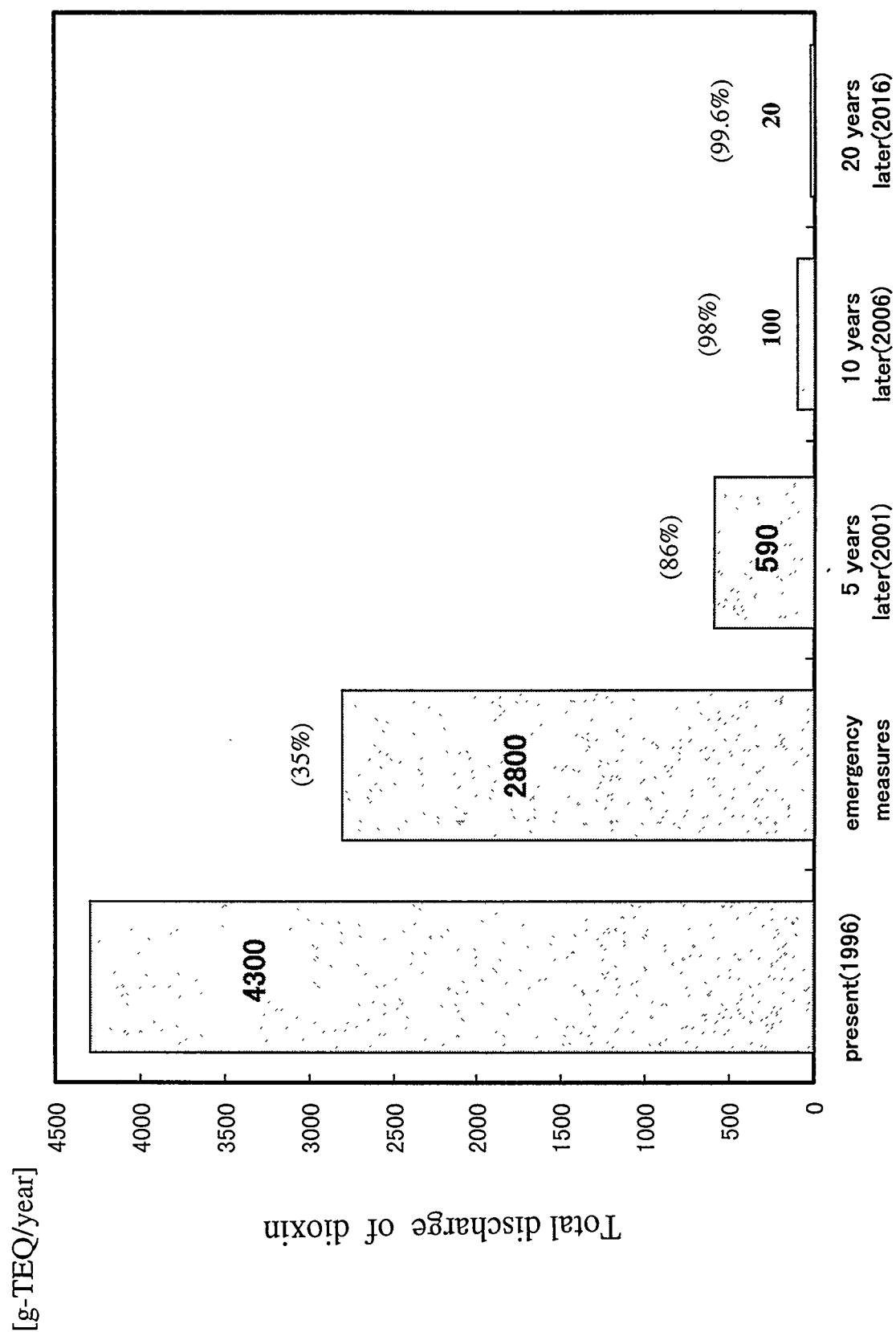


Figure 10. Total discharge and reduction rate of dioxin

TECHNICAL SESSION II

*Emerging Issues &
Technologies*

How Big Should a New Energy Recovery Facility Be?

A. John Chandler
A.J. Chandler & Associates Ltd.
12 Urbandale Avenue
Willowdale, Ontario, Canada M2M 2H1

INTRODUCTION

Careful attention must be paid to characterizing the municipal waste stream, both now and in the future, if the capacity (size) of waste management facilities are to be optimized for economic and environmental benefits. This is particularly important for municipal waste combustion facilities where significant capital expenditures are required before any waste can be handled. Too large a facility can bring undue financial strain; too small a facility will create a need for more landfill capacity reducing the potential benefits of energy recovery and increasing the long-term release of methane, a potent greenhouse gas, from these materials.

Modern waste management systems seek to obtain a least cost solution while maintaining environmental objectives. To meet these requirements, modern systems include elements of reduction; diversion through recycling or reuse; and disposal, including energy recovery and landfilling. The exact proportion of materials handled by each of these alternatives is a function of the characteristics of a community's waste stream and the economics of applying the various alternatives. Managers need to evaluate the concerns of local citizens to arrive at the best solution for their community. More and more, these managers are coming to appreciate that waste is like any other commodity in our society—it creates a monetary dynamic that influences management decisions.

As more waste is generated, municipalities can move to modify the system by raising tipping fees or taxes, but this can have undesired effects. For example, several years ago Metropolitan Toronto increased landfill tipping fees for commercial users. In response, these users simply transported more waste to the United States. Local revenues dropped and the overall public cost of waste disposal increased because commercial revenues no longer offset comparatively expensive local recycling programs. In addition, the reduced rate of landfilling delayed closing of some landfills because materials were no longer available to complete the closure plan.

Other examples of unexpected results from interventions in waste management systems can be cited. The German "green-dot" system sought to separate consumer packaging from the waste stream by requiring that manufacturers deal with these materials. This did not reduce the cost to society—it merely shifted the point of payment. The "green-dot" system led to a glut of material on the recycling market. In October 1996, Germany enacted the Closed Cycle Economy Law. This law put material recycling and waste combustion with energy recovery on an equal footing. The recycling industries that grew over the past few years in response to the artificially created need to recycle materials irrespective of cost or true societal benefit may now face economic ruin as waste flows to the most cost effective management alternative.

Different waste management alternatives can also be selected to address environmental concerns, but these selections can also effect the ultimate mix of waste disposal options. For instance, European countries are moving towards limiting the level of carbon in waste deposited in landfills to minimize both future ground water pollution and greenhouse gas emissions. In turn, this is increasing the demand for waste combustion with energy recovery.

The suggestion that municipal waste combustion (MWC) with energy recovery might become part of a community's solid waste management system usually draws negative response. Some of the criticisms originate from genuine concerns about the effects such projects might have on the environment and human health. Other criticisms are based on the belief that incinerators, a major capital expense, will become a financial burden to an unwary community. Some even suggest that incineration will encourage a sense of complacency among those who should be striving to reduce the volume of the waste stream. Since the MWC must have enough fuel for economic operation, this last argument goes, MWCs discourage 3-R activities--reduction, reuse and recycling--by requiring all the available MSW to feed its insatiable appetite.

Many of these concerns have a basis in fact. Comparatively higher emissions characterized many older MWCs; however, state-of-the-art facilities now have such low emissions that conventional stack testing methods must be modified to even detect emitted compounds. Excessive costs characterize facilities built on unreasonable expectations (i.e., future waste growth, explosive energy price increases, or technically impossible performance). Creative analysis of the amount of waste that can be diverted through innovative 3-R initiatives are frequently used to support the theory that there is not enough material for all management options to co-exist. This argument falsely presumes that no prudent amount of MWC capacity can co-exist with 3-R activities in a given waste shed.

While most people would like to select the optimal set of waste management alternatives for their community, they are faced with the problem of determining the highest or best use of the materials in their waste stream. There are, unfortunately, no universally acceptable standards for making this decision. This evaluation uses a responsible and prudent guideline — build MWCs to handle what is likely to be left after application of the 3-R's — to reach the conclusion that MWCs and the 3-R's are compatible as long as the materials and resources which have a higher and better use are reduced, reused, or recycled instead of being recovered (incinerated at an energy recovery facility). This paradigm leads to the conclusion that it is certainly safe to build MWC capacity equal to half a waste shed's current disposal needs and it is probably justified to equal today's disposal requirements.

MUNICIPAL SOLID WASTE CHARACTERISTICS

The starting point for estimating future effects of various 3-R strategies is a comprehensive picture of today's waste stream. The amount and nature of solid waste generated in a community depends not only on population, season and business economic cycle, but also the demographics of the community. The 1991 Gore & Storrie study¹ of MSW composition and generation rates in different Ontario communities clearly shows these effects.

Not only is it necessary to know what is in the waste stream, but it is also necessary to know how much material is already being removed. Projections of waste and composition over the planning cycle must account for these factors, especially since they form the basis for evaluating management options. The potential effects of reduction, reuse and recycling initiatives must be combined with the future quantity estimates to establish the amount and characteristics of the residual (post 3-R) waste requiring management.

Composition

Most people associate MSW with the materials discarded directly by households. However, in actual practice, it also includes the employment related solid wastes discarded by industrial, commercial and institutional (ICI) sources. Such material resembles the residential waste stream because it contains newspapers and magazines, beverage cans, and food wastes. Process waste streams coming from industrial sources like foundry sand, prompt (in-house) steel making scrap and chemicals, etc. are not usually considered to be MSW. Construction and demolition debris (C&D) is MSW only in a very general sense, since the characteristics of the debris are so different from household wastes. Consistent with the pioneering work done by Bird and Hale² to characterize municipal discards in Canada, in this paper we consider only the residential and ICI wastes that would be targeted for reduction, reuse, recycling and, lastly, recovery.

Only limited field data exists for Ontario waste composition; there have been few published reports of detailed waste stream evaluations in Ontario after 1980. As a starting point in this evaluation, Ontario based data were modified using information from various other studies that characterized 3-R materials to account for changes that have occurred since the base data were gathered. Incidentally, since most of Canada and the United States share a generally common heritage and have many common expectations, the MSW streams are generally similar.

The Bird and Hale baseline data represents the composition of MSW in the late 1970s. Recognizing that changes in the economy and the use of different materials leads to a changing mix in the waste, it is necessary to adjust the 1980 figures for both effects. Using the sectorial generation rates from Franklin Associates³, the 1980 levels were escalated to 1990. These were then adjusted using The WASTE Program⁴ data, a sampling and analysis program undertaken in suburban Vancouver, British Columbia in 1991 which developed a comprehensive picture of waste received at an MWC. However, since The WASTE Program's data include the effect of Vancouver's successful blue-box program, this influence was factored out. Next, using the results of the year-long 1990 multi-borough sorting study in New York City⁵, the Vancouver composition information was adjusted to reflect gross discard levels. The resulting estimated 1990 municipal solid waste composition for Ontario is shown in Table 1. The projected distribution of materials in Ontario's 1990 MSW stream shown in Table 1 are generally consistent with the 1991 Gore & Storrie results for the residential solid waste sampled in southern Ontario.

Table 1 contains projections of the waste stream composition for both the years 2000 and 2010. The waste mix changes over the years due to differences in sectorial generation rates. A good example of the effects of the sectorial generation rate shifts is the increased amount of plastic in the 1991 waste stream compared to that present in 1980. This has been matched by a decline in glass and ferrous metal packaging over the same time period.

The analysis in this report deals solely with changes that will occur in the composition and quantity of 100 kg of waste placed at curbside in 1990 as compared to that present in 2000 and 2010. It assumes that trends in waste generation seen over the past decades will continue; however, it also reflects changes in society's willingness to divert material from the disposal alternative.

The percentages in Table 1 represent the proportion of the individual components present in either the Gross or Net Discards. To calculate the Net Discards, the Gross Discards level outlined in the preceding paragraphs was adjusted to reflect recycling rates. The Gross Discard rates were adjusted for each of the subsequent periods to develop the basis for estimating waste composition at those times. An additional factor, population growth, has been disregarded in the present analysis. The Gross Discards in 1990 would have been 114 kg for every 100 kg of solid waste placed at the curb. By 2000, the Gross Discards are projected to grow to 128 kg and by 2010 to 145 kg of solid waste. The Net Discards for these periods will vary as a function of the success of diversion programs.

Impacts of Reduction, Reuse and Recycling

Reduction, reuse and recycling all conserve resources and minimize the amount of material left over for ultimate disposal. Various strategies exist to accomplish high diversion rates. For example, Table 2 includes British Columbian data which suggest that high deposits on containers result in excellent recovery rates. We have assumed that recycling could expand to look more like the British Columbia situation.

We have also assumed that recycling will increase from today's level. Present recycling rates can be characterized as the median rates from the 1991 Gore & Storrie study in Ontario. Estimates of the potential extent of recycling extend to between the low and the high recycling estimates for the year 2000 prepared by the USEPA and used in their Report to Congress, but could be further extended to include those identified by the Center for the Biology of Natural Systems (CBNS) that suggests higher rates are possible by 2010.

If entire communities are as motivated as true believers, and cost is not a consideration in an era of competing demands on public funds, the major difference between the high and low estimates is the inclusion of more types of recycled materials in later years. By 2010, 25% of the books, boxboard, diapers and mixed paper and 37% of the assorted plastics in categories 3 to 7 might be recycled. Also, half the wood and lumber and food wastes are assumed to be diverted by 2010. Achieving these recycling rates is dependent upon many things, not the least of which is the technical and economic feasibility of recycling some of these materials. Some of these considerations are contained in the following section.

Recycling Combustibles. Combustibles are the part of the municipal solid waste stream. They are broadly classified as:

- forest products (paper, cardboard and boxboard),
- derived from fossil fuels (plastics and waxes),
- yard and garden waste (grass, leaves, brush, stumps, etc.),
- food preparation waste (garbage for want of a better word), and
- textiles.

Paper Products. As may be expected, each time paper is recycled, some of the fibre is lost because it becomes too short to be recovered. The remaining fibre is somewhat oxidized causing it to lose some of its strength and become more brittle. Consequently, there is a limit to both the number of times fibre can be recycled and the amount of recycled fibre that can be used in new paper products without

seriously degrading the product's properties. It is estimated that 15 to 25% of the recycled paper volume will end up as waste from the process⁶. This reality implies that it is not necessary to worry about recovering 100% of the paper products; only a certain amount, albeit a large fraction, of recycled fibre can be utilized even after worldwide fibre recovery capacity is fully expanded.

Plastics. Plastics are also recyclable combustibles. While research is underway to develop processes which can dissolve mixed plastics and recover their individual resins, the current method of recycling is to physically separate the recovered items by plastic type and colour for reuse. Thus, today's recycling methods address the relatively pure plastics used in packaging and food service applications, but they do not manage engineered plastics used in housewares and toys. They also do not address the special plastics found in video tapes, records, disks and diskettes. Current initiatives will likely lead to new technologies; but for the foreseeable future, a residual, not readily recyclable, plastics stream is likely to remain.

Textiles. This category is made up of textiles, rubber and shoes. The amount of rubber is small and includes tires, inner tubes, hockey pucks and soccer ball bladders. There is a ready market for used natural and synthetic textiles, so much of this category can be recycled. We are unaware of any use for worn-out shoes and know that they do not readily compost.

Yard and Garden Waste. The grass component is made up of grass and leaves and the simple expedient of using a mulching mower or having a back-yard compost heap (provided they are legal and properly operated to avoid nuisances) will eliminate much of this category. The brush category includes stumps, trunks and branches. While these may be usable in fireplaces, a substantial chipper is needed to convert this material into mulch or bulking agent for composting so collection is the most likely alternative for most of this material. The wood category can be similarly chipped and used if it is not impregnated with fungicides or coated with lead based paints.

Recycling Noncombustibles. Metals and glass are readily recyclable provided they are separated into marketable categories. Aluminum and tin cans are very high grade feed stock for making new aluminum and steel products. Other metals, like copper wiring and brass plumbing fixtures, are also recyclable once any organic coatings are removed.

While there are limited uses for mixed colour cullet in glass making, colour sorted glass has a much wider use. The market for coloured glass is limited. It is not used as much in North American packaging as it is in Europe and importing products in green and brown glass containers to North America leads to an accumulation of these materials.

Projections of Waste Composition and Quantity

As the foregoing shows, there is a wide potential for employing various techniques to reduce the MSW stream. Forecasting the characteristics and quantities of future MSW streams is not an exact science. Indeed, for the purposes of this assessment, precisely defining the future is unnecessary. Rather, we should use the estimated extremes to bracket future reality. Thus, the results presented here represent reasonable bounds for levels of reduction, reuse and recycling likely to be achieved by the years indicated.

The recycling rates shown in Table 3 include an allowance for both contaminated materials which become dirty through reuse and are not suitable for recycling and for the proportion of people who, after any amount of education and inducement, simply will not or do not comply with the recycling guidelines. Figure 1 estimates MWC composition and the changes in discard quantity over time:

- In 1990, every 100 kg of MSW at the curb would represented an average of 114 kg of waste generated.
- By 2000, the Gross Discards will be 128 kg. Depending upon the level of recycling achieved, between 92 and 61 kg will remain to be set out at the curb.
- By 2010, Gross Discards will rise to 145 kg. Again, depending upon the level of reduction, reuse and recycling achieved, between 103 and 53 kg will remain for ultimate disposal.

Because the estimates bracket the range of anticipated diversion effectiveness, we would not expect to have more post 3-R waste than is shown in Figure 1 under the low recycling (high net disposal) scenario. Nor would we expect to have less post 3-R waste than is shown under the high recycling (low net disposal) scenario.

Figure 2 shows the composition of municipal solid waste in 2010. Extensive 3-R management activities are expected to remove between 35 and 70 kg of paper for every 100 kg of waste currently discarded. The amount of food waste will be cut in half, to some extent as the result of less spoilage and wastage due to improved packaging, and the balance due to composting and in-sink garbage grinders. Material that is not diverted does not lend itself to alternative disposal. Either it should not be composted in residential settings (meat scraps and fat attract vectors and scavengers and create a public health problem) or it is bones and the like which do not compost well. Glass recycling is projected to increase as is the recycling of plastic containers and films. Yard waste is expected to be substantially reduced through the use of mulching lawn mowers, backyard composting and separate municipal collection of yard waste. Textiles will be recycled as well.

Having developed a description of the MSW stream in 2010, the issue of using MWC technology can be addressed.

INCINERATION'S PERCEIVED EFFECTS ON THE PUBLIC'S MOTIVATION TO CONSERVE

Incineration, whether in an energy recovery facility or in a mass destruction box, can be viewed as a simple solution to solid waste disposal. With an MWC available, people may feel that they do not have to participate in recycling programs because their waste is being volume-reduced prior to landfilling. Also, if an incinerator is available, the public is aware that existing landfill capacity can be extended by a factor of 5 to 10. As a consequence of this perception, many 3-R supporters feel that if incineration is encouraged, a moral incentive to reduce, reuse, and recycle is removed.

Incinerators are also perceived as insatiable monsters. This historical perception is the result of the method of financing prevalent in the United States. Many, if not most, U.S. incinerators are industrial

revenue bond financed. As part of the financing package, the users pledge to deliver enough waste to the facility to keep it full. This pledge, when coupled with an energy purchase contract and technical (performance) guarantees, provides, in effect, a revenue guarantee that secures the debt. Thus, the basis for the argument, "If the 3-Rs are promoted, these communities face financial ruin because the anticipated revenues are not realized".

While the existence of these perceptions cannot be disputed, the reality is that as long as the MWC is properly sized, there is no conflict. The facility cannot process waste beyond its capacity, so 3-Rs are needed to extend landfills to the greatest extent. Also, in a comprehensive waste management system, the MWC recovers energy that would otherwise be lost and acts as a final hurdle for solid waste to clear before burial. Properly sized, incinerators ensure maximum recovery of materials and energy and minimum depletion of the landfill resource.

Effect of Changed Solid Waste Composition and Fuel Properties

Table 3 is a summary of the post 3-R discards fuel properties. These were estimated by combining individual component properties in proportion to the amount of each present. As diversion strategies are implemented, the first impact is to remove non-combustible recyclables. This has the effect of reducing fuel ash content and increasing the heating value. As diversion implementation continues, combustibles like paper and are targeted. These remove energy content and also reduce ash levels so the net impact is only a slight decrease in heating value. Assuming an extensive, CBNS type intensive diversion effort is put in place, the projected heating value actually rises because a relatively greater percentage of the waste is engineered and other plastics which do not presently have technically viable recycling options.

As the fuel properties change, so does the sustainable capacity of the incinerator facility in tonnes per day. The energy recovery capacity is fixed by the boiler design and physical installation, only so many joules of energy can be fed to the system within a given time frame. Changes in waste composition and waste chemistry result in changes in daily throughput capacity. In terms of tonne per day nameplate capacity, an incinerator built for today's waste will only handle 91-95 percent of the designed tonnage if it is being fed the year 2000 waste mix and 90-98 percent of design tonnage when fed the year 2010 mix. The residues produced, including moisture added for dust control and lime from the acid gas control system, will decrease 8 to 10 percent with low levels of recycling and increase 15 to 40 percent with high recycling rates compared to the residue generated in 1990.

COMPATIBILITY ASSESSMENT

As the 3-Rs are implemented, less material remains to be incinerated. The bottom line is that even if we can afford and induce the general public to reduce, reuse and recycle waste to the extent contemplated by advocates of CBNS, we will only reduce the amount requiring ultimate disposal to 1/3 to 2/3 of the amount generated before application of the 3-Rs. That is, an MWC designed to recover the energy content and recycle the residual metals and ash from about half of today's collections will likely still be needed in 2000 and 2010 under the most aggressive scenario analyzed. In reality, a capacity equal to today's net discards may actually be needed to accommodate the residual waste stream after reasonable diversion efforts.

Another way to look at prudent capacity is to ask how much of the residual solid waste collections (not picked up as a part of a 3-R program) will be needed to support a plant designed to handle today's solid waste stream. Answering this question requires considering the changes in waste fuel properties as a result of 3-R implementation and changes in waste characteristics over time.

The fuel properties govern how much solid waste can be burned in an incinerator because these systems are not tonnage devices, they are usable energy devices. An energy recovery incinerator cannot consume more waste than its energy recovery equipment is capable of removing. While contrary to convention, EFW's should be rated in kg/h of steam raised or mWe generated, not tonnes per day.

Figure 3 illustrates the effect of recycling and changing fuel characteristics on heating value. Note that, regardless of the level of recycling accomplished, the energy value increases between 1990 and 2010. Municipal solid waste has been changing. In the early 1980s, 10,500 kJ/kg (4,500 Btu/lb) was considered a typical heating value for as-discarded MSW. Today, we believe that MSW typically displays a heating value around 12,800 kJ/kg (5,500 Btu/lb). As 3-Rs are implemented, the heating value is expected to continue to rise. The increase in heating value, however, is from around 12,800 kJ/kg (5,500 Btu/lb) to around 14,000 kJ/kg (6,000 Btu/lb) — an increase that is much less than that already successfully handled by operating MWCs. At the same time, the ash content of as-discarded MSW will rise or fall depending on the effectiveness of 3-R programs with increasing effectiveness resulting in more ash which translates to more residue.

Figure 4 shows that a plant designed to process 100 TPD of as-collected municipal solid waste today will be able to process between 90 and 95 TPD of as-collected MSW in 2000. The exact value depends upon the extent of 3-R implementation and its impact on the final fuel properties. That same plant will be able to process between 90 and 98 TPD of as-collected MSW in 2010.

CONCLUSION

This paper provides a projection for the amount and composition of waste likely to be available in future years from a fixed population. The projection shows that under the low recycling scenario, if incinerator capacity equal to today's generation rate were built, recycling would accommodate the growth in waste production. If we take the high recycling rate projection, a need will remain for managing about half the waste that is currently being put out at the curb.

These projections do not account for widening the waste shed area, nor do they account for increases in population between now and 2010. The projections suggest that reasonably sized incinerator facilities can co-exist with even the most intensive recycling, reduction and reuse activities.

If we were to build enough capacity to recover the energy in half the waste collected today, that capacity should remain full into the foreseeable future. Even with maximum 3-R implementation, some waste will still go to the landfill without energy recovery and unrecycled metals will be lost to the disposal site. With minimum expected 3-R implementation, incinerator capacity equal to today's disposal will be needed instead of the half indicated under the maximum 3-R scenario.

Certainly reasonable amounts of energy recovery capacity, say equal to half of today's discards, will be needed, regardless of the success of 3-R programs.

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Table 1. Estimated MSW composition for Ontario in 1990 and subsequent years.

PARTITIONED CATEGORIES	1990 DISCARDS		2000 DISCARDS			2010 DISCARDS		
	GROSS	NET	GROSS	HIGH NET	LOW NET	GROSS	HIGH NET	LOW NET
Paper	63.23	53.88	76.56	46.18	19.35	92.06	55.28	21.10
Kraft & Corrugate	19.13	19.13	23.05	11.98	2.30	27.91	14.51	2.79
Newsprint	13.82	4.47	15.51	8.07	1.55	17.34	9.01	1.73
Fine Paper	14.26	14.26	19.92	10.36	1.99	25.57	13.30	2.56
Magazines & Glossy	2.13	2.13	2.45	1.27	0.24	2.94	1.53	0.29
Books & Phonebooks	1.31	1.31	1.50	1.50	1.50	1.80	1.80	1.35
Boxboard	2.00	2.00	2.30	2.30	2.30	2.75	2.75	2.07
Diapers	2.31	2.31	2.31	2.31	2.31	2.31	2.31	1.74
Mixed Paper	8.28	8.28	9.52	8.38	7.14	11.43	10.06	8.57
Glass	5.21	4.10	4.29	2.61	1.84	3.84	2.39	1.73
Beer Bottles	0.06	0.00	0.04	0.00	0.00	0.04	0.00	0.00
Softdrink-Refillable	0.65	0.65	0.49	0.01	0.00	0.42	0.00	0.00
Softdrink-Non-refillable	0.75	0.75	0.57	0.07	0.01	0.49	0.06	0.01
Liquor & Wine	0.87	0.31	0.66	0.37	0.07	0.56	0.32	0.06
Containers-Food	1.12	0.62	0.85	0.48	0.08	0.73	0.42	0.07
Containers-Other	0.37	0.37	0.35	0.35	0.35	0.33	0.33	0.33
Flat & Cullet	1.40	1.40	1.33	1.33	1.33	1.26	1.26	1.26
Ferrous Metals	4.13	3.66	3.84	3.30	3.05	3.63	3.22	3.03
Beer Cans	0.06	0.01	0.05	0.01	0.00	0.04	0.00	0.00
Softdrink Cans	0.04	0.03	0.03	0.01	0.00	0.02	0.00	0.00
Food Cans	1.22	0.82	0.95	0.48	0.24	0.73	0.37	0.18
Other	2.81	2.81	2.81	2.81	2.81	2.84	2.84	2.84
Non-ferrous Metals	1.19	0.85	1.44	0.78	0.43	1.44	0.75	0.42
Beer Cans	0.38	0.04	0.41	0.05	0.00	0.46	0.05	0.00
Food Containers & Foil	0.36	0.36	0.46	0.23	0.00	0.44	0.22	0.00
Manufactured Aluminum	0.42	0.42	0.53	0.47	0.40	0.50	0.44	0.38
Other Non-ferrous	0.03	0.03	0.04	0.04	0.03	0.04	0.04	0.03
Plastics	8.47	7.36	11.00	9.31	9.20	12.81	10.82	9.43
Container-1(PETE)	0.09	0.01	0.16	0.01	0.00	0.17	0.02	0.00
Container-2(HDPE)	1.14	0.11	1.62	0.08	0.00	1.92	0.10	0.00
Container-3(PVC)	0.04	0.04	0.06	0.05	0.03	0.08	0.06	0.04
Container-4(LDPE)	0.03	0.03	0.04	0.04	0.04	0.05	0.05	0.03
Container-5(PP)	0.16	0.16	0.22	0.22	0.22	0.26	0.26	0.17
Container-6(PS)	0.02	0.02	0.04	0.04	0.04	0.04	0.04	0.03
Container-7(other) & Unidentified	0.10	0.10	0.14	0.14	0.14	0.16	0.16	0.10
Film & Bags	1.95	1.95	2.47	2.47	2.47	2.87	2.87	1.81
Housewares	4.24	4.24	5.37	5.37	5.37	6.24	6.24	6.24
Toys	0.69	0.69	0.87	0.87	0.87	1.01	1.01	1.01
Tapes & Films	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
Ceramics & Rubble	1.65	1.65	1.56	1.56	1.56	1.59	1.59	1.59
Wood (lumber)	3.34	3.34	3.95	3.95	3.95	4.58	4.58	2.29
Food Wastes	16.65	16.65	15.88	15.88	15.88	15.49	15.49	7.75
Textiles/leather/rubber	4.42	4.42	4.61	4.61	4.61	4.58	4.58	2.55
Textiles	3.94	3.94	4.09	4.09	4.09	4.06	4.06	2.03
Rubber	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Footwear	0.41	0.41	0.44	0.44	0.44	0.45	0.45	0.45
Yard Wastes	4.03	3.00	4.03	3.06	0.64	4.03	3.06	0.64
Grass & Leaves	3.43	2.40	3.43	2.61	0.34	3.43	2.61	0.34
Brush & Stumps	0.60	0.60	0.60	0.46	0.30	0.60	0.46	0.30
Fines	0.85	0.85	0.80	0.80	0.80	0.81	0.81	0.81
Petroleum & Chemicals	0.24	0.24	0.23	0.23	0.23	0.23	0.23	0.12
GRAND TOTAL	113.42	100.00	128.18	92.25	61.53	145.10	102.82	51.46
GRAND TOTAL W/O YARD	109.38	97.00	124.15	89.19	60.89	141.07	99.75	50.82

Table 2. Comparison of present and future recycling levels in various jurisdictions.

		PROGRAM ELEMENT EFFICIENCY			
		—BLUE-BOX—			
		B.C. TYPE	MEDIAN		
PARTITIONED CATEGORIES	DEPOSIT LAWS	1991 ONTARIO	USEPA		CBNS TYPE
			MINIMUM	MAXIMUM	INTENSIVE
Paper					
Kraft & Corrugate			48%	90%	90%
Newsprint		68%	48%	90%	90%
Fine Paper			48%	90%	90%
Magazines & Glossy			48%	90%	90%
Books & Phonebooks					25%
Boxboard					25%
Diapers					25%
Mixed Paper			12%	25%	25%
Glass					
Beer Bottles	96%		43%	90%	90%
Softdrink-Refillable	98%		43%	90%	90%
Softdrink-Non-refillable	79%		43%	90%	90%
Liquor & Wine		64%	43%	90%	90%
Containers-Food		45%	43%	90%	90%
Containers-Other					
Flat & Cullet					
Ferrous Metals					
Beer Cans	77%	57%	50%	75%	75%
Softdrink Cans	59%	34%	50%	75%	75%
Food Cans		32%	50%	75%	75%
Other					
Non-ferrous Metals					
Beer Cans	77%	57%	50%	99%	99%
Food Containers & Foil		0%	50%	99%	99%
Manufactured Aluminum			12%	25%	25%
Other Non-ferrous			12%	25%	25%
Plastics					
Container-1(PETE)	83%	61%	48%	99%	99%
Container-2(HDPE)	90%		48%	99%	99%
Container-3(PVC)			24%	50%	50%
Container-4(LDPE)					37%
Container-5(PP)					37%
Container-6(PS)					37%
Container-7(other) & Unidentified					37%
Film & Bags					37%
Housewares					
Toys					
Tapes & Films					
Ceramics & Rubble					
Wood (lumber)					50%
Food Wastes					50%
Textiles/leather/rubber					
Textiles					50%
Rubber					
Footwear					
Yard Wastes					
Grass & Leaves		30%	24%	90%	90%
Brush & Stumps			24%	50%	50%
Fines					
Petroleum & Chemicals					50%

Table 3. Post 3-Rs residue fuel quality.

year	gross generation	low recycling	high recycling	gross generation	low recycling	high recycling	gross generation	low recycling	high recycling
1990 2000 2010	Discards			Relative Plant Capacity			Total Residue--% of feed		
	113.6	100.0		97.5%	100.0%		21.7%	21.6%	
	128.4	92.2	61.5	91.0%	94.5%	97.5%	19.1%	19.9%	23.6%
	145.4	102.8	51.5	87.8%	90.8%	89.5%	17.4%	18.5%	27.5%
1990 2000 2010	Higher Heating Value -- Btu/lb			Lower Heating Value -- Btu/lb			%--Carbon		
	5,537	5,416		4,876	4,752		30.7	30.1	
	5,863	5,688	5,586	5,193	5,006	4,885	32.3	31.2	29.7
	6,044	5,878	5,982	5,370	5,194	5,302	33.3	32.2	32.0
1990 2000 2010	%--Hydrogen			%--Oxygen			%--Nitrogen		
	4.18	4.12		24.5	24.4		0.37	0.40	
	4.41	4.24	4.07	25.6	23.8	19.4	0.35	0.42	0.52
	4.54	4.38	4.42	26.6	24.7	19.7	0.34	0.40	0.04
1990 2000 2010	%--Sulfur			%--Chlorine			%--Moisture		
	0.095	0.098		0.14	0.16		26.0	26.7	
	0.097	0.099	0.096	0.16	0.22	0.32	24.8	27.4	30.8
	0.099	0.100	0.098	0.17	0.23	0.64	23.9	26.3	25.6
1990 2000 2010	%--Ash								
	14.1	14.0							
	12.3	12.7	15.1						
	11.1	11.7	17.1						

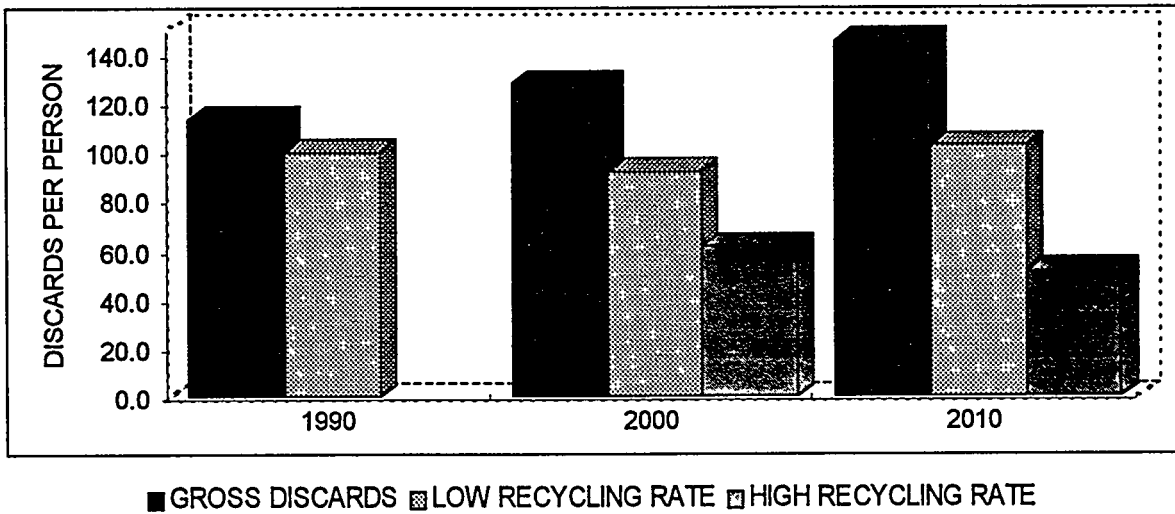


Figure 1. Impact of recycling on discard rate normalized to 100 pounds today.

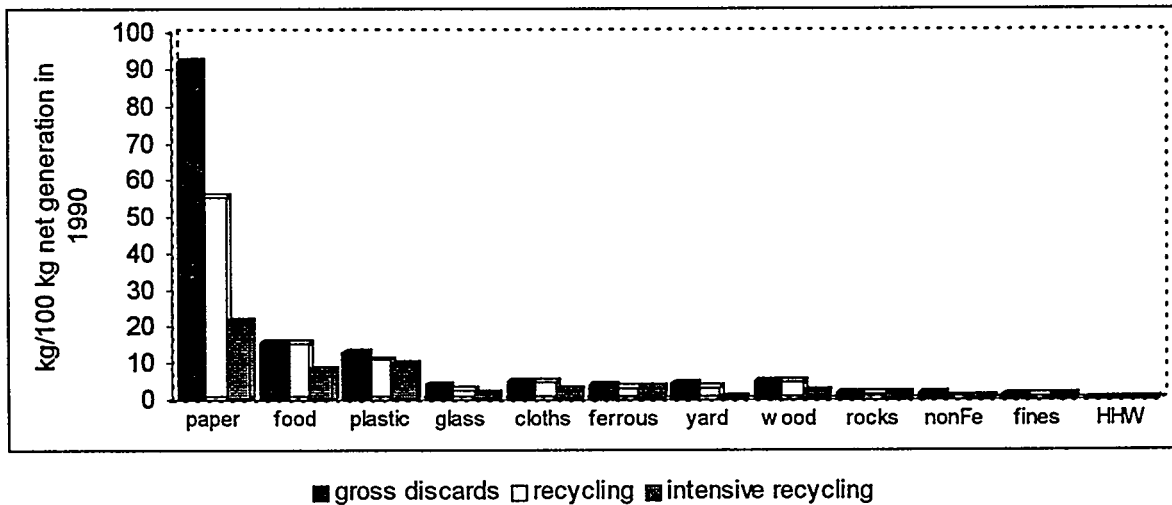


Figure 2. Solid waste composition in 2010 as generated and after 3-Rs.

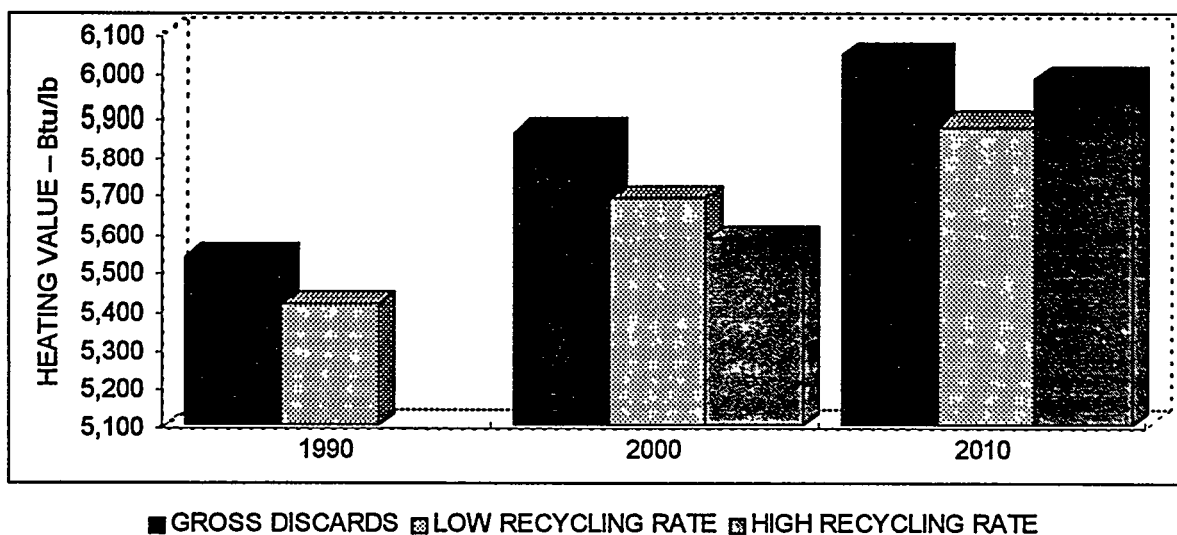


Figure 3. Impact of recycling on heating value.

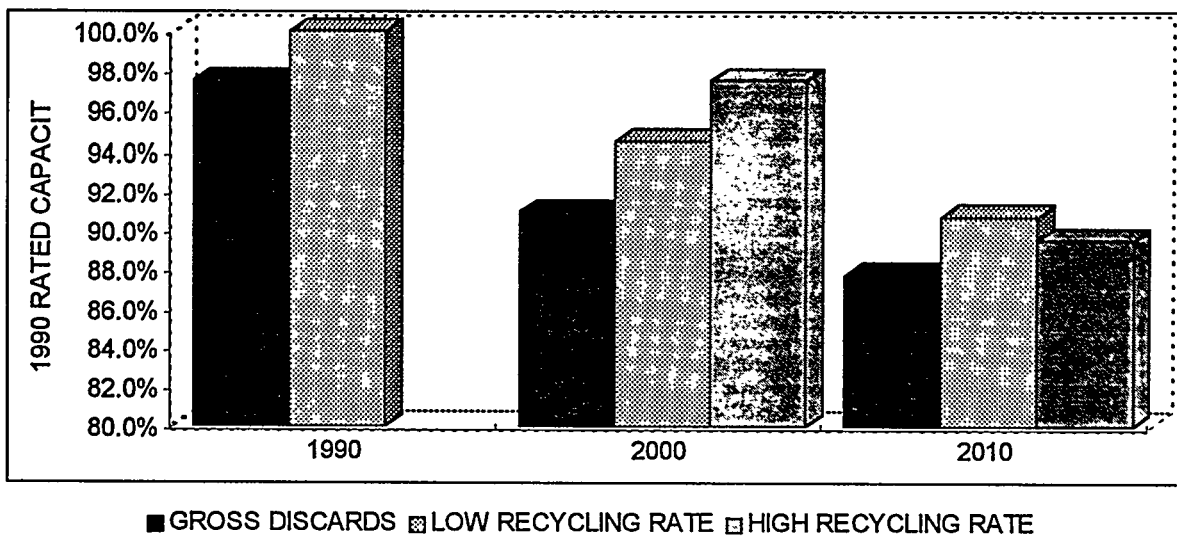


Figure 4. Impact of 3-Rs on EFW capacity normalized to today's new discards.

NAWTEC V

Presentation abstracted from the following APME Technical Paper

**Electrical and Electronic Plastics Waste Co-Combustion
with Municipal Solid Waste for Energy Recovery**

February 1997

Juergen Vehlow
Forschungszentrum Karlsruhe

Frank E. Mark
DOW Europe

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Authors:

Juergen Vellow

Forschungszentrum Karlsruhe

Frank E. Mark

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A technical
paper from:

APME
ASSOCIATION OF PLASTICS

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SUMMARY



Co-combustion tests of E+E plastics waste with municipal solid waste (MSW) in a MSW combustion pilot plant (TAMARA) at the Forschungszentrum Karlsruhe (FZK) in Germany have clearly shown that this recovery route is environmentally sound. These tests have demonstrated that medium to high amounts (3-12 wt %) of plastics waste from end of life E+E equipment can be safely added to today's municipal solid waste to generate useful energy. The major conclusions of this test programme can be summarised as follows:

- *The high heat value of added plastics waste has a very beneficial effect on the required inert character of the grate ash residue. Higher burnout is caused by a more intensive combustion*
- *Clean gas emissions recorded for the PCDD/Fs comfortably achieved the lowest regulatory limits as required by the German BImSch V 17th*
- *Controlled MSW combustion has again confirmed that it is an effective "dioxin sink" with a destruction efficiency of > 90%*
- *Installed European municipal solid waste combustor (MSWC) capacity will allow energy recovery of significant amounts of specified E+E plastics waste without affecting investigated operational limits*
- *Higher levels of halogens in the raw gas will not cause higher emissions, as today's wet, dry or semi dry control systems are well capable of handling such levels*
- *E+E waste fractions should be treated for efficient metal separation prior to combustion. Heavy metal amounts in the E+E plastics waste then conform to the range of typical municipal solid waste combusted today*
- *Higher amounts of halogens: E+E waste containing bromine (Br) and chlorine (Cl) did not increase the presence of dioxins and furans. Increased Br content will only shift the Br/Cl homologue ratio for PXDD/Fs and not cause any catalytic effect*
- *A detailed analytical characterisation of the plastics waste has shown that the major portion of heavy metals in E+E waste is not due to the plastics, but comes from a poor level of metal separation.*

1. INTRODUCTION

The recovery or disposal of end-of-life electrical and electronic (E+E) equipment is receiving considerable attention from industry organisations such as APME in order to supply factual information which can be used in the development of a clear industry strategy(1,2,3). It is hoped that such information will persuade EU member states to define the best management practices for this waste stream.

One of the difficulties regarding the recovery or disposal of E+E waste is a lack of data regarding its behaviour when incinerated (4,5,6,7). This lack of data has led to unfounded conclusions by some parties that plastic wastes contain harmful halogenated species which are difficult to treat and remove, and when incinerated contribute to the emission of halogenated species and are responsible for the major portion of emissions.

APME has a comprehensive testing programme investigating the impact of plastics on municipal solid waste (MSW) incineration. APME's previous work has demonstrated the positive, beneficial effects of mixed waste plastics in the MSW energy recovery process as well as studying halogen behaviour during the combustion of packaging plastics waste and construction foam from the building industry. The current study was designed to evaluate the incineration of MSW containing typical levels of electrical and electronic (E+E) plastic waste, as well as MSW containing E+E waste in amounts up to 12%. Parameters investigated included characterisation of the base MSW feedstock, different E+E waste streams and the incineration parameters related to the base feedstock containing 3, 6 or 12% added-E+E waste. The incineration parameters included combustion efficiency, halogen content and emissions from heavy metal content and emissions from trace levels of halogenated organics. In addition, the types and quantities of plastic waste materials used in today's E+E equipment were simulated in order to approximate the composition of future waste streams.

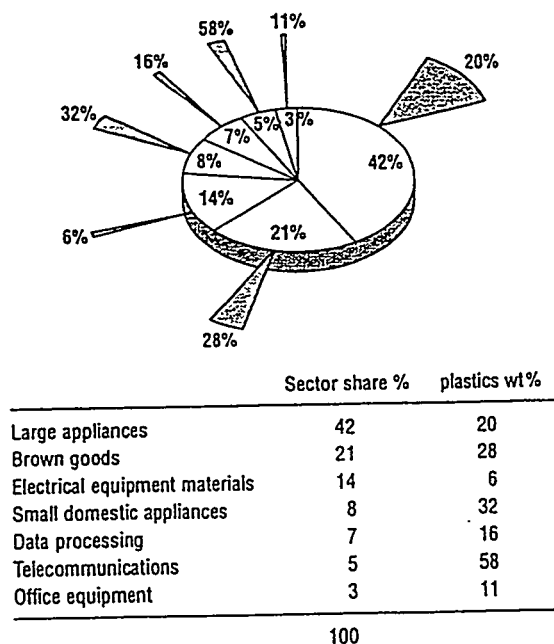
The materials investigated were representative samples from the major market sectors of consumer, commercial and industrial goods. They were of reasonable size (several hundred tonnes) and came from commercial operations in Germany, The Netherlands and Sweden. Today other countries do not have sufficient collection, dismantling and treatment capacities to provide large, representative samples.

E+E MARKET INFORMATION: CONSUMPTION

2. E+E MARKET INFORMATION: CONSUMPTION

Typical E+E market information is available from a SOFRES study commissioned by APME (8). Plastics consumption in 1992 for this sector was estimated at 1.15 million tonnes in Europe, representing 16 % of the total E+E equipment by weight. The following sector share and the weight% of plastics in each sector is given as:

Figure 1:
TOTAL E+E SECTOR MARKET ANALYSIS Source: APME(8)



For a better understanding, the E+E waste sector can be sub-divided into consumer, industrial and commercial goods. Within the consumer sector, a further division is commonly made into brown or white goods. The white goods sector contains refrigerators, freezers, washing machines etc. which are not part of this study. These are usually collected in schemes separate from other consumer equipment. Shredder or recycling operators do not commonly mix white goods shredder residues with those of brown goods (TVs, videos and audio equipment). For an accurate comparison of ESR

(electrical shredder residue) compositions, a clear understanding of the source of the waste was needed.

The following examples are given to explain and illustrate the very different types of equipment which are considered:

Figure 2.
EXAMPLES OF MAJOR E+E MARKET SECTORS

Consumer	(1) small appliances e.g. hairdryers, toasters, heaters, irons, toothbrushes
	(2) medium sized appliances e.g. VCRs, coffee & kitchen machines, vacuum cleaners
	(3) larger size units e.g. PCs, TVs, Hi-fi equipment
Commercial	(4) electronics medium size parts e.g. PCs, fax machines
Industrial	(5) electrical switch gear equipment
	(6) electronic instrumentation and control systems.

3. ELECTRICAL + ELECTRONIC EQUIPMENT PLASTICS WASTE

3.1. E +E EQUIPMENT IN MSW

At the present time very little E+E equipment waste is combusted in MSW combustors (MSWC).

The increasing European MSWC capacity (34 MMt in 1992) designed for energy recovery and efficient flue gas cleaning is sufficient to combust certain fractions of special E+E equipment waste streams. If it is assumed that 5-10 wt% of the MSW feed comprised suitable E+E equipment waste then all of today's E+E plastics waste could be handled by existing MSWC capacity. This demonstrates the potential importance of MSWC as a recovery route.

Efforts by APME to define the E+E content in MSW in Germany resulted in a figure of about 1 wt% within the residual MSW (equivalent to 140 kg/year per person).

The recycling of plastics, paper, glass and metals reduces the commonly accepted value of 300 kg MSW/person/year to a figure of 140 kg of which around 1 kg/person/year can be attributed to E+E waste (9). As older equipment is replaced and taken out of stock this figure is likely to increase.

3.2 SOURCE SEPARATED E+E MATERIALS

Electronic and electrical equipment is sometimes collected by local authorities, but the information on E+E waste categories is rather scarce. Similarly the number of pilot projects to collect E+E waste in Europe is also limited (10, 11). Very little is known about the polymer composition in different types of equipment. Nevertheless the total amount of source separated E+E equipment is growing rapidly although as yet the waste amounts are still unclear. For these trials, it was therefore necessary to get E+E waste for TAMARA, the MSW combustion pilot plant of the FZK in Karlsruhe, from larger scale commercial operations. A very detailed identification and classification of the different E+E articles has been made for countries like Germany by the Zentralverband Elektrotechnik-und Elektronikindustrie e.V. (ZVEI) (12) and France by the Fédération des Industries Electriques et Electroniques (FIEE) (13), with reports on material stream identification by article from Institut für Umweltechnologie und Umweltanalytik e.V. (IUTA) (14) and the company Schleswag (15).

Three medium sized suppliers of E+E plastics waste streams in Germany were asked to provide pretreated E+E waste. The pretreatment was not done specially for TAMARA, but was typical of commercial operations by the following companies:

IUTA	Consumer waste
(EGR) Elektro-Geräte Recycling GmbH	Commercial/small industrial waste
SCHLESWAG	Industrial (low, medium, high volume) waste

4. E + E POLYMERIC MATERIALS USED FOR THE CO-COMBUSTION TESTS

4.1. WASTE MATERIALS FROM DIFFERENT MARKET SECTORS

IUTA: CONSUMER

The Institute for Environment Technology and Environmental Analysis (IUTA) has dismantled 1400 items of E+E equipment from the cities of Essen (20%) and Duisburg (80%) in Germany. All equipment was dismantled manually to get a better overview of the material streams. 15 % (210 t) of the input was plastics. Two thirds of these 210 tonnes were unidentified composites or polymer blends. From this unidentified amount of 140 tonnes, samples were taken according to the German specification guideline for shredder residue Länderarbeitsgemeinschaft (LAGA) specification PN 2/78.

The sampling was done over a period of two years in 1993/94 and resulted in 12 tonnes of E+E plastic waste. A 1000 kg sample for the TAMARA tests was collected from the 12 tonnes according to the same German guideline LAGA specification PN 2/78.

EGR: COMMERCIAL

The Electrical Equipment Recycling Company (EGR) collects E+E equipment from the Rhein-Ruhr area in Germany. EGR has an annual capacity of 2500 tonnes for E+E equipment waste treatment. Most of the industrial and commercial equipment is dismantled manually. From an amount of 144 tonnes which included TVs, audio equipment, radios, vacuum cleaners, and PCs (including housings, screens, printers and photocopiers), 15 % were plastics. A certain portion is suitable for mechanical recycling, and the remainder has to be disposed of by alternative means. Representative amounts of 100 tonnes E+E equipment were collected during 1992 and treated similarly to the shredder residue from IUTA. From the recovered 10 tonnes of plastics, 1 tonne was blended and shipped to TAMARA.

E + E POLYMERIC MATERIALS USED FOR THE CO-COMBUSTION TESTS

SCHLESWAG: INDUSTRIAL

The third source came from the company Schleswag Recycling GmbH in Brunsbüttel in the north of Germany. This operation consists of two stages. The first is dismantling and separation into the following fractions: metal housing, printed circuit boards, cables, plastic housing and screens. The second operation consists of a conventional shredding and separation phase with the following fractions being produced: iron, aluminum, plastics, thermoset plastics with fibres and metal granulate. Members of ZVEI supplied 60 tonnes of old E+E equipment resulting in 3.9 tonnes of materials to be specially treated, 26.7 tonnes of valuable metals and 29.7 tonnes (50 %) of a mixture which can only be thermally treated. The first coarse shredded fraction comprises about 25 wt% of plastics. This coarse material was shredded a second time on one of the four mechanical separation lines resulting in a fines fraction. This was the material evaluated at TAMARA.

This fraction of fines still contains high amounts of inert substances (>35 % wt) with very small metal parts barely observable to the naked eye. This amount of fillers and

fibers is significant, contributing to high amounts of ash. The total mass balance data is very well described in (15).

4.2. PLASTIC MATERIALS FROM TODAY'S E+E EQUIPMENT

A simulation of the types and quantities of plastics materials used in current E&E equipment was made to approximate the composition of future waste streams arising from the disposal of such equipment. The composition of an average E&E polymer mixture in Europe supplied by APME members was simulated by blending together materials typical of those sold in the market today. The materials can be separated into two categories by burning characteristics, horizontal burning or flame retarded. The ratio between these two classes is 66 % to 34 % respectively.

The overall composition assumed for today's European market agrees very closely with the SOFRES report (8) and is given as follows:

Figure 4:
POLYMER COMPOSITION FOR TODAY'S E+E
EQUIPMENT.

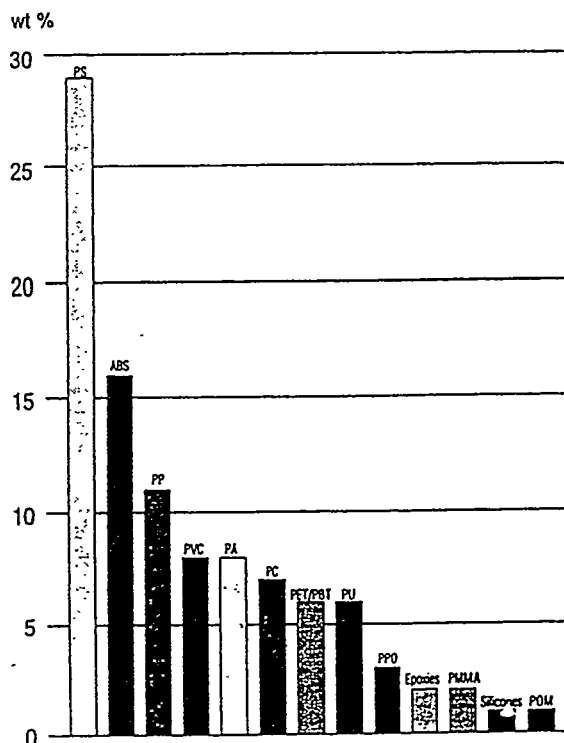
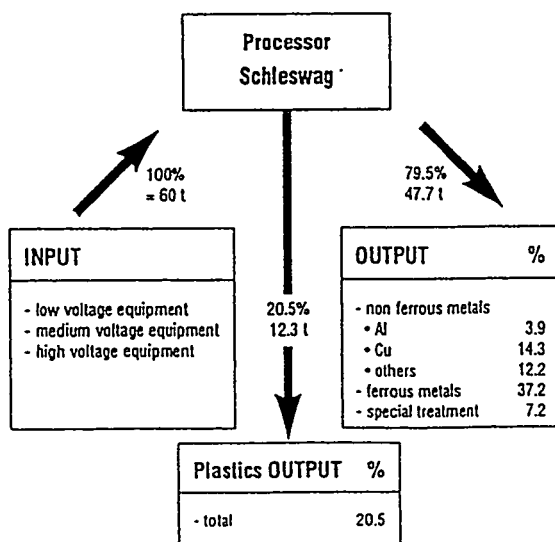


Figure 3
E+E INDUSTRIAL EQUIPMENT PROCESSING

E+E INDUSTRIAL GOODS PROCESSING AT SCHLESWAG Material composition and amount for trials



The products requested from the APME member companies should be typical of normal commercial grades with respect to composition. 3 tonnes of these materials were blended at an outside commercial facility and then shipped to TAMARA.

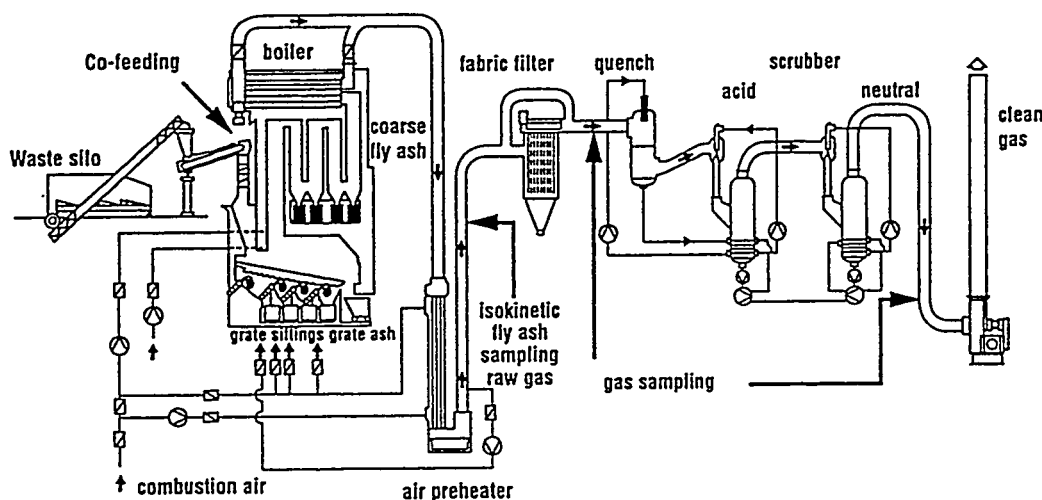
4.3. E+E MATERIALS PRETREATMENT

Thermal recovery of large E+E type equipment involves a thorough pretreatment process. The operational steps may vary from company to company although most use the following sequence: dismantling

5. TEST INCINERATOR TAMARA

The Karlsruhe test incinerator TAMARA is a mass burner with a nominal throughput of 250 kg/h of preconditioned waste (16). The pilot plant has been described in detail in an earlier APME TEC report (17). A schematic drawing of this incinerator is given in Fig. 5. The design of the combustion chamber can be changed from the original counter current into one of parallel flow geometry by the installation of variable roof elements. The first test trials were conducted using the

Figure 5
SCHEMATIC DRAWING OF THE KARLSRUHE TEST INCINERATOR TAMARA FOR MUNICIPAL SOLID WASTE



to remove hazardous compounds or parts, coarse shredding, ferrous and non-ferrous metal removal, followed by a second size reduction and air separation. For the TAMARA experiments shredding is necessary to get sufficiently homogenized good quality fuel but also to obtain sufficiently small pieces to be able to feed into the chute of the furnace.

All E+E streams tested went through some type of shredder. Hazardous components such as mercury and PCBs were removed after dismantling.

parallel flow design whereas during the second campaign only two roof elements were installed forming a middle flow configuration. In the first case the residence time of acid gases and alkaline fly ashes is extended and as a consequence the fly ashes will contain higher amounts of e.g. chlorides or bromides.

Dust removal is performed by means of a fabric filter consisting of PTFE fabric tubes coated with a GORETEX[®] membrane. This filter is operated at a temperature of approx. 200°C. For flue gas cleaning a two-stage wet scrubbing system is installed.

The impact of the E+E waste plastic materials on the scrubbing system is not covered here but in the original

FUEL COMPOSITION

FZK report or in (17). The majority of measurements have been done on the raw gas to understand the effect of E+E plastics waste on the combustion process. It is widely known that clean gas concentrations do not relate to the combustion conditions. They show the effect of the emission reduction system.

The basic fuel burnt in TAMARA is a shredded and sieved household waste which is enriched by 25 % of a pelletised RDF(Refuse Derived Fuel). The mean Cl and heavy metal content is slightly lower than that of typical Central European household waste.

The E+E materials were rather inhomogeneous, except the new E+E materials, and a thorough mixing in Karlsruhe of the large amounts proved to be impossible. As an alternative, representative samples of the feed during each of the co-combustion tests were taken, homogenised, subsampled and analysed. Figures 7, 8 and 9 give the concentrations of some important elements for the basic fuel and for the E+E materials averaged per test campaign. Typical standard deviations of the data are in the order of ± 10 %. For low concentrations even higher values have to be considered. It must be mentioned that the first test campaign was performed in the summer whereas the second one took place in winter. This explains some minor changes in the composition of the basic feed.

6. FUEL COMPOSITION

6.1. STANDARD FUEL ANALYSIS

For reference comparative reasons, analysis of the various E+E plastic waste was carried out by both FZK and GfA, Gesellschaft für Arbeitsplatz - und Umweltanalytik mbH (Munster). Some key items of standard fuel characterisation: heat value, ash, etc. are shown in Figure 6. A more detailed fuel analysis overview is shown in Figures 7 and 8. Aspects more important for E+E plastics waste, such as the analysis for metals and for dioxin and furan content, are covered later.

Special importance was given to the elemental analysis of bromine and chlorine contents. Bromine analysis was performed by four different parties all

experienced in this field. The ratio of antimony to bromine is a very good indicator of the accuracy of bromine content analysis.

The range of bromine content covered was quite large, from a very low level of around 0.4 wt% up to 4 wt%. The consumer type equipment had a low level of about 0.4 wt%. The commercial material could be assumed to be more representative for the commercial/industrial E+E plastics as there is more flame retardant product used. The ratio of bromine to antimony on a weight for weight basis ranged from about 2 to 7. This is in line with the experience of formulating flame retardant products by addition of bromine plus antimony to gain beneficial synergistic effects.

Figure 6
E+E WASTE PLASTICS FUEL ANALYSIS
(Test series)

	Source of E+E waste					
	Consumer	Commercial		Industrial		Today's polymer market mix
Test series	(1)	(1)	(2)	(1)	(2)	
Heat Value, Hu, GJ/t	35	32		25.5		35
Ash, wt%	3-5	3-5		35-40		6.5
Bromine, wt%	0.4	4.1	1.5	1.3	0.6	0.9
Chlorine, wt%	0.4	2.3	1.1	0.7	0.2	3.5
Antimony, wt%	0.2	1.3	0.2	0.35	0.2	0.3

A comparative fuel analysis is shown in the following table where all elements in the E+E plastics waste are compared to the basic fuel of the TAMARA runs. The results of the analysis are from FZK and may differ slightly from earlier data measured by GfA.

Figure 7
CONCENTRATIONS OF SELECTED ELEMENTS IN THE BASIC FEED AND IN THE DIFFERENT E+E MATERIALS
(data in mg/kg)

material	basic fuel	basic fuel	consumer	Today's polymer market mix
test series	1	2	1	2
Cl	5800 ± 230	6150 ± 300	3895	38550 ± 2000
K	9500 ± 500	7100 ± 800	1050	2150 ± 400
Ca	34000 ± 2500	32000 ± 5000	1200	7000 ± 1500
Ti	1120 ± 140	1420 ± 240	1730	4550 ± 620
V	46 ± 18	47 ± 12	36	900 ± 15
Cr	109 ± 12	150 ± 30	63	53 ± 8
Fe	5800 ± 900	6400 ± 650	1700	287 ± 36
Ni	69 ± 13	56 ± 13	88	30 ± 1
Cu	109 ± 22	112 ± 36	1900	137 ± 55
Zn	470 ± 30	430 ± 70	620	292 ± 18
As	17 ± 4	25 ± 11	9	47 ± 2
Br	62 ± 13	34 ± 10	4290	8600 ± 1000
Rb	22 ± 3	17 ± 2	30	20 ± 3
Sr	130 ± 19	108 ± 17	18	79 ± 17
Mo	7 ± 2	7 ± 1	2	4 ± 1
Cd	10 ± 3	9 ± 3	240	41 ± 6
Sn	26 ± 4	24 ± 5	85	18 ± 15
Sb	31 ± 8	26 ± 4	2000	2630 ± 110
Ba	410 ± 75	660 ± 320	250	-
Pb	410 ± 40	600 ± 350	146	1890 ± 50
P	1880	2080	250	1200

Figure 8
CONCENTRATIONS OF SELECTED ELEMENTS IN THE BASIC FEED AND IN THE DIFFERENT E+E MATERIALS
(data in mg/kg)

material	commercial		industrial	
test series	1	2	1	2
Cl	22970	10990 ± 1400	7435 ± 10	1865 ± 30
K	1500	3080 ± 230	1350 ± 100	2700 ± 170
Ca	2500	2550 ± 750	50000 ± 300	73900 ± 1100
Ti	18350	15200 ± 300	3350 ± 120	1500 ± 180
V	155	880 ± 30	149 ± 11	900 ± 15
Cr	164	250 ± 25	384 ± 1	140 ± 50
Fe	950	440 ± 120	3250 ± 300	2830 ± 260
Ni	780	550 ± 90	170 ± 50	200 ± 40
Cu	1140	82 ± 32	105000 ± 5000	77500 ± 6500
Zn	3350	1540 ± 320	5100 ± 800	4720 ± 70
As	38	29 ± 3	46 ± 1	45 ± 1
Br	41100	15000 ± 900	12550 ± 250	5750 ± 300
Rb	51	55 ± 30	21 ± 7	51 ± 9
Sr	36	22 ± 5	215 ± 8	222 ± 23
Mo	36	13 ± 4	35 ± 4	15 ± 8
Cd	124	123 ± 44	94 ± 7	29 ± 4
Sn	880	63 ± 39	2130 ± 10	1230 ± 230
Sb	13200	1950 ± 430	3500 ± 400	2200 ± 300
Ba	590	n.m.*	580 ± 15	571 ± 13
Pb	152	96 ± 19	2050 ± 320	1890 ± 50
		n.m.	n.m.*	8150

FUEL COMPOSITION

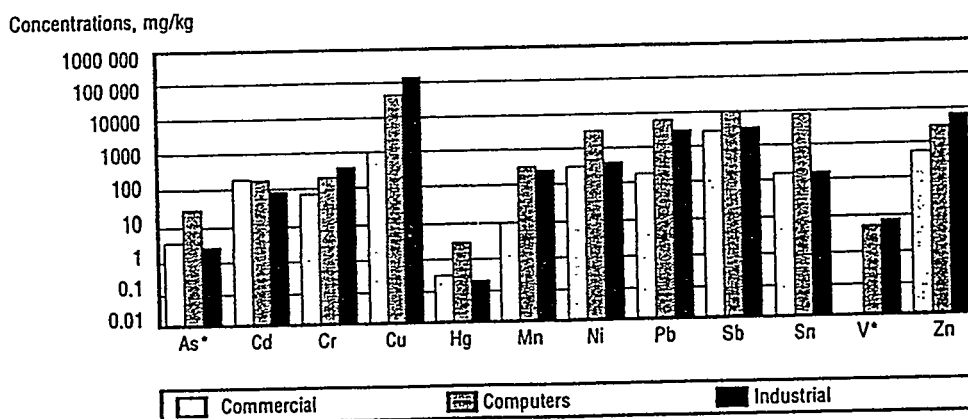
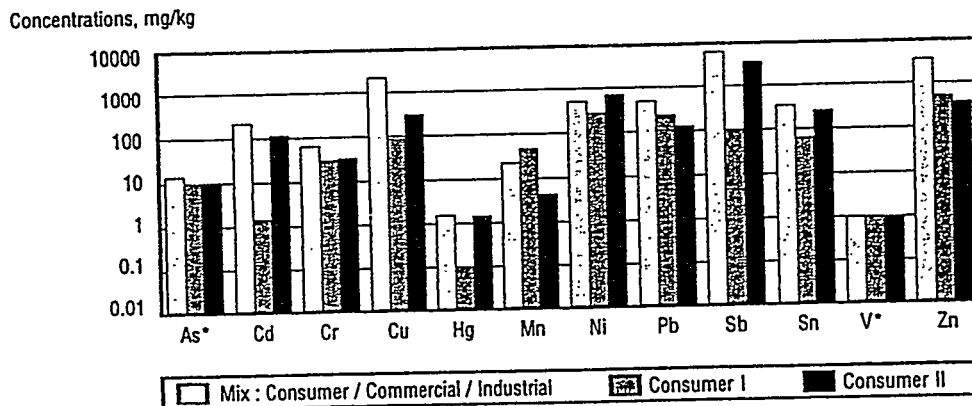
6.2 METAL ANALYSIS OF USED PLASTICS FROM VARIOUS E+E SECTORS

The broad range of metals of E+E plastics waste can be seen in Figure 9. The range is rather wide and could vary by more than several orders of magnitude.

materials (ferrous and non-ferrous metals, glass, polymer > 2 mm and rest < 2 mm) were removed. This prepreparation step made sure that residual metal content related only to the polymer. Analytical techniques have been described in earlier APME reports (18).

Figure 9
COMPARISON OF E+E WASTE METAL CONTENT

*Detection limits : As = 10 mg/kg, V = 1mg/kg



All samples were analysed for metal content by the same laboratory using the same test procedure. Prior to the polymer milling and grinding to reach a sufficiently small particle size for elemental analysis, the different

The samples representative for the computer sector came from Sweden, and represent today's personal computer (PC) market quality for all 4 equipment units: monitors, processing units, printers and keyboards.

The average data are representative of a broad market mix. The second sample from the consumer sector is representative of a small section of the market, mainly TVs and audio-visual equipment. Prior to analysis, the elemental metallic parts were removed as far as possible by hand. Differences in results between the two laboratories for elements primarily found in the polymer were acceptable. Larger differences are seen for e.g. copper, which is influenced mainly by separation of the metal. The high level of metallic content originates from wire.

The type and quality of pretreatment of the E+E plastics waste have a major influence on the amounts of metals left in the polymer/metal mixture. Low levels of elemental metals are achieved by a well run magnetic or eddy current separation. High levels of metal content are the result of a poor physical separation. Earlier results in the literature (1) claiming very high contents of metals in the polymer phase may have resulted from poor separation techniques to remove ferrous and non-ferrous metals.

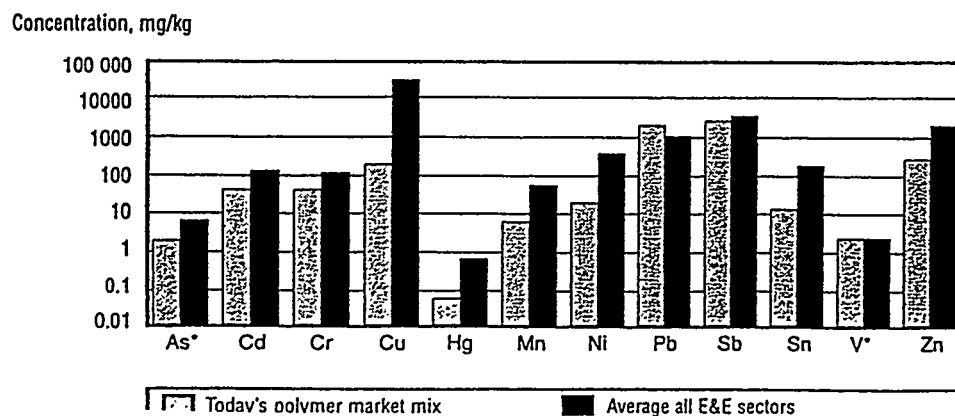
6.3. PLASTIC MATERIALS FROM TODAY'S E+E EQUIPMENT

The plastics studied above were from current E+E waste, i.e. from 'old' E+E equipment. They do not

represent the materials used in E+E equipment being sold today. There have been many changes in materials, colorants and additives, and it is important to understand the composition of today's materials, which will make up the E+E waste of the future.

The new plastic materials were sampled and analysed in a similar way to the previous samples from commercial operations. It is interesting to compare the new and older materials from the point of view of levels of metallic elements, as well as the numbers and types of metal found. The total amount of heavy metals was significantly less with a maximum of 0.4 wt%. There were only two major metal elements, lead and antimony, found in today's plastic materials mix; with roughly equal concentration levels of 0.2 wt%. Other heavy metals such as arsenic, cadmium, cobalt, mercury, nickel, titanium, vanadium and tin are at very low concentrations compared to the levels previously found in the commercial waste samples. It is reasonable to conclude that recovered plastics in the future will not be the source of high levels of metals. The fact that these metal elements are found in the commercial samples was due to incomplete recovery during the metal separation processes.

Figure 10
METALS COMPOSITION COMPARISON OF OLDER VS. CURRENT POLYMERIC MATERIALS



6.4. FLAME RETARDANT ANALYSIS

The range of different flame retardant materials in today's E+E market sector is quite broad and cannot be covered here. Major elemental components like aluminum (Al), bromine (Br), chlorine (Cl), magnesium (Mg) and phosphorous (P) have been looked at in more detail. Each flame retardant class gives rise to specific questions in the context of combustion. The more volatile elements were examined with respect to air and water emissions, whereas the less volatile elements should be judged on their behavior in the solid residue (grate ash). Results from leaching tests are still not subject of a common regulatory understanding (19) and have therefore been omitted.

In order to judge the destruction efficiency of the TAMARA facility, the levels of brominated flame retardant compounds in the polymer matrix were determined in a similar way to the levels of brominated dioxins and furans. It is important that waste management routes for E+E equipment should particularly address this aspect of complete destruction of all organo-halogen compounds.

Chemical analysis of the flame retardant content of mixtures of E+E waste polymers is not standardised today by any European or national standardisation body.

Analysis of typical flame retardant compounds such as polybrominated diphenylethers (PBDPEs), tetra-bromo-bisphenol A (TBBA) and polybrominated biphenyls (PBBs) has been accurately demonstrated only in single polymers or known constant polymer mixtures. Therefore an inter-laboratory comparison between two well known certified German laboratories GfA and ITU (Ingenieurgesellschaft Technischer Umweltschutz) was initiated.

In most samples the levels of PBBs were below the detection limit. Only in the industrial sample was a significant level of PBBs (50 mg/kg) found. PBDPEs were detected in all three samples with levels ranging from 0.01 to 2.0 wt%. The amount of TBBA found in all samples ranged from 0.01 to 0.60 wt%.

The accuracy of these results is satisfactory considering the fact that both laboratories had different methods of sample pretreatment, e.g. solvent extraction techniques. Calibration was done with solutions of available native congeners of the compound classes to be analysed.

Comparing the validated bromine content from four laboratories with the bromine content of the three flame retardant compounds, the following conclusions can be drawn: in addition to PBB, PBDPE and TBBA, all polymer samples contained significant levels of other brominated flame retardant compounds in the polymer matrix and the levels of the three flame retardants which could be identified ranged from 5% to 50% in the various samples.

6.5. CONCLUSIONS

A detailed analytical characterisation of the plastics waste has shown that :

- Analysis of halogen levels found that the level of bromine ranged from as low as 0.4 wt % for the consumer sector, to as high as 4 % by weight for industrial high voltage applications. Ratios of Br to antimony (Sb) were between 2 and 7, which is in agreement with typical industry formulations for flame retardancy. The chlorine level ranged very widely from as low as 0,2 % to several % by weight
- The bromine level is directly linked to the amount of flame retardant. Analytical work was carried out to determine the level of flame retardant for three commercial compounds sold today namely, PBB, PBDPE and TBBA. In practice, the two latter compounds contribute the majority market share, with PBB being a relatively small contributor and other Brominated Flame Retardants (Fr-Br) from older products
- The amounts of micro-organic species such as halogenated dibenzo-para-dioxins and furans (PXDD/F) were analysed, and compared with the

limits of the German ordinances. Although the range of levels found was quite large, the average content value met the German regulations

- These levels of halogenated dioxins and furans in existing (old) end of life E+E equipment suggests that mechanical recycling of plastics waste as an option for these articles should be considered carefully. In such cases, combustion or chemical treatment of these older articles which ensures total and safe destruction of dioxins and furans are proven options.

7. TEST PROGRAMME

The TAMARA test programme lasted about two weeks. Two test runs were conducted per day, each lasting four hours. On the first and on the last day of each week, two reference tests were performed which burnt only the basic fuel. The test programme is detailed in Figure 11. During the first week of tests, the combustion chamber was in a parallel flow geometry and in the second week, a middle flow system was installed. The combustion temperature was kept at approx. 900°C in the first and approx. 930°C in the second week.

Figure 11
E+E MATERIAL ADDITIONS DURING THE TEST PROGRAMME

code	test series	E+E material	addition in wt%
ref. 1.1	1	-	0
ref. 1.2	1	-	0
E+E.1.1	1	consumer	3
E+E.2.1	1	commercial	3
E+E.3.1	1	industrial	3
E+E.3.2	1	industrial	6
ref. 2.1	1	-	0
ref. 2.2	1	-	0
ref. 3.1	2	-	0
ref. 3.2	2	-	0
E+E.4.1	2	today's polymer market mix	6
E+E.4.2	2	today's polymer market mix	12
E+E.2.2	2	commercial	6
E+E.2.3	2	commercial	12
E+E.3.3	2	industrial	12
ref. 4.1	2	-	0

SAMPLING AND ANALYSIS

8. SAMPLING AND ANALYSIS

During all test trials, the raw gas was permanently monitored for the concentrations of O_2 , CO_2 , CO , HCl , SO_2 , NO , H_2O , and NH_3 . Isokinetic gas sampling was performed by FZK in the raw gas upstream of the fabric filter. The fly ashes sampled here were used for all sorts of analyses. All other solid streams, the input as well as the residue streams were sampled taking care to obtain representative sampling, subsampling and sample pretreatment by following the recommendations of the International Ash Working Group (19).

Close to the position of the FZK isokinetic sampling train, the German certified analytical laboratory GfA had installed their own isokinetic probe for sampling of halogenated dibenzo-p-dioxins and dibenzofurans.

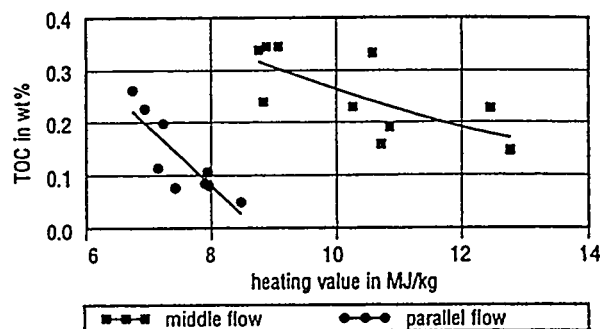
FZK conducted most of the inorganic analysis by applying total digestion to all solid samples for metal analysis. The organic samples were digested by pyrolysis followed by combustion in pure oxygen. For metal analysis, Total Reflecting X-Ray Fluorescence Analysis (TXRF) was used. Anions were analysed by means of ion chromatography. In addition, selected samples were analysed for special elements by GfA, IUTA, and other industry laboratories for comparison. In all cases different digestion and analysis methods were applied.

The clean up and the analysis of halogenated organic compounds was done by GfA following their own protocols (20). PCDD/F were analysed for comparative purposes by FZK.

9. COMBUSTION CONDITIONS

The combustion quality was not negatively influenced by the addition of the E+E plastic materials. As already experienced from the co-combustion of mixed post-consumer plastics waste (21), the increased heating value of the plastics improved the burnout in all residue streams. As can be seen in Fig. 12, these experiments revealed a significant reduction in the TOC of the bottom ashes. This effect is more pronounced in the parallel flow geometry of the combustion chamber due to the higher temperature at the back end of the grate.

Figure 12
TOC IN THE BOTTOM ASHES VS.
HEATING VALUE OF THE FEED



The burnout in the raw gas was extremely low during all test runs ($CO < 5 \text{ mg/m}^3$ and TOC in the fly ashes $< 700 \text{ ppm}$). A major difference could not be detected between the two configurations.

9.1. RESIDUES

An efficient metal separation prior to combustion in a MSWC plant is strongly recommended. If metal separation prior to combustion is inadequate, a substantial amount of metallic species such as Cu and Pb can be found in the grate siftings and to a minor extent in the bottom ashes. These metals are not totally oxidized inside the combustion chamber. They tend to melt down and seep through between the grate bars. This behavior may endanger the operational function of the grate. On the other hand metallic species deteriorate the bottom ash quality. Hence an efficient metal separation prior to combustion in a MSWC plant is strongly recommended. In one preliminary test run, not included in this report, a deterioration of the grate ash characteristics for a high metal content in the feed could be confirmed.

10. THE ROLE OF VOLATILE ELEMENTS IN MSW COMBUSTION

10.1. HALOGENS IN MUNICIPAL SOLID WASTE

In previous investigations (21) at TAMARA with packaging plastics and construction foam from the building industry, halogen (Cl, Br, F) behavior has been documented.

The levels of Br investigated here extend the experience to even higher Br concentrations.

THE ROLE OF VOLATILE ELEMENTS IN MSW COMBUSTION

The level of bromine in municipal solid waste and the chemical form in which it is introduced into the MSW is not well understood. Only very few investigations (22,23) concerning MSW composition have concentrated on this aspect. Older estimates in the literature range from 6 to 90 mg Br/kg MSW. The TAMARA feed has averaged around 200 mg/kg. APME's bromine balancing measurements calculate a feed concentration of about 30 to 60 mg Br/kg MSW (24). The contributions of bromine entering the waste can be natural bromine sources, bromine from flame retarded polymers and other bromine containing materials such as textiles.

Higher bromine levels in the feed to the combustor may influence the emission and residue disposal characteristics. The following aspects were examined during the trial:

- I. What was the bromine path through the main units : furnace and scrubber of a typical MSWC?
- II. Where did the bromine leave the MSWC: grate ash, liquid effluent and/or gaseous emission?
- III. What gaseous bromine containing compounds were formed ?

IV. How, and to what extent, did bromine act as a promoter to increase the concentration of certain chloro-bromo-organic species in the gaseous phase, as had already been proposed (25).

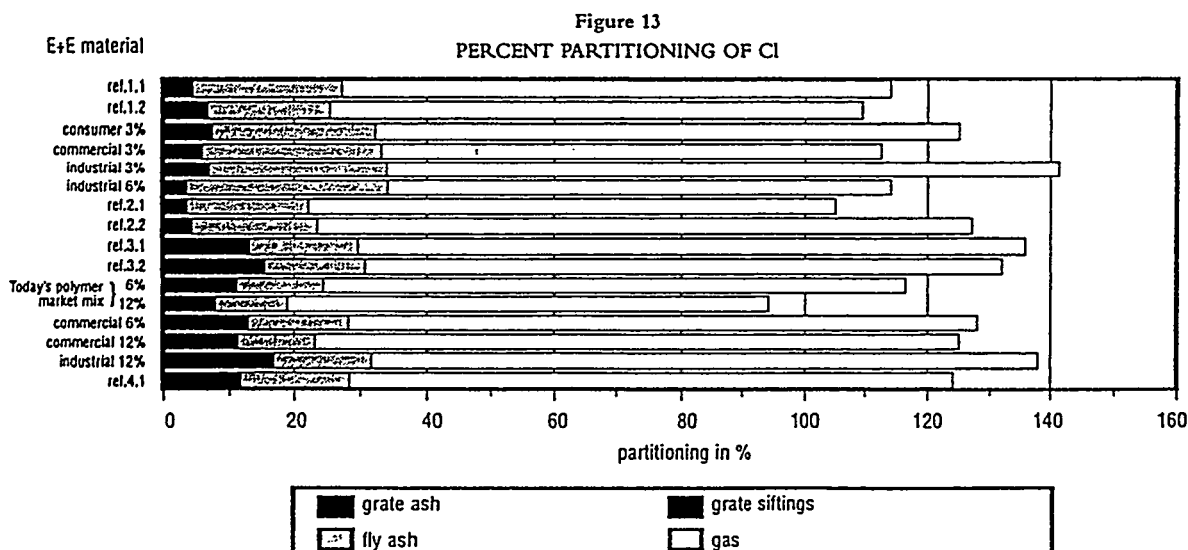
ELEMENT PARTITIONING: Cl

Earlier investigations had shown the distribution of Cl in the various streams for a very broad range from as low as 0.6 wt % to 3 wt %. Due to the importance of chlorine in the discussion of the formation of dioxins and furans the results from these tests are shown.

The Cl load in the feed varies between approx. 0.6 and 1,2 wt% based on output and input analysis. The comparison of the input numbers to the outputs analysed in the different compartments is shown as a percent partitioning in Fig. 13.

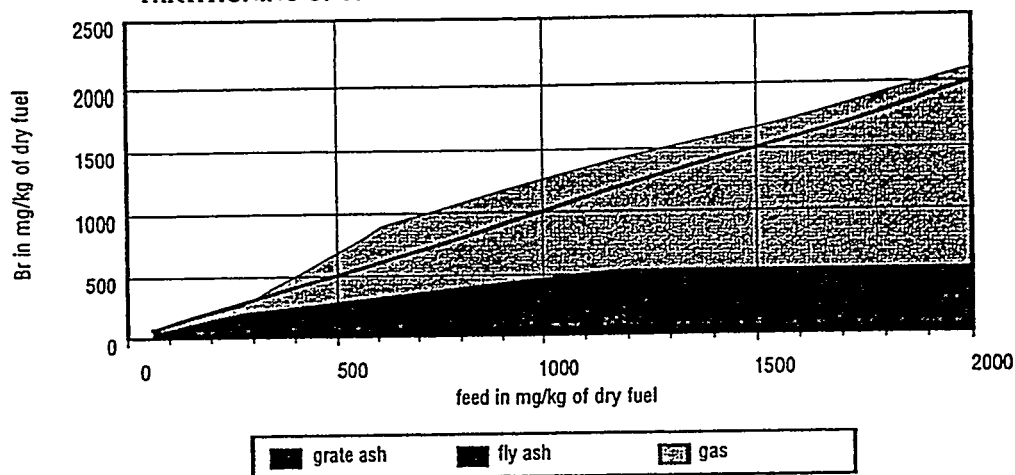
The Cl data show a substantial scattering and the averaged output is approx. 10 - 20 % higher than the input. This indicates errors caused during sampling, sample preparation, digestion or analysis. It is very likely that the digestion of the high volatile organic components causes most of the differences.

But taking into account the relative homogeneity of some of the feed materials and the analytical error of all different analyses this result can be deemed satisfactory. It is well known, from full scale incineration plants, that



THE ROLE OF VOLATILE ELEMENTS IN MSW COMBUSTION

Figure 14
PARTITIONING OF Br IN THE PARALLEL FLOW COMBUSTION CONFIGURATION



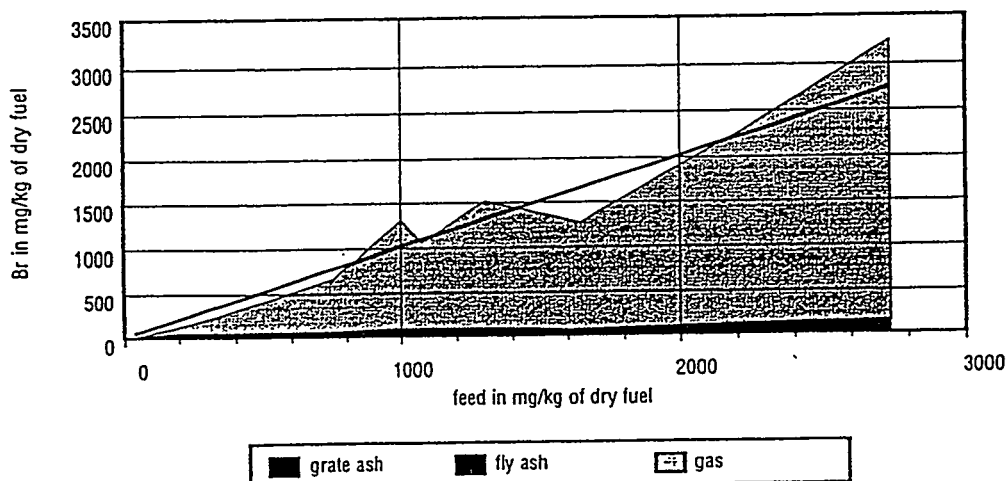
about 70 - 80 % of the total Cl inventory is found in the gas phase. This was confirmed by the tests for high Cl and very high Br concentrations.

A more detailed investigation revealed a significant difference of the partitioning depending upon the geometry of the combustion chamber. During the first test campaign the fly ashes carried a significantly higher fraction of the Cl inventory than they did in the second campaign. The probable reason was the higher residence time of the acid HCl and the alkaline fly ashes at high temperatures in the parallel flow configuration.

ELEMENT PARTITIONING: Br

The geometrical effect was more easily seen for the Br behaviour (Figs 14 and 15). Fig. 14 shows the sum of analysed output streams plotted against the sum of analysed input. Dry fuel is in this case the total feed, basic fuel and E+E materials without water. Again the output data were to some extent exceeding the inputs. The potential errors should be the same as those already discussed for Cl. In general the agreement of both Br balances can be deemed satisfactory. Figure 14 also indicates an increasing incorporation of Br into the fly ashes with increasing Br input. At very high input the curve seems to level off.

Figure 15
PARTITIONING OF Br IN THE MIDDLE FLOW COMBUSTION CONFIGURATION



This might be caused by the exhausted alkalinity of the fly ashes. In almost all cases the pH of the fly ashes was in the order of 6.5 - 7, which is common in most modern large scale operations.

In the second test campaign (Fig 15) when TAMARA was operated in a middle flow combustion chamber design and even higher amounts of Br were added along with the E+E material, only smaller fractions of Br were found incorporated in the fly ashes.

The differences between the total fly ash concentrations, however, are difficult to explain purely on the basis of changes in combustion geometry.

10.2. METALS IN MUNICIPAL SOLID WASTE

Two different types of metal species can be differentiated by their volatility behaviour.

Lithophilic elements stay mostly in the grate ash and do not volatilise. In this case it is the residue characteristics that are important. The others are subject to volatilisation and could cause emissions if not properly equipped.

The degree to which metals from plastics could be released to the environment through the stack depends on the levels of metals in the raw gas after the boiler. This amount is related to the following factors: metal volatility, fuel bed temperature T_b , raw gas temperature T_g in the combustion chamber, solid matter concentration X_s in the raw gas and air velocity v .

$$\text{Volatility} = F(T_b, T_g, X_s, v, \dots)$$

Due to experimental difficulties of sampling hot and high solid concentration gases, reported raw gas solid content values X_s relate mostly to the boiler exit. The air velocity v in the combustion chamber directly influences X_s . The bed temperature T_b of a MSWC, depends on the type of grate design. T_g covers the range of 850°C to 950°C. Raw gas dust concentrations are comparatively low due to low gas velocities; typically 4 m/sec in the furnace.

Al and Mg are typical lithophilic elements and stay completely in the grate ash (17). The oxides and silicates of Al and Mg have very high boiling points and show no volatility. The concentration ranges of the MSW typically found are 0.2 to 1.0 wt % of Mg and 2 to 4 % of Al. Due to the high base load concentration in the MSW, relative small additions through the E+E plastics do not change the total concentration in the grate ash.

10.3. FATE OF HEAVY METALS IN COMBUSTION

Heavy metals were examined in more detail because of the environmental concern from both the public and authorities. Heavy metals may be present in the following phases in the combustion system:

GAS PHASE:

1. volatilised gas
2. as an aerosol in the gas phase

SOLID PHASE:

3. bound to fly ash particles
4. in the solids (ash and slag)

Specific heavy metals are classified mainly by the two or three official emission classes of the waste incineration or combustion Directives. Potential critical elements from plastics are cadmium from class I, lead, antimony and zinc from class II and nickel and cobalt from class III. Heavy metal balances around MSWC have been done (26,27,28) to establish volatility numbers. Some volatility data are shown below:

Figure 16
TYPICAL VOLATILITY NUMBERS FOR METALS

Cd	85 to 90	wt%	high volatile heavy metal
Zn, Sb, Pb	30 to 50	wt%	medium volatile heavy metal
Ni, Cu	1 to 10	wt%	low volatile heavy metal

HALOGENATED MICRO-ORGANICS

It can be seen from Figure 16 that most of the metals in E+E type plastics waste do not show a high volatility. The most critical heavy metals from an emission directive viewpoint are Cd followed by Pb, Sb and Zn.

ELEMENT PARTITIONING: Sb

The element antimony (Sb) is quite frequently added to improve the flame retardant behavior of E+E plastic materials. A relation of 3 - 4 to 1 is typical in flame retarded plastics for Br and Sb. This approximate value was also found in the E+E waste materials used here. Fig. 17 details the percent balances for Sb found during all of the test trials. In most cases the balances match nicely to 100 %. In two tests, during the addition of 6 and 12 wt. % of the commercial material, extremely high output numbers were found. The resultant discrepancy is most likely due to an underestimation of the input. The graph demonstrates the well known influence of increased Cl levels upon the volatilisation of Sb (21).

Estimates of the partitioning of other elements confirmed the findings of former experiments for the volatilisation of heavy metals such as Zn, As or Sb.

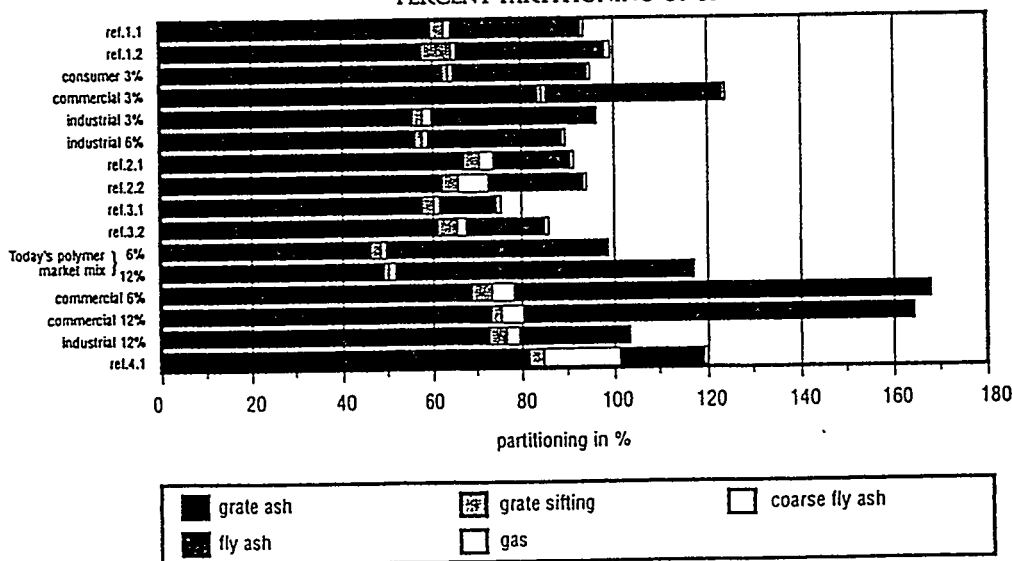
11. HALOGENATED MICRO-ORGANICS

Because of their persistancy in the environment, halogenated micro-organics are seen as a very specific class of dangerous substances. As a consequence of the sensitive nature of this subject, specific emphasis was given to all three following aspects: their content in E+E waste, potential emissions and their degree of destruction.

11.1. DIOXIN AND FURAN CONTENT IN E+E WASTE

Two ordinances exist in Germany regulating the transport and handling of hazardous materials: "The German Regulations for Hazardous Materials", and a second regulating materials brought to the market in "The German Chemicals Restriction Ordinance" enacted July 16, 1994. The same 17 poly-chlorinated (PCDD/F) and 8 poly-brominated (PBDD/F) dioxins and furans are mentioned in both ordinances. Limit values are given for single congeners like the 2,3,7,8 PCDD/F as well as for groups of dioxin and furan compounds. Limits for mixed halogenated (PXDD/F) are not specified. The feed materials for the TAMARA campaigns as well as for the broad range of specific market samples were analysed.

Figure 17
PERCENT PARTITIONING OF Sb



It is known from the literature that TV housings made out of polystyrene and containing deca-bromo-diphenyloxide as fire retardants may contain certain amounts of brominated furans/dioxins (29).

Within APME's programme to gather analytical data of polymers used in the E+E area, additional samples were analysed from typical E+E waste. In summary it was found that PXDD/F content is very broad, ranging from <1 ppb to several hundred ppb. The average value is around 20 ppb (micrograms per kg) and meets the German regulations. It can be further concluded that the amount of brominated dioxins/furans belonging to the group of 8 selected 2,3,7,8-PBDD/Fs is larger than the equivalent chlorinated group with 17 PCDD/Fs.

The level of total PXDD/Fs in old end-of-life E+E equipment still in circulation suggests that material recycling of plastics from these articles should be looked at with great care.

Disposal of these articles through methods like combustion or feedstock recycling, ensuring total and safe PXDD/F destruction, is to be preferred.

11.2. HALOGENATED DIOXINS AND FURANS PXDD/F IN THE RAW GAS

11.2.1. PCDD/F IN THE RAW GAS

A moderate increase of Cl input in the combustion chamber should not significantly influence the formation of PCDD/F. Former experiments in TAMARA did not show an effect even if the Cl load was elevated by a factor of 5 (21). This has been supported by similar tests in a German full scale MSW incinerator (24).

Two recently published studies on the relationship of PVC and PCDD/F in waste combustion also gave no indication of a significant correlation (26,27).

There is one paper claiming an increase in PCDD/F when electronic waste flame retarded by polybrominated diphenylethers is co-combusted in a MSWC plant (25).

Although the effect seems statistically insignificant such potential influences also had to be considered in our experiments. More recent investigations in Dutch incineration plants have not confirmed a correlation between Br and the total dioxin formation (28). A recently published study on the role of Br in the de novo synthesis in a model fly ash system has also not confirmed the promoting effect of Br (30).

Figure 18
PCDD LEVELS IN THE RAW GAS

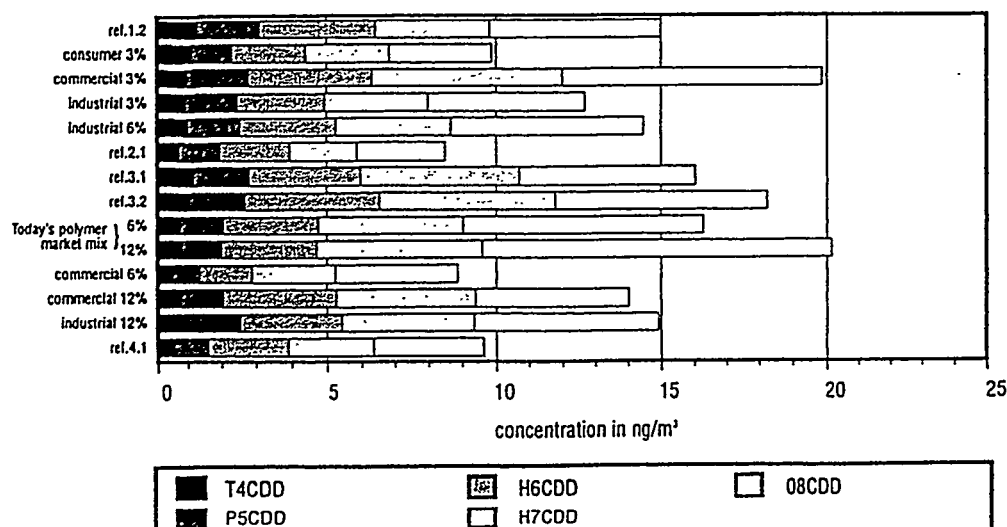
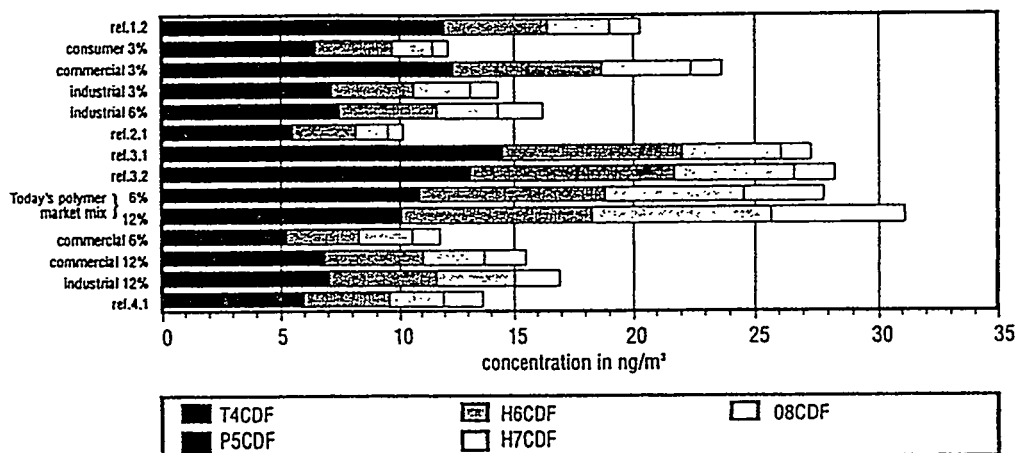


Figure 19
PCDF LEVELS IN THE RAW GAS



The levels of PCDD and PCDF in the raw gas of TAMARA have a tendency to decrease with increasing time of operation. This has already been extensively documented and can be compared with the time behavior of large scale boilers due to dust accumulation. Hence the actual reference level of PCDD/F for certain co-combustion tests is somewhere between the initial and the final reference test results.

The PCDD and PCDF concentrations analysed by FZK and two outside laboratories were in most cases very close to each other. Figs. 18 and Fig. 19 detail the sum of homologues obtained for PCDD and PCDF in the raw gas of TAMARA. The data show typical scattering. A significant increase caused by the co-combustion of the flame retarded E+E materials is not apparent. This was valid for the PCDD as well as for the PCDF, especially when the experiments with high additions of E+E materials were taken into consideration.

The homologue pattern of both classes of compounds stayed about constant. There was no influence of the elevated Cl or Br load to be seen as documented for construction foam from PUR and XPS nor was there an observed influence of the changed combustion chamber configuration.

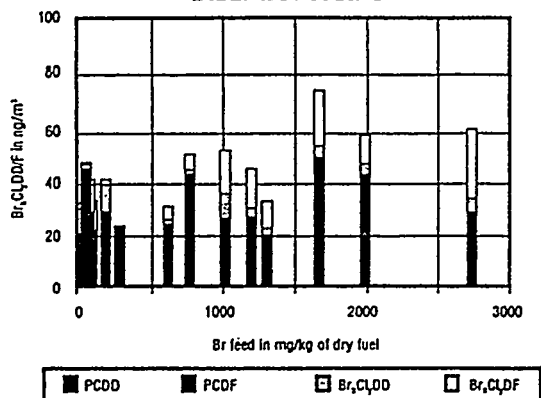
11.2.2 Br CONTAINING DIOXINS AND FURANS IN THE RAW GAS

Data for PCDD and for PCDF did not show a significant influence of the elevated Br input. The situation changes as far as bromine containing dioxin and furan is concerned. According to the literature (23), brominated and mixed halogenated compounds add only a small percentage to the PCDD/F levels in MSWC. This was also confirmed by the co-combustion of XPS and PUR foams in TAMARA (17).

The analysis of brominated and mixed halogenated dibenzo-p-dioxins and dibenzofurans was also performed by GfA and ITU. Figure 20 shows the respective Br containing homologues analysed in the raw gas of TAMARA. Again previous results were confirmed:

- I. the formation of furans exceeded that of dioxins
- II. there were only very low levels of brominated homologues found
- III. the prevailing homologues were those containing one Br atom
- IV. homologues containing two Br atoms were only detected if very high amounts of E+E waste material (which means Br) were added
- V. homologues containing more than two Br atoms were not found.

Figure 20
SUM OF HALOGENATED DIBENZO-P-DIOXINS AND
DIBENZOFURANS



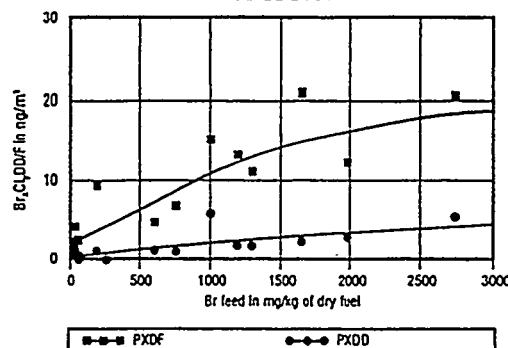
The foam tests cited above showed that the formation of Br containing dioxins and furans was limited and was responsible for approx. 20 - 30 % of the total dioxin and furan level in the raw gas if high amounts of Br were added to the feed stream. In Fig. 20 all of the analysed chlorinated and Br containing homologues are summed up for all test runs.

Fig. 20 also demonstrates that the mixed Cl/Br containing furans in these tests sometimes reached the same order of magnitude as the purely chlorinated ones. This was observed in the two tests when 12 wt. % of commercial or industrial E+E material was co-combusted. The dioxins were always lower in concentration by a factor of 3 - 4 than the furans and did not add substantially to the total sum of the halogenated compounds in question.

In all tests the total dioxin/furan load in the raw gas did not exceed the typical operation window of TAMARA which is in the range of 20-120 ng/m³. This means that the contribution of brominated species is of no concern for MSW emissions from incineration plants fitted with modern air pollution control systems.

The level of mixed halogenated dioxins and furans is correlated to the bromine concentration in the fly ash in Fig. 21. The saturation effect observed to produce PBCDD/Fs in earlier test campaigns (17) is also shown here. It can therefore be concluded that the chemical form of the Br input is of no significance.

Figure 21
INFLUENCE OF Br CONTENT IN FLY ASH ON
PBCDD/Fs



11.3. DESTRUCTION EFFICIENCY

The destruction efficiency of the TAMARA pilot plant for the halogenated dioxins and furans has been calculated to support this waste management route. A realistic scenario case has been chosen for this evaluation. The total halogenated dioxin and furan input stream from the E+E plastics waste can be estimated from the measured concentrations (see chapter 6.4). The range was very broad as indicated and a value of 2 micro g PXDD/F /kg E+E plastics waste was chosen. This concentration times the mass stream of E+E plastics waste of 15 kg/h leads to the total PXDD/F input from the plastics. For the total amount of PXDD/F, all 25 compounds from the German Dioxin Ordinance were taken into account. This resulted in a figure of about 0.030 mg PXDD/Fs per hour.

The PXDD/F mass contribution of the MSW can be estimated from literature data. The PCDD/F content in MSW ranges are very wide and a good average is 5 micro g/kg MSW. The total input for the most realistic case is then 0.5 mg PCDD/F per hour taking a medium value for the PCDD/F concentration. The grand total input of E+E waste and MSW is around 0.6 mg PXDD/F per hour.

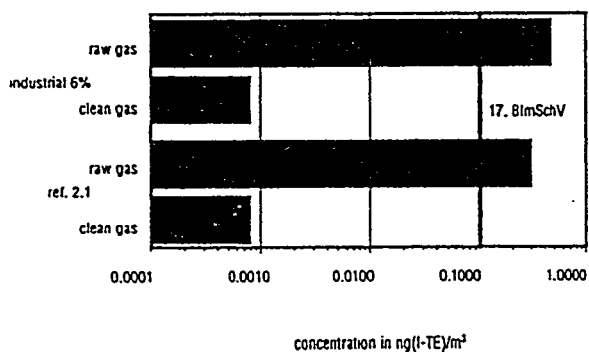
Taking the solid and the gas phase concentration into account, the outgoing stream is estimated on the basis of the raw gas analysis. The total chlorinated and halogenated dioxins and furans were measured at maximum to about 45 ng PCDD/F /m³ and 23 ng PBCDD/F /m³ respectively leading to an out flowing flux of 0.061 mg PXDD/F / h with 900 m³/h flue gas volume. The total degree of dioxin and furan destruction is therefore greater than 90 % (24).

RECOMMENDATIONS

11.4. PCDD/F IN THE CLEAN GAS

The clean gas emissions were measured for two cases ref 2.1 and the addition of 6% industrial type E+E materials in the Tamara pilot plant. This is not normally done and was only to demonstrate the effectiveness of active carbon addition to reduce the amounts of PCDD/F in the clean gas. The level of less than 0.001 ng (I-TE)/m³ is typical for this safe emission control technology. The required 0.1 ng (I-TE)/m³ limit from the German BImSchV 17th is easily met. Actual emissions are less than 5% of the required limit in Fig. 22.

Figure 22
E&E CO-COMBUSTION - PXDD/PXDF IN RAW AND
PCDD/PCDF IN CLEAN GAS



12. RECOMMENDATIONS

On the basis of all of the results presented in this report, we are lead to the following conclusions:

The tests supported MSW combustion as an environmentally and economically sound recovery route for limited amounts of specific E+E waste plastics. The metal content, however, should be reduced in order to minimize the amount of metallic species in the grate siftings.

CONTRIBUTIONS:

During this project a number of people have cooperated from different companies: Elf Atochem: A. Jean, Bayer: M. Rohr, Dow Europe: EE. Mark, Du Pont de Nemours: J.M. Falguière and representing the organisations involved: APME: R. Martin, EBFRIP/BFRIP/EFRA: M. De Poortere, FZK: J. Vehlow, B. Bergfeld, T. Wanke, ZVEI: W. Pauli (ABB). Their dedication and efforts are appreciated.

This project was supported by the following associations: APME: the Association of Plastics Manufacturers in Europe, BFRIP: the Brominated Flame Retardant Industry Panel, EBFRIP: their European equivalent, EFRA: the European Flame Retardant Association, FZK: Forschungszentrum Karlsruhe and FIEE: the French Electrical and Electronic producer organisation.

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Co-Combustion of E+E Waste Plastics in the TAMARA Test Plant

Jürgen Vehlou

Thomas Wanke, Britta Bergfeldt, Frank E. Mark*

Forschungszentrum Karlsruhe GmbH

Institut für Technische Chemie, Bereich Thermische Abfallbehandlung

Weberstr. 5

D-76133 Karlsruhe, Germany

*Dow Europe S.A.

Bachtobelstr. 3

CH-8810 Horgen, Switzerland

ABSTRACT

The co-combustion of different amounts of various plastic fractions of electrical and electronic (E+E) waste together with municipal solid waste has been tested in the Karlsruhe test incinerator TAMARA. The tests revealed no negative influences upon the combustion process. In general the increased heating value of the fuel causes an improved burnout in all residue streams. The halogens Cl and Br added with the plastics are mainly transferred as HCl or HBr into the flue gas. An influence upon the formation of chlorinated dioxins and furans could not be observed. With increasing Br feed bromine containing homologues were detected in the raw gas. The furans formed easier than the dioxins and those homologues carrying one Br atom were by far prevailing. Even at high Br input the total amount of mixed halogenated species was limited to approximately 30 % of the total load of such compounds which did not leave the typical operation window for PCDD/PCDF in TAMARA. The co-combustion tests demonstrated that MSW combustion is an ecologically acceptable and economically sound disposal route for limited amounts of specific E+E waste.

INTRODUCTION

The plastic fraction of electrical and electronic (E+E) waste is a material the disposal of which is in discussion at various forums. Different waste management routes including material recycling, chemical recycling and energy recovery are under evaluation. Municipal solid waste combustion (MSWC) as a means for recovery of the energy stored in the plastics seems to be a promising option. Existing research of various groups^{1, 2}, however, has mostly focused on assumed negative effects of heavy metals like Cd, Cu, Pb and Sb and the halogens bromine and chlorine. The effect flame retardancy related compounds or elements may have upon the formation of organic micropollutants such as chlorinated, brominated or mixed halogenated dibenzo-p-dioxins (PCDD) and dibenzofurans (PCDF) is controversially discussed, too.

Due to the lack of documented operational experience and to the limited awareness about bromine containing materials a research program for co-combustion experiments in a test incinerator was launched by the Forschungszentrum Karlsruhe (FZK) and a project group under the umbrella of APME (Association of Plastics Manufacturers in Europe). The goals of the project were to study the effects of

- higher E+E waste concentrations in order to simulate real life worst case conditions,
- higher concentrations of volatile heavy metals in the feed due to E+E products,
- flame retardancy related organic compounds like polybrominated diphenylethers (PBDPE), biphenyls (PBB), and tetra-bromo-bisphenol A (TBBA) as well as the active elements like bromine, phosphorous or chlorine.

The major results of the tests carried out in two test campaigns are compiled in this paper.

THE TEST INCINERATOR TAMARA

The Karlsruhe test incinerator TAMARA³ is a mass burner with a throughput of 250 kg/h of precondi-

tioned, mainly shredded waste. TAMARA has installed a reciprocating grate and the design of the combustion chamber can be changed from the original counter current configuration into a parallel flow geometry by the installation of variable roof elements.

The dedusting is performed by means of a fabric filter which is operated at approx. 200 °C. For flue gas cleaning a two-stage wet scrubbing system is implemented. The E+E material was added by a separate feeding system directly into the feeding chute. An isokinetic sampling train is installed upstream of the fabric filter in order to get representative samples of the gas phase as well as of the particulate matter in the raw gas. All other solid streams were sampled caring for a representative sampling, subsampling and sample pretreatment. The sampling and analysis of chlorinated dioxins and furans was done by FZK and simultaneously by two German commercial analytical laboratories, GfA (Münster) and ITU (Berlin).

TAMARA is equipped with a variety of monitoring systems to document all mass streams, temperatures, pressures etc. The major gas components in the raw gas are monitored on line, e.g. O₂ by an ZrO₂ electrode, CO₂, CO, HCl, SO₂, NO, N₂O, H₂O by means of spectroscopic or electrochemical methods.

MATERIALS AND TEST PROGRAM

Material Categories. Since the information on E+E waste categories is rather scarce and very little is known about the article type and the respective amounts of waste the E+E waste sourcing was from larger scale commercial operations to get representative testing materials. The pretreatment was part of the commercial operation today practiced by the following companies:

IUTA	consumer type (small appliances, kitchen machines, PC, TV, ...)
EGR	commercial / small industrial type (medium size parts, PC, fax machines, ...)
Schleswig	industrial (electrical housings, switches, main frames, ...)

The composition of the actual European average polymer mixture has been simulated by blending materials today sold on the market. Members of the APME have supplied these market typical qualities. The overall composition assumed for today's and future European market agrees very closely with the SOFRES report⁴ (PS 29%, ABS 16%, PP 11%, PA 8%, PVC 8%, PC 7%, PET/PBT 6%, PU 6%, PPO 3%, PMMA 2%, Epoxies 2%, POM 1%, Silicones 1%).

Inorganic Composition. Table 1 compiles the concentrations of some elements in the different feed streams which are characterized by a substantial additional input during the co-combustion tests. An increase in load has in particular been expected for the flame retardancy related elements Cl, Br and Sb. Especially for the industrial material a high amount of metallic species, e.g. Cu and Pb had been anticipated and were indeed found.

Organic Composition. To analyse for the organic compounds used for flame retardancy in the E+E materials is a difficult task since there is only limited information about the types of used for that purpose in plastics for the E+E market and there is no standardized method for the isolation and analytical procedure in mixed plastics. Furthermore some of the originally used materials are polymerized during the blending procedure and hence there is no way to analyze for them in the finished product.

Therefore an interlaboratory comparison of the analysis of the consumer, commercial and industrial material was initiated between two well known certified German laboratories, GfA and ITU. The analytical review was limited to three classes of compounds, that is PBB, PBDPE and TBBA.

The accuracy of these quantitative results is satisfactory considering the fact that both laboratories had different methods for sample pretreatment, e.g. solvent extraction techniques. The calibration was done with solutions of available native congeners of the compound classes to be analyzed. The PBB levels were below detection limits in all samples but in the industrial material. Here a typical concentration of

50 mg/kg was found.. PBDPE were detected in all three samples with levels ranging from 100 to 20 000 mg/kg. The amount of TBBA found in all samples ranged from 100 to 6 000 mg/kg.

The analysed flame retardants contributed only 5 – 50 % to the directly analysed Br content in the various E+E plastics. One explanation is that other compounds have been used for flame retardancy, too, the other one is that some flame retardants have been compounded into the plastic matrix and cannot be recovered any more.

Another class of organic micropollutants regulated in German ordinances for the transport and handling (German Regulations for Hazardous Materials) and for the marketing of materials (German Chemicals Banning Ordinance) are chlorinated and brominated dioxins and furans. Both ordinances set limits for single isomers like the 2,3,7,8-TCDD and for the sum of 17 chlorinated and 8 brominated isomers. Limits for mixed halogenated congeners are not specified.

In a special program APME organised the analysis not only of the TAMARA samples but of a large number of market products. In summary the concentration of halogenated dioxins and furans varies substantially ranging from < 1 to several hundred µg/kg. The average value is around 20 µg/kg and meets the German regulations. Another finding of the program was that the amount of brominated congeners belonging to the group of 8 selected PBDD/PBDF is larger than the equivalent group of 17 chlorinated congeners.

The total level of halogenated dioxins and furans in existing end of life E+E equipment suggests that material recycling of plastics from these articles should be looked at with great care. Disposal by other methods such as combustion, gasification, or thermolysis which guarantee a total destruction of these compounds is to be preferred.

Test Program. The test program comprised about two weeks of TAMARA operation. Two test runs were conducted per day, each lasting four hours. On the first and on the last day of a week two reference tests were performed burning the basic fuel only. During the tests in the first week the combustion chamber was in a parallel flow geometry, in the second week a middle flow was adjusted. The combustion temperature was kept at approx. 900 °C in the first and approx. 930 °C in the second week. The co-feeding was 3, 6 and 12 wt % in the case of the commercial and the industrial material, 6 and 12 wt % for the new and 3 wt % for the consumer material.

DISCUSSION OF RESULTS

Combustion Efficiency

Some important data for the evaluation of the experiments are compiled in Table 2. The data show the increase in heating value of the feed stream with increasing addition of E+E waste plastics. The combustion temperatures, the CO levels and the raw gas concentrations of HCl and HBr are given, too.

The combustion quality was not negatively influenced by the addition of the E+E materials. All parameters and raw gas concentrations showed rather constant numbers during the different trials. As had already experienced from the co-combustion of mixed post-consumer plastic waste the increased heating value of the plastics improved the burnout in all residue streams⁵, especially in the grate ashes as can be seen in Fig. 1. Due to the higher temperature on the back end of the grate the effect is more pronounced in the parallel flow tests. The burnout in the raw gas was extremely low in all test runs (CO < 5 mg/m³ and TOC in the fly ashes < 700 ppm) and a major difference could not be detected between the two configurations.

No traces of the brominated flame retardants analysed in the E+E materials could be detected in raw gas samples. In view of the well known high destruction potential of waste combustion⁶ this result had been

expected. Similar statements can be made for the brominated dioxins and furans. Only trace amounts of furans were detected in the raw gas of one single reference test and during the addition of 3 wt. % of commercial material. Due to the low input numbers and the high analytical error no quantitative destruction yields were calculated. The same stays for the PCDD/PCDF since the major fraction found in the raw gas has been originated in the boiler and a distinction between compounds having survived the combustion process and those having been synthesized post combustion cannot be made.

During the co-combustion of the industrial material which contained visible amounts of Cu fibres and metallic residues from the circuit boards, pure metals were found in the grate siftings. To avoid his unwanted effect a thorough metal removal of the E+E waste material is recommended.

Element Partitioning

The addition of E+E waste caused – depending upon the material – a more or less substantial increase of the halogens Cl and Br as well as of some heavy metal inventories (Sb, Cu, Pb) in the feed stream. Out of the total number the flame retardancy born elements Cl, Br and Sb will be discussed in short terms.

The analysed Cl varied between approx. 6 000 and 12 000 ppm. The comparison of this input numbers to the outputs analysed in the different compartments is shown as a percent partitioning in Fig. 2. The Cl data show a substantial scattering and the averaged output is 10 – 20 % higher than the input which is a satisfactory result for this kind of balancing. About 70 – 80 % of the total Cl inventory is found in the gas phase. The respective HCl concentrations in the raw gas cover the range of 670 to 1 000 mg/m³ (compare Table 2). A more scrutine investigation reveals a significant difference of the partitioning depending upon the geometry of the combustion chamber. During the first test campaign the fly ashes carry a significantly higher fraction of the Cl inventory than they do in the second campaign. The reason is the higher residence time of the acid HCl and the alkaline fly ashes at high temperatures in the parallel flow configuration.

This effect is more easily seen in the behaviour of Br. Fig. 3 and Fig. 4 show the sum of Br in the analysed output streams plotted against the respective number of the analysed input. Again the match of both of the Br balances can be called satisfactory. The graphs indicate an increasing incorporation of Br into the fly ashes with increasing Br input in the parallel flow co-combustion tests. At high input the curve seems to level off. In the middle flow tests when even higher amounts of Br were added along with the E+E waste only smaller fractions of Br were found in the fly ashes. This distinction is hard to be explained by the change in combustion geometry only. The analysed K and Ca concentrations suggest a higher alkalinity of the fly ashes in the first campaign.

As an example for the typical results of heavy metal balancing the percent partitioning of Zn is shown in Fig. 5. Although the variability of the data is higher than found in the case of the halogens the match of this balance can be called satisfactory, too. The scattering is more distinct for metals like Cu and Pb which are often found as pure metals in the E+E waste.

An important element involved in the flame retardancy of E+E materials is Sb. Fig. 6 compiles the percent balances for Sb as found during all of the test trials. Except for two tests, where the input was most likely underestimated, the balances close very well.

PCDD / PCDF in the Raw Gas

Former experiments in TAMARA did not show an effect even if the Cl load was elevated by a factor of five⁵. This has been supported by similar tests in a German full scale MSW incinerator⁷ and by two recently published studies upon the relationship of PVC and PCDD/F in waste combustion⁸. There is one paper claiming an increase in PCDD/F if electronic waste flame retarded by polybrominated diphenylethers is co-combusted in a MSWC plant⁹. This could not be confirmed by TAMARA tests on the co-combustion of flame retarded XPS and PUR foams¹⁰.

The levels of PCDD and PCDF in the raw gas of TAMARA tend to decrease with increasing time of operation. Hence the matching reference level of PCDD/F for a certain co-combustion test is somewhere between the respective initial and final reference test results. The PCDD and PCDF concentrations analysed by FZK, GfA and ITU were in most cases very close to each other. The raw gas concentrations of PCDD and PCDF are compiled in Table 3. Fig. 7 depicts the sum of homologues as a function of the Br level in the feed stream. The data show the typical scattering. A significant increase or homologue change caused by the co-combustion of the flame retarded E+E materials is not revealed.

Br Containing Dioxins and Furans in the Raw Gas

This situation changes as far as bromine containing homologues are concerned. According to literature and to the above cited TAMARA tests brominated and mixed halogenated compounds add only a small percentage to the PCDD/PCDF levels in MSWC^{10, 11, 12}. The sum concentrations of bromine containing dioxins and furans are compiled in Table 3 which also contains the Br input data. Fig. 8 and Fig. 9 show the sum of Br containing homologues analysed in the raw gas of TAMARA. There were next to none purely brominated homologues found. The prevailing homologues analysed were those containing one Br atom. Homologues containing two Br atoms were only detected if very high amounts of Br were added and those containing more than two Br atoms could not be detected. The formation of bromine containing furans exceeded that of dioxins.

The formation of bromine containing furans increases with increasing Br input and seems to level off at high Br loads (compare Fig. 10). The effect is less pronounced for the dioxins the concentrations of which, however, are very low. These findings confirm the results of the above cited foam co-combustion tests.

The graph in Fig. 11 demonstrates that the Br containing furans in these tests sometimes reached the same order of magnitude than the purely chlorinated ones. This has been observed in the two tests when 12 wt. % of commercial or industrial E+E material were co-combusted. The dioxins were always lower in concentration by a factor of 3 – 4 than the furans and did not add substantially to the total sum of the halogenated compounds in question.

In all tests the total dioxin/furan load in the raw did not exceed the typical operation window of TAMARA which is shown in the background of Fig. 11 and covers the range of 20 – 120 ng/m³. Samples taken after the flue gas had passed a charcoal filter resulted in residual PCDD/F concentrations of <0.001 ng/m³. Bromine containing homologues could not be detected. This means that the contribution of brominated species is of no concern for the emission of MSW incineration plants as far as a modern air pollution control system is installed.

CONCLUSIONS

Co-combustion tests of different types E+E waste and MSW in the Karlsruhe test incinerator TAMARA were performed looking for real effects in a modern MSW combustor. Up to 12 wt. % of E+E material was added to the basic fuel. The following most important results were obtained:

- The combustion process was not negatively influenced even if high amounts (up to 12 wt. %) of E+E material were added to the basic fuel.
- The increase in heating value improved the burnout of the bottom ashes.
- Residual organic compounds indicating unburnt flame retardants could not be detected in the flue gas.
- The levels of Cl in the feed were moderately, those of the flame retardancy related elements Br and Sb as well as those of a number of heavy metals were substantially increased by the addition of the E+E wastes. Some metals, especially Cu and Pb may be present in the metallic state and tend to sift through the grate. Hence a thorough metal separation from the E+E plastic waste prior to combustion is strongly recommended.
- The increased Cl and Br levels caused no significant increase of the concentrations of PCDD or

PCDF in the raw gas.

- The formation of limited amounts of brominated and chlorinated dioxins and furans was observed with the furans exceeding the dioxins by a factor of 3 – 4. For both classes of compounds mainly homologues carrying one Br atom were detected.
- At high input of E+E waste Br containing homologues added up to 50 % to the total load of dioxins and furans. The data obtained did not leave the typical operation window of TAMARA.
- Air emission sampling during some co-combustion tests resulted in PCDD/PCDF concentrations of $<0.001 \text{ ng/m}^3$ showing that activated carbon is effectively removing the moderate to low PXDD/PXDF concentrations in the raw gas to almost zero levels.

The co-combustion experiments did not show severe influences upon the quality of waste incineration. The expected promoting effect upon the production of Br containing dibenzo-p-dioxins and dibenzofurans stayed moderate even if high amounts of E+E material were added. In full scale incineration plants the co-feeding of high calorific waste fractions will be limited to 3 – 5 wt % as a worst case. In those cases the increase in dioxin and furan levels will stay within the window of the PCDD/F levels typically found in such incineration plants.

On the basis of the results presented here it seems a fair statement:

- MSW combustion is an ecologically acceptable and economically sound disposal route for limited amounts of specific E+E waste. The metal content, however, should be reduced as is done today in most recycling operations in order to reduce the maintenance of the grate and to minimise the amount of metallic species in the grate siftings.

ACKNOWLEDGMENTS

This project has been supported by the following associations: APME (Association of Plastics Manufacturers in Europe), BFRIP (Brominated Flame Retardant Industry Panel), EBFRIIP (their European equivalent), EFRA (European Flame Retardant association), FIEE (Fédération Française des Industries Electriques et Electronics), FZK (Forschungszentrum Karlsruhe), ZVEI (Zentralverband der Elektro- und Elektronikindustrie).

A number of people from different companies have contributed to the performance of the project: H. Geisert, H. Gramling, R. Härtel, H. Reis, R. Siegel (FZK), J.M. Falguière (Du Pont), R. Martin (APME), W. Pauli (ABB), M. de Poortere (EBFRIIP/BFRIP/EFRA), M. Rohr (Bayer). The authors are very grateful for all of these contributions.

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Table 1 Concentrations of selected elements in the materials of the 2nd campaign (data in mg/kg, consumer data of 1st campaign)

	basic fuel	consumer	commercial	industrial	new material
P	2080	250	2600	8100	1200
Cl	6150	3895	10990	1865	38550
Cu	112	1900	82	77500	137
Zn	430	620	1540	4720	292
Br	34	4290	15000	5750	8600
Cd	9	240	123	29	41
Sn	24	85	63	1230	18
Sb	26	2000	1950	2200	2630
Pb	600	146	96	1890	1890

Table 2 Lower heating value of feed, temperature in the combustion chamber, oxygen, HCl and HBr in the raw gas for all test trials

	H _l kJ/kg	T °C	O ₂ vol %	CO mg/m ³	HCl mg/m ³	HBr mg/m ³
ref.1.2	6960	894	9.7	1.2	730	3
cons.3%	7950	900	9.9	1.7	680	9
comm.3%	7910	912	9.9	2.1	900	204
ind.3%	7960	901	10.0	1.7	840	72
ind.6%	8480	893	10.4	3.6	850	131
ref.2.1	7440	892	9.9	1.2	750	3
ref.3.1	8880	930	10.0	0.0	790	4
ref.3.2	8770	912	10.3	0.1	760	3
n.mat.6%	10580	923	10.5	1.8	870	63
n.mat.12%	12440	949	10.5	0.0	1010	119
comm.6%	10260	926	10.5	0.1	860	157
comm.12%	12760	937	10.9	0.2	940	292
ind.12%	10840	932	10.6	0.3	800	141
ref.4.1	8840	939	9.9	0.3	670	4

Table 3 Br input and raw gas concentrations of chlorinated and mixed halogenated dioxins and furans

test	Br input mg/kg	PCDD ng/m ³	PCDF ng/m ³	Br _x Cl _y DD ng/m ³	Br _x Cl _y DF ng/m ³
ref.1.2	67	15.0	20.2	0	0
cons.3%	270	9.8	12.1	0	0
comm.3%	1979	19.8	23.6	3.13	12.4
ind.3%	606	12.6	14.2	1.2	5.0
ind.6%	1193	14.4	16.2	2.0	13.5
ref.2.1	68	8.4	10.1	0	0
ref.3.1	57	16.0	27.2	0.5	2.5
ref.3.2	45	18.2	28.2	0.5	2.5
n.mat.6%	757	16.3	27.8	1.1	7.1
n.mat.12%	1650	20.1	31.0	2.5	20.9
comm.6%	1297	8.8	11.7	1.9	11.4
comm.12%	2735	14.0	15.5	5.8	20.6
ind.12%	1000	14.9	16.9	6.1	15.6
ref.4.1	38	9.6	13.6	1.2	4.3

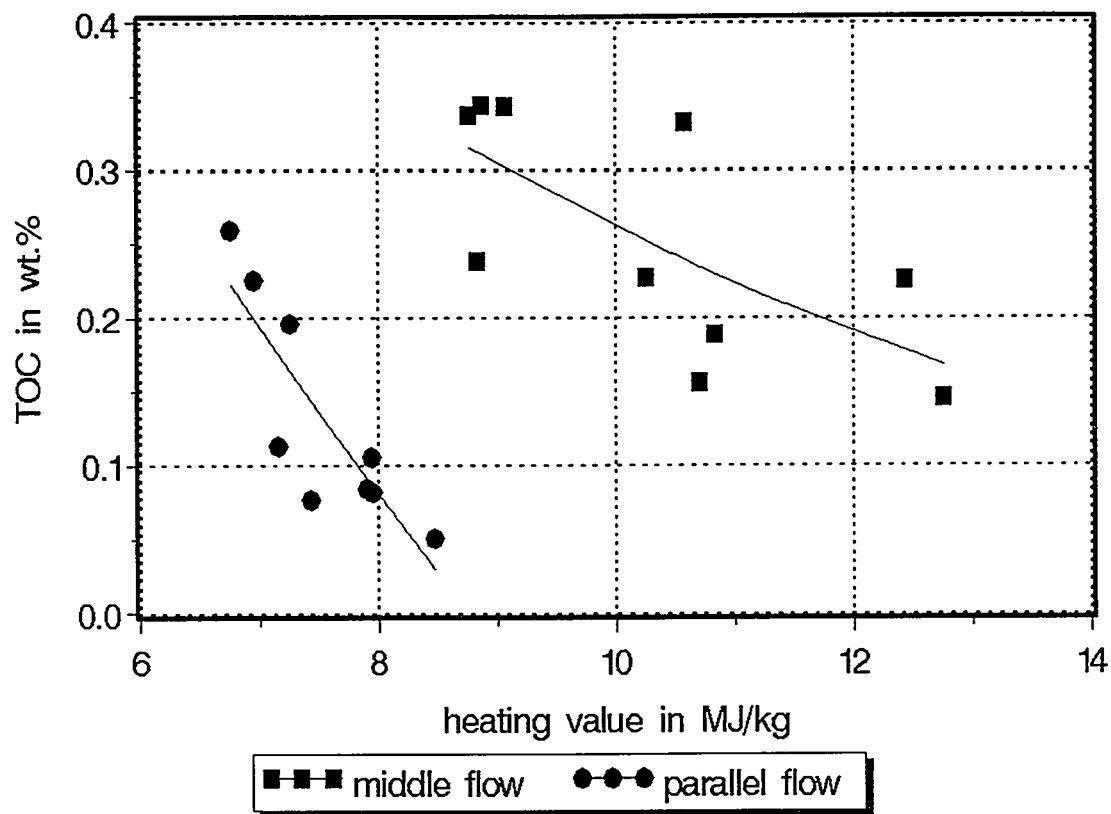


Fig. 1: TOC in the grate ashes vs. heating value of the feed

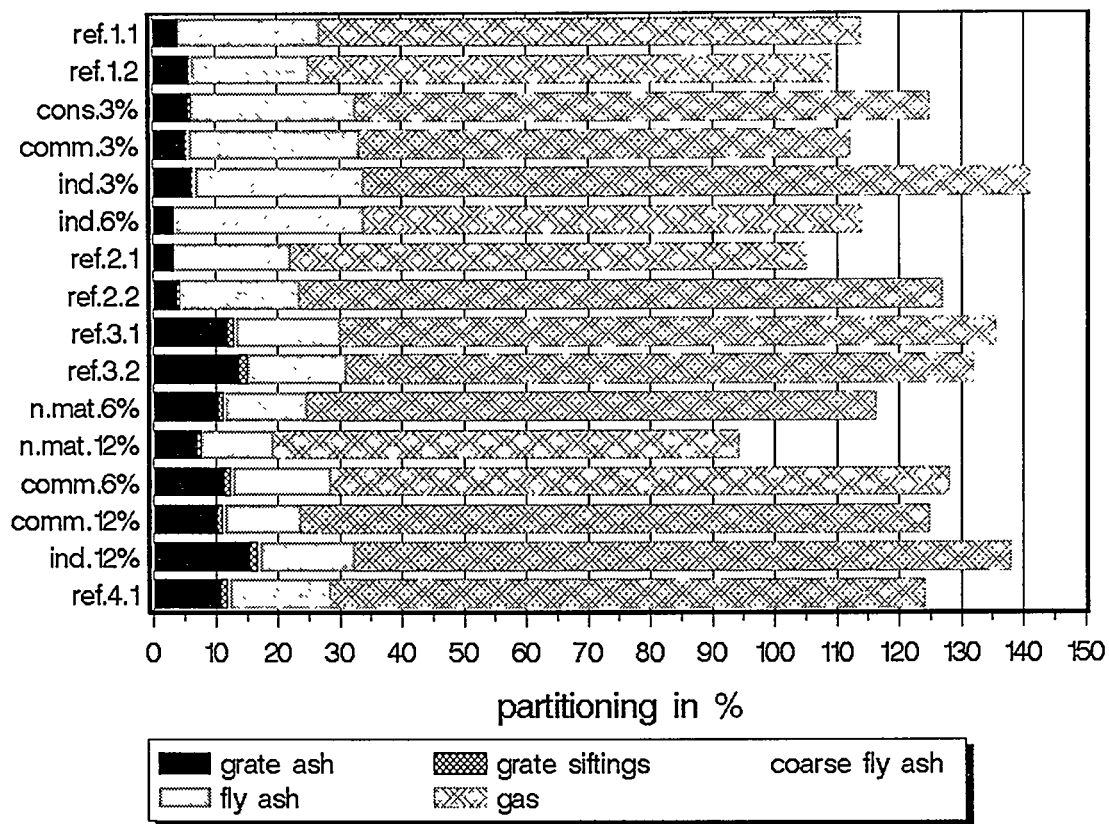


Fig. 2: Percent partitioning of Cl

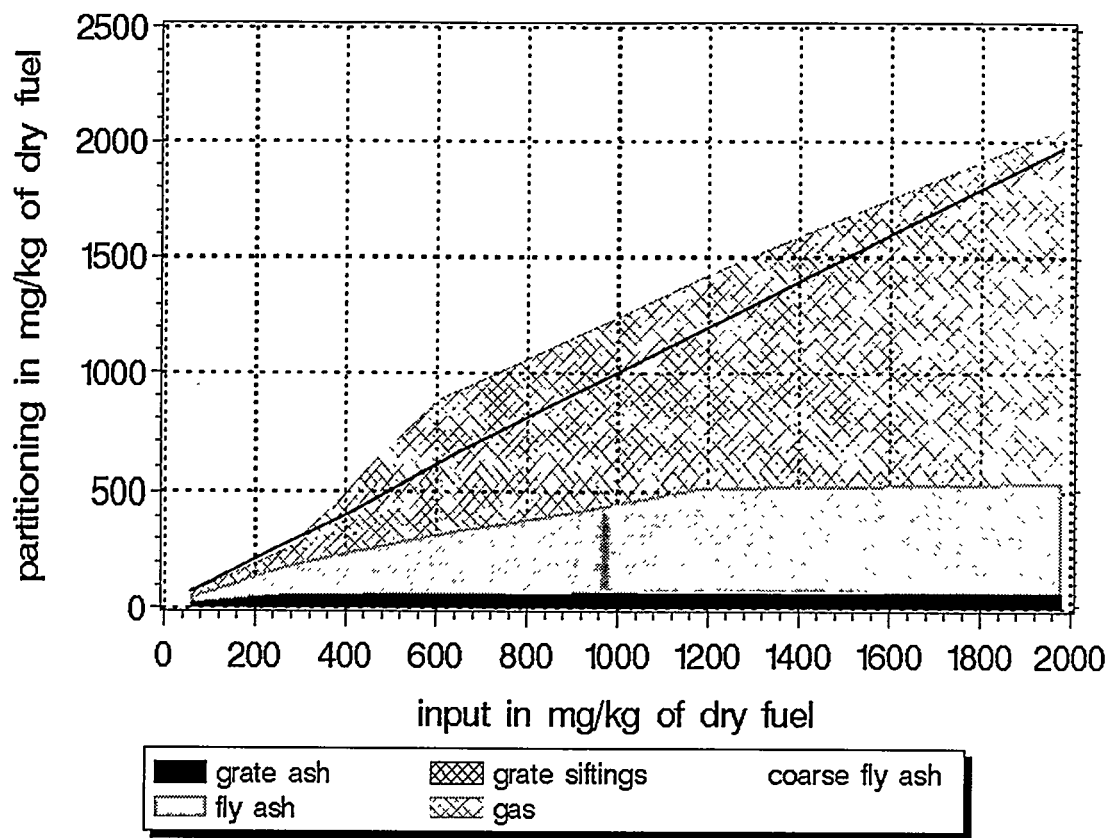


Fig. 3: Partitioning of Br in the parallel flow combustion geometry

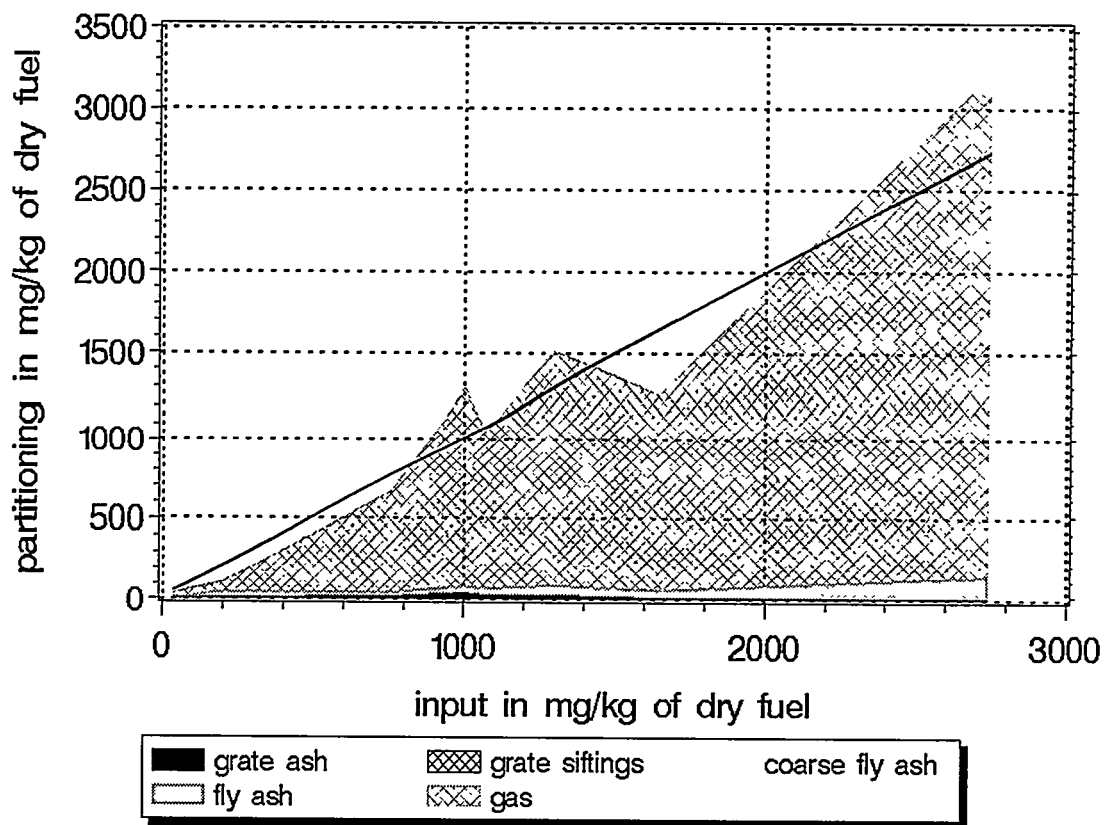


Fig. 4: Partitioning of Br in the middle flow combustion geometry

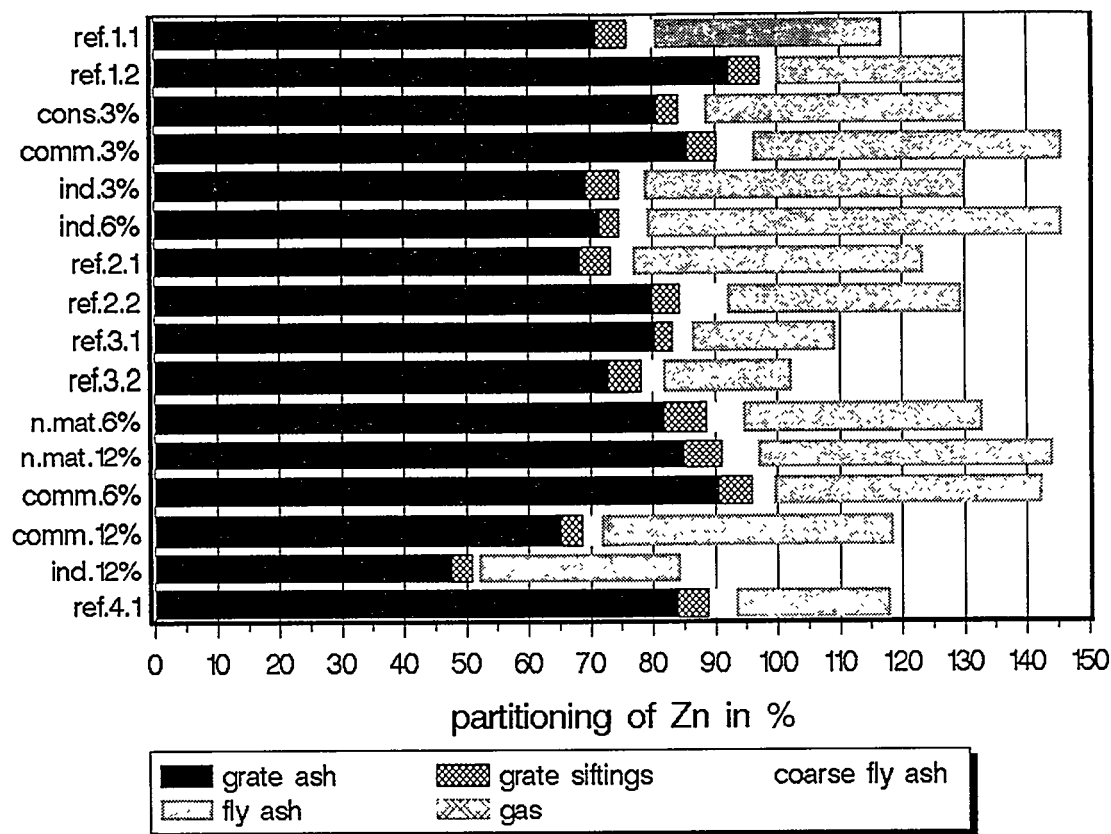


Fig. 5: Percent partitioning of Zn

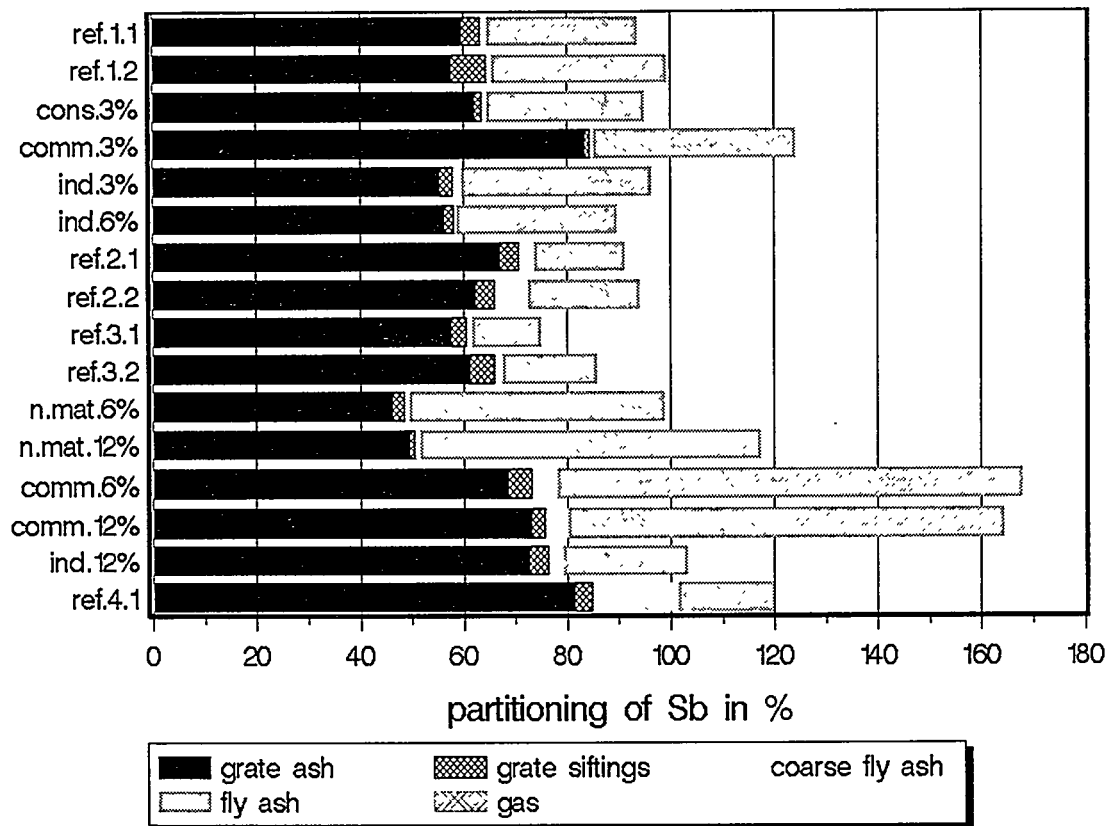


Fig. 6: Percent partitioning of Sb

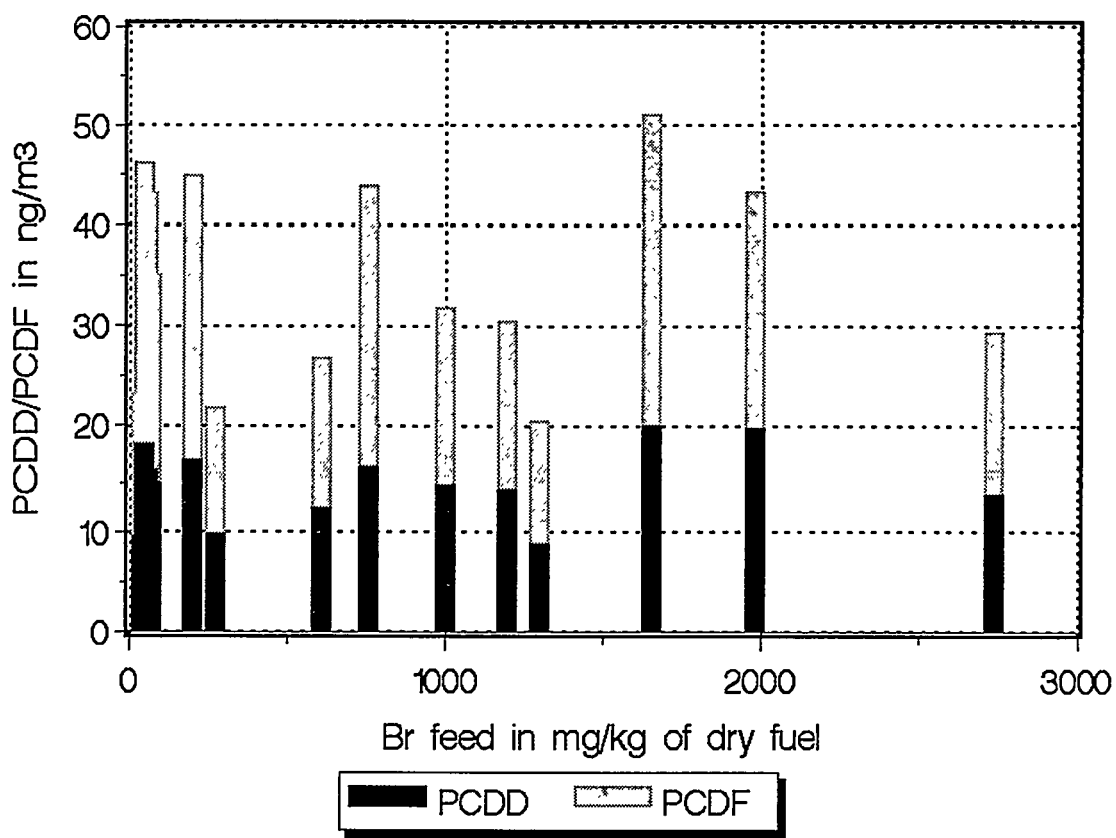


Fig. 7: Sum of PCDD/PCDF levels in the raw gas

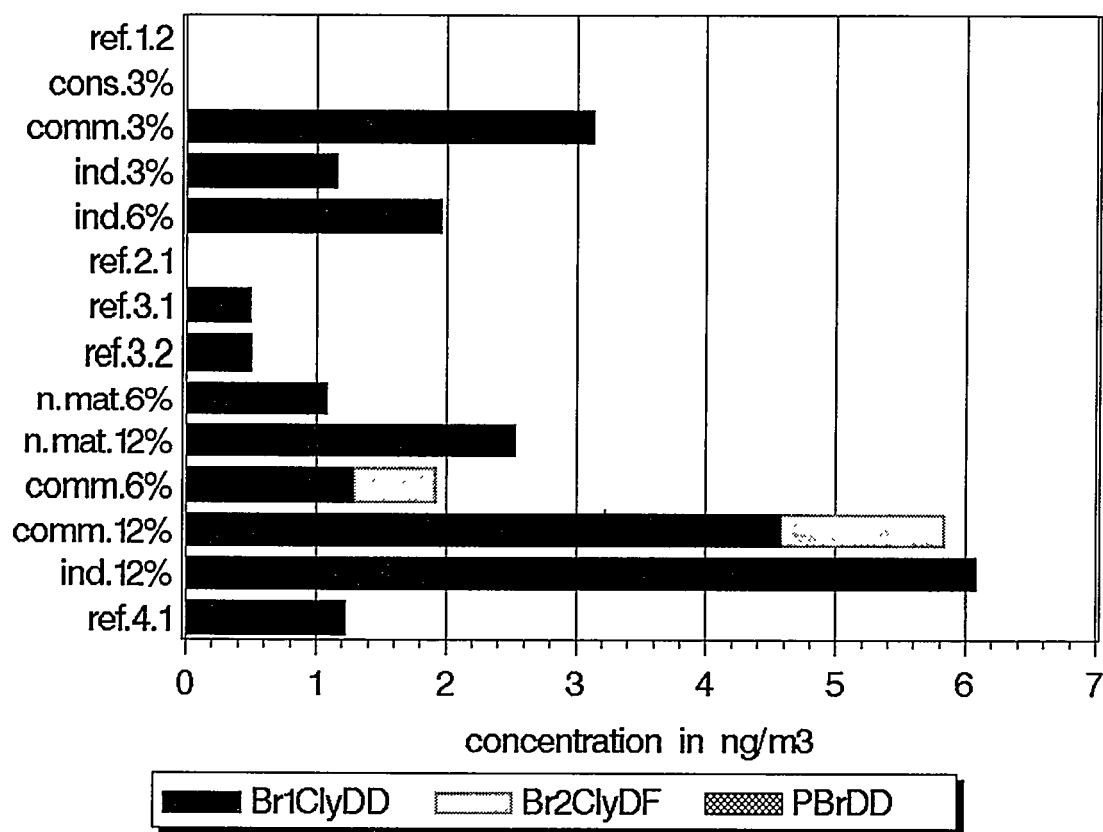


Fig. 8: Br containing dioxins in the raw gas

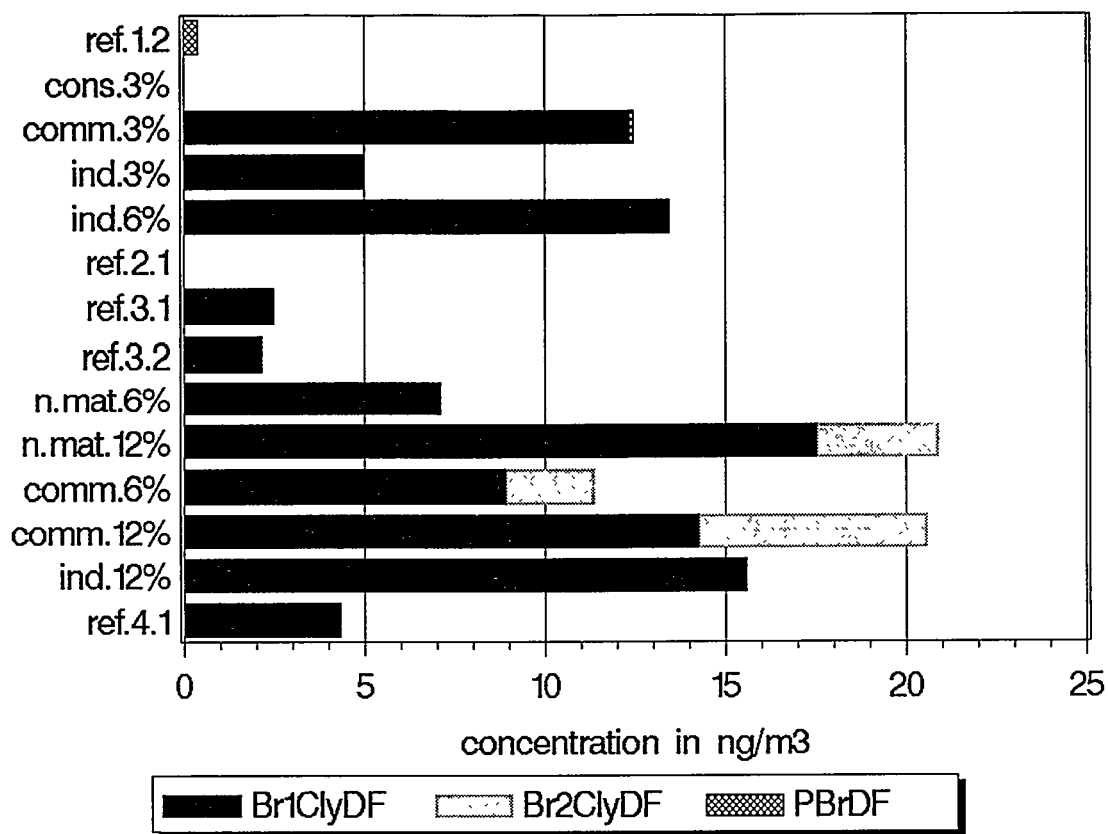


Fig. 9: Br containing furans in the raw gas

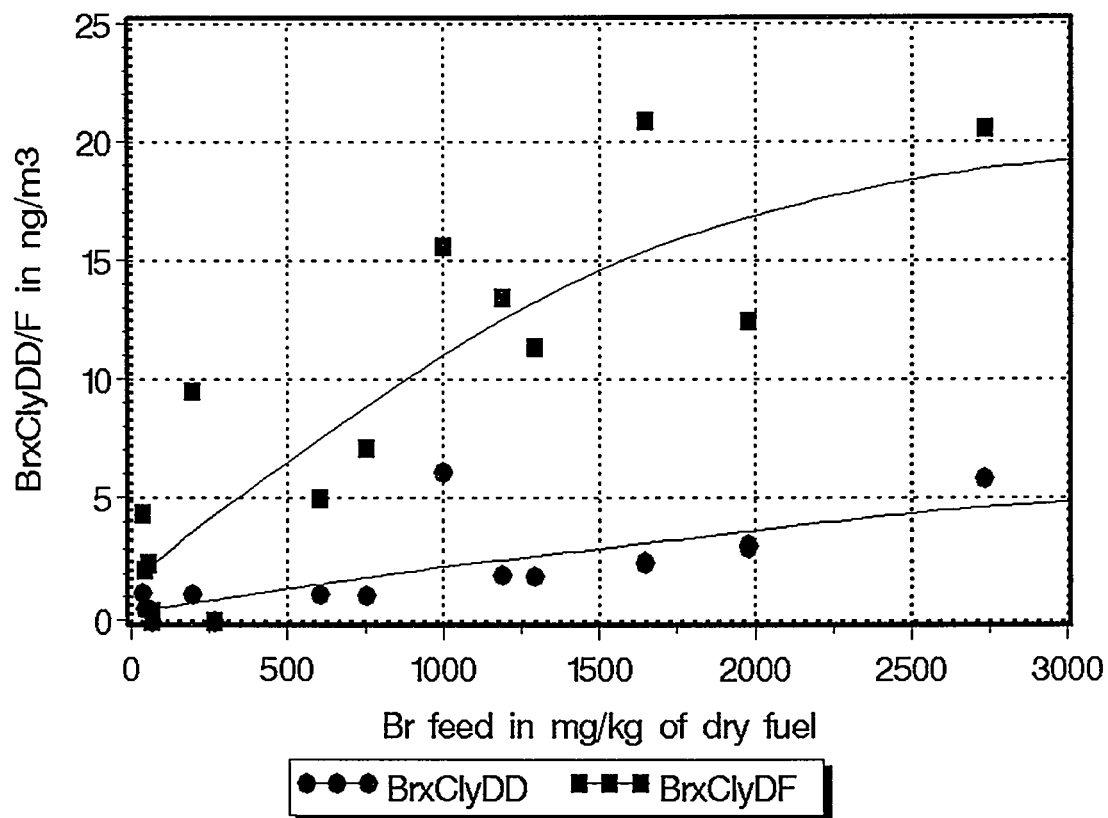


Fig. 10: Bromine containing dioxins and furans versus Br feed

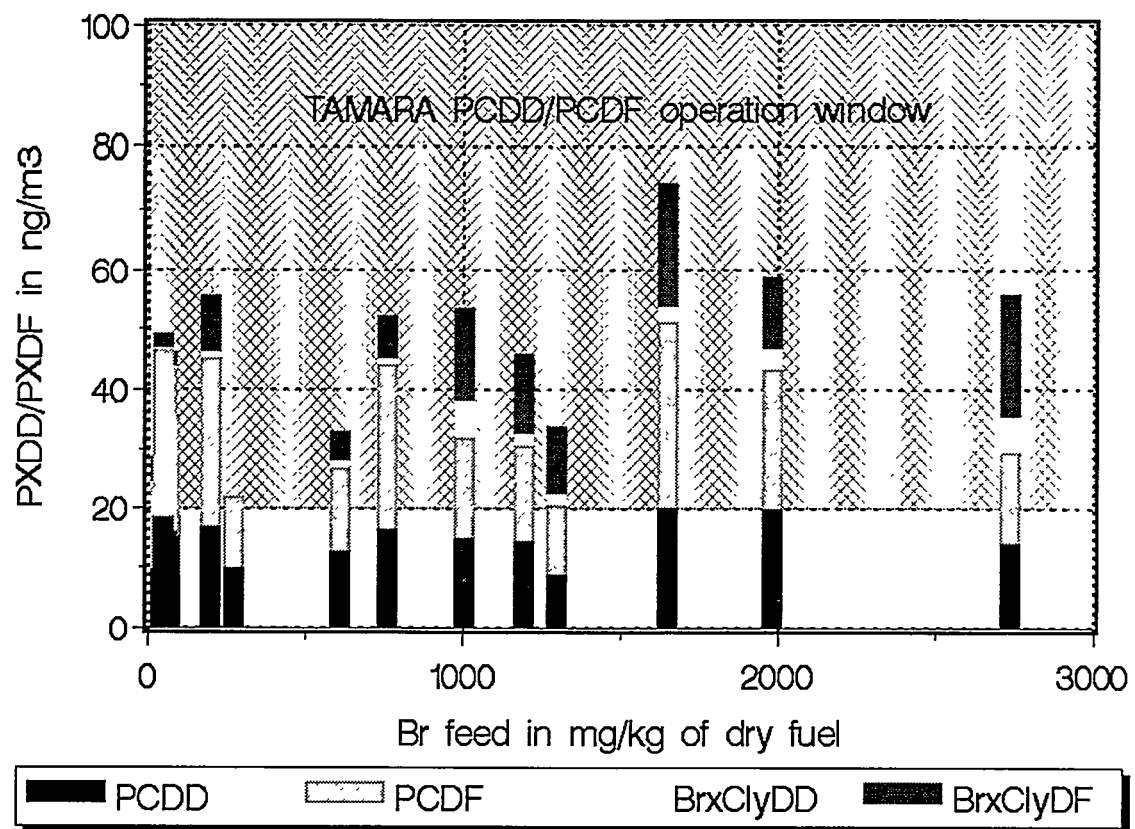


Fig. 11: Sum of halogenated dioxins and furans

Achieving 40 CFR Part 60 Subpart C_b CO Emission Requirement
On Large RDF-Fired Municipal Waste Combustors

Mathew J. Clark
HDR Engineering, Inc.
128 S. Tryon St., Suite 1400
Charlotte, NC 28202

Bryan S. Sturgies
HDR Engineering, Inc.
128 S. Tryon St., Suite 1400
Charlotte, NC 28202

INTRODUCTION

Carbon Monoxide (CO) is a colorless and odorless gas that is created when carbon based fuels are incompletely combusted. Some level of CO is produced in all practical carbon fuel combustion operations. Exposure to concentrations of CO above the permissible limit has been determined by the scientific community to be harmful to the general public. Congressional passage of the 1990 Clean Air Act required the U.S. Environmental Protection Agency (EPA) to establish concentration limits for CO as well as other products of the combustion process for affected facilities. As a result, the EPA recently promulgated 40 CFR Part 60, Subpart C_b for existing Municipal Waste Combustors (MWC). Included in these new requirements will be a CO emission concentration limit.

The refuse derived fuel (RDF) fired plant is one category of municipal waste combustor (MWC) that will be subjected to the new requirements. RDF is produced when municipal solid waste is processed to obtain a smaller and more consistent fuel particle size. RDF can be combusted to release energy for steam and/or electrical production. RDF is usually combusted by feeding it onto a traveling grate although other means have been developed, including co-firing with other fuels and fluidized bed combustion. RDF-fired unit capacity ratings are determined based on tonnage of fuel combusted per day (tons/day). The EPA established the new emission requirements based on this capacity rating. Large RDF facilities (more than 250 tons/day) will be limited to a CO concentration of 200 ppm_{dv} @ 7% O₂. Although a recent court ruling has delayed the execution of the new requirement, the final CO concentration limit for large RDF-fired "units" is expected to remain unchanged.

Eight large RDF plants were surveyed to characterize their ability (or inability) to meet the newly promulgated requirement for CO. The reported range of typical CO emission concentrations was from 50 to 400 ppm_{dv} @ 7% O₂. Some units will not have difficulties meeting the new CO emission concentration limit and some will have to consider operational changes and possible equipment modifications to meet the new requirement. This paper attempts to define what equipment and operational characteristics allow for the performance differences observed and also identifies techniques that can be implemented to help compliance efforts.

RDF PLANT BACKGROUND

The history of the RDF-fired waste-to-energy (WTE) plant is relatively short in comparison to other forms of combustion technology such as coal, oil, gas, and wood firing. The first applications used RDF as a supplementary fuel for conventional electric utility boilers. RDF was usually suspension-fired in combination with pulverized coal or atomized oil or gas. By the mid 1970s, new plants were being designed primarily to burn RDF. The designs were conventional stoker grate arrangements.

The first RDF facility designs were based on the proven technology of wood firing. It was believed at that time that the combustion characteristics of wood were similar to RDF. Fuel feed systems and boiler design both relied heavily on wood fired designs. These wood fired based designs incurred various problems leading boiler manufacturers and equipment designers to make significant improvements in the combustion process of RDF on stoker grates over the next ten years.

Today there are approximately eleven large waste-to-energy plants operating twenty-eight boilers on RDF. Four boiler manufacturers dominate the landscape by providing the majority of boilers for these

large RDF applications, they include; ABB-CE (12 boilers), Babcock and Wilcox (7 boilers), Riley Stoker (5 boilers), and Zurn Industries (4 boilers). Each of these manufacturers have their own design signature that encourage or inhibit compliance with the new regulations.

Due to implementation of more stringent 40 CFR Part 60 Subpart C_b emission requirements for existing large RDF-fired facilities, operators must consider their impact and possible retrofit options. Modifications may include acid gas scrubbers for hydrogen chloride (HCl) and sulfur dioxide (SO₂) control, fabric filter baghouses for particulate control, and selective non-catalytic reduction systems for nitrogen oxide (NO_x) control.

FACILITY DESIGN CONSIDERATIONS

The investigation of various CO emission levels was based on the “three T’s of combustion”, time, temperature, and turbulence. The majority of combustion takes place prior to the furnace exit. The design of the fuel feed system and furnace are two areas of system design that directly affect the three T’s of combustion and determine how complete the combustion of the RDF will be. The fuel feed system must distribute the fuel evenly on the grate. This insures that a constant undergrate air pressure will deliver the air where it is needed. The geometry of the furnace and the overfire air (OFA) ports provide the turbulence necessary for good combustion. The grate area and furnace volume determine the residence time and temperature of the gas particle as it travels through the furnace.

Fuel Feed System

The typical fuel feeding system injects the fuel in the front of the boiler and tosses it towards the rear. The objective of the system is to get the best fuel distribution front-to-back and side-to-side on the grate. Typically, three to eight individual feeders are used. Some feeders have the ability to vary the transport air pressure to improve front to back distribution. These feeder types generally provide a more even bed depth and consequently better mixing.

Many types of conveyors and system designs are used to divide and consistently convey the RDF to the feeder. Two systems commonly found are shown in Figures 1 and 2. The largest contribution the conveying system can make to controlling CO concentration emissions is to not plug. A fuel system plug often results in high CO spikes while the plug is being cleaned. However, considering that the CO emission levels are based on a 24 hour average, the conveying system does not make or break a units ability to meet the limit.

Boiler Design

The furnace is the envelope in which the majority of combustion takes place. Fuel and air are introduced on the grate which provides the floor of the “box”. The size (or volume) of the box determines how much time gas particles will spend before exiting. The grate size and speed determines how much time the fuel will spend in the furnace and the bed depth required to meet steam demand. Overfire air provides the oxygen and turbulence to complete the combustion process started on the grate.

One factor considered by boiler designers is the amount of energy (Btu/hr) released per cubic foot (ft³) of volume. This factor is termed “furnace liberation rate” and is expressed in Btu/hr/ft³. Table 1 depicts liberation rates for the RDF facilities surveyed. This number varies significantly for the

identified units. The magnitude of this number is not significantly correlated to the CO level as can be seen by the accompanying graph of Typical CO vs. Liberation Rate, Figure 3.

A more important indicator of CO emission concentration controllability is the physical geometry of the furnace. The two lowest typical CO levels were reported by facilities with Babcock and Wilcox's CCZTM design furnaces. This furnace design, shown in Figure 4, includes two opposing noses in the lower portion of the furnace. The significance of this furnace design is not related to furnace size, but to design features which promote better mixing of the fuel and available combustion air. In contrast, competing furnace designs do not encourage turbulence above the firing grate, mainly due to the lack of furnace constriction created by multiple noses.

Another design criteria used by boiler design engineers is grate heat release rate. This factor is expressed in Btus/hr/ft² and is simply the fuel heat input divided by the grate area. For a desired grate heat release rate and known fuel input, the grate dimensions are set. The grate heat release rate is fairly consistent for the units surveyed as depicted in Table 2 and its accompanying graph, Figure 5. Again, little correlation was observed between CO levels and grate heat release rate. It is important to note that grate size and speed will mandate the bed depth on the grate for a given firing rate. From this data, it can be observed that there is consensus that a bed depth of 6 - 12 inches results in good undergrate air distribution and allows for burnout of the fuel on the grate, provided the fuel is evenly distributed front-to-back and side-to-side.

Overfire Air System

The goal of the overfire air (OFA) system is to promote mixing of fuel and combustion air to complete the conversion of carbon to carbon dioxide (CO₂) without adding substantially to the undergrate air (UGA) provided for primary firing of the fuel on the grate. Boiler suppliers have taken very different approaches and made significant changes to these systems during the design evolution. The conventional front and rear wall, multi-level ports were the starting point for all boilers. As Babcock and Wilcox developed the CCZTM furnace for RDF firing, the main overfire air ports were located in the bottom nose. B&W also increased the diameter of the ports as their design evolved. This furnace configuration results in the lowest CO levels reported by the RDF plant operators surveyed. The design evolution of the ABB-CE boilers went to a proven technology implemented on CE utility boilers, tangential overfire air nozzles. This configuration is shown in Figure 6. While this technology has proven itself successful in many applications on different fuels, operators of ABB-CE RDF-fired boilers have chosen to return to conventional front and rear wall OFA nozzles, for reasons other than CO control. Other boiler designs are using OFA ports located at various elevations on the front and rear walls. Optimization programs have shown some success controlling CO with the conventional arrangement of OFA ports. To achieve this, operators must carefully set up a matrix of various OFA pressures and OFA/UGA splits while recording CO emissions. The settings can be optimized for the boiler load and fuel conditions at the time of setting. Unfortunately, these may not be the optimum settings for all conditions.

OPERATIONAL CONTROL MEASURES

Operational techniques can be employed by plant operations staff to help mitigate excess CO emissions resulting from combustion incompleteness. Measures such as controlling the fuel distribution and bed depth, steady steam load control, overfire air location and header pressure adjustment, and firing of

auxiliary fuels can be implemented to reduce the average CO concentration measured and reported by continuous emissions monitoring systems (CEMS). Several facilities surveyed use these techniques, independently or in combination to help them comply with the existing and new CO emission concentration limits.

In general, these techniques can be categorized into two types; pre-combustion techniques which attempt to create optimum combustion so that generation of CO is limited, and post-combustion techniques which attempt to reburn the CO released from the grate before it exits the furnace.

Maintaining an even distribution of fuel on the grate is critical to controlling CO emission concentrations. Improperly delivered fuel to the grate can result in piles of fuel which create a reducing environment at the ignition point. Additionally, undergrate combustion air bypasses piled grate fuel due to the induced pressure drop created and compounds the problem, thus poor combustion and elevated CO levels. The causes for uneven fuel distribution include the design of the fuel delivery system, as discussed above, and instability of the fuel demand signal from the boiler controls.

The ideal conditions for CO control include a constant fuel feed rate and air flow. This is of course impossible due to variability of the fuel characteristics and changes in boiler demand. Fuel characteristics cannot be controlled by the plant operator, but steps can be taken to reduce changes in the boiler demand. The control system should be configured so that steam header pressure controls the fuel feed rate. Other control schemes may be currently utilized by operators that are counter-productive to CO control. For instance, programs which attempt to change boiler demand among operating boilers to optimize efficiency may result in additional fuel demand swings.

Unsteady fuel feed rates will lead to uneven distribution of fuel on the grate. It also can contribute to increased incidences of fuel system pluggage which further exacerbates the problem and leads to a vicious cycle.

Co-firing RDF with other grate fired solid fuels such as stoker coal or wood chips is another pre-combustion methodology for CO control. Co-firing with these higher heating value fuels increases furnace temperature and encourages CO destruction. This method is available but usually prohibitive due to the cost of the fuel and the operational and maintenance costs considerations. Operators of plants designed to co-fire solid fuels have found that higher grate temperatures lead to slagging problems on the grate, and have discontinued co-firing.

As previously discussed, injection of overfire air is a post-combustion CO control technique that is widely used by RDF-fired facility operators. The technique is employed to oxidize the CO in a high temperature, highly turbulent area of the furnace above the firing grate so that carbon reburn will occur. The most common problem associated with OFA injection is determining where to put the air and at what pressure it should be injected. CO gases are primarily emitted from the firing grate in a stratified manner and usually do not become evenly dispersed in the flue gas stream until after passing through the boiler's convection pass. Because the firing grate is in constant motion, excess CO emitted from the grate as a result of fuel piling becomes a moving target. To combat this problem, a grid of OFA should be generated above the firing grate to oxidize the excess CO regardless of where it is being generated on the grate. More specifically, OFA should be injected at different elevations and progressive pressures to allow for greater penetration and full coverage of the furnace. RDF facilities having success controlling CO inject OFA at elevations from 5 to 50 feet above the grate and vary OFA header pressures from 5

inches to 30 inches wg. Each individual boiler should be evaluated to determine the optimum locations for, and pressures of, injected OFA.

The use of auxiliary burners is becoming more widespread for CO control applications. Burners are located above the firing grate and fired with approximately 20% excess air to create a conducive environment for secondary combustion of the CO gases emitted from the firing grate. Clean burning natural gas is the fuel of choice, however, #2 fuel oil can be used if natural gas is unavailable. Dual fuel burners are recommended where gas curtailments are a potential concern. The burners must be strategically located above the furnace to reburn CO gases released from the firing grate. Control can be manual or automatic using a furnace temperature control signal and/or the CEMS corrected CO signal. This post-combustion CO control methodology, much like co-firing solid fuels, can be prohibitive due to the fuel and equipment costs. However, if CO compliance is unachievable through other methods described previously, introduction of a second fuel may be necessary to continue operation.

CO - DIOXIN EMISSION CORRELATION

The Subpart C_b CO emission concentration limit was developed with the assumption that both Dioxin/Furan and CO emissions were indicators of complete combustion. In a strict sense, this may be true, especially for plants built without acid gas control and designed for higher allowable particulate emissions. For these plants, dioxin emissions may be extremely high.

In the case of the Norfolk Naval Shipyard Steam Plant in Portsmouth, VA, operated by the Southeastern Public Service Authority of Virginia, Dioxin/Furan emissions are well below the proposed limits while CO levels have not been maintained below the proposed limit. This facility was recently retrofitted with spray dryer absorbers and fabric filters. Furthermore, Penobscot Energy Recovery Company (PERC) in Orrington, Maine has encountered a similar non-correlation as illustrated in Figure 7 which demonstrates that the perceived correlation between low CO concentration levels and low Dioxin/Furan levels does not always exist.

CONCLUSIONS

Control of CO emission levels in a RDF-fired application is not achieved by one single action or installation of a certain piece of equipment. The plant operator must be cognizant of all variables which affect CO emissions.

Most operators of large RDF plants have the tools and knowledge to operate within the new emission concentration limit for CO. Others will need to embark upon programs to identify and implement the changes required to lower CO emission concentration levels.

Based on the results of this study and considering the economics, the following recommendations would be made for an operator considering a CO control program. These items are listed in descending order of importance:

1. Implement boiler control program changes to level-out fuel feed rates to the greatest extent possible.

2. Develop OFA testing matrix and conduct tests to establish OFA settings and UGA/OFA splits for various loads and fuel conditions.
3. Consider boiler geometry retrofits which will result in better combustion.
4. Retrofit fuel feed system.
5. Implement natural gas and/or fuel oil auxiliary burners for CO control.

Actual equipment retrofits would require significant capital expenditures. Before any retrofit is implemented, an operator would need to extensively study the costs and benefits to justify the project and to make sure it would be effective in reducing CO emissions. The only benefit of such a retrofit may be achieving the future CO emission concentration limit. The actual benefit to the environment should be considered by governmental agencies prior to imposing costly permit requirements on individual operators.

ACKNOWLEDGMENTS

1. Lane Brown, Plant Manager, Southeast Public Service Authority of Virginia, Portsmouth, Virginia
2. Carlo White, Technical Manager, Penobscot Energy Recovery Company, Orrington, Maine
3. Matt Hughes, Environmental Engineer, Maine Energy Recovery Company, Biddeford, Maine
4. Mike DePero, Environmental Engineer, Solid Waste Authority of Palm Beach, West Palm Beach, Florida
5. Wayne Hanson, Plant Manager, United Power Association, Elk River, Minnesota
6. Robert S. Sommers, Plant Manager, Solid Waste Authority of Central Ohio, Columbus, Ohio
7. Mark Turner, Manager of Environmental Services, SEMAS RR Facility, Rochester, Massachusetts
8. Ronald Davies, Plant Manager, Honolulu Resource Recovery Venture, Honolulu, Hawaii

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Table 1. Comparison of Surveyed Units' Liberation Rate

Facility	Units	Capacity TPD/unit	Boiler Manufacturer	Boiler MCR steam/hr	Furnace Vol. cu-ft	Typical CO ppmdv	Liberation Btu / hr / cu-ft
Palm Beach	2	900	B&W CCZ	322,000	32,787	55	14,030
MERC	2	300	B&W CCZ	105,000	7,092	90	21,151
Elk River	1	600	B&W	176,000	16,895	125	14,882
SEMASS	3	900	Riley Stoker	280,000	42,120	140	9,497
PERC	2	350	Riley Stoker	133,400	11,232	200	16,967
Columbus	4	500	B&W	165,000	9,185	300	25,663
SPSA	4	500	CE, VU-40	180,000	17,658	400	14,562
Honolulu	2	890	CE, VU-40	244,000	26,532	100	13,138

Table 2. Comparison of Surveyed Units' Heat Release Rate

Facility	Units	Capacity TPD/unit	Boiler Manufacturer	Boiler MCR lbs steam/hr	Grate Area sq-ft	Typical CO ppmdv	HR Rate Btu / hr / sqft
Palm Beach	2	900	B&W CCZ	322,000	630	55	730,159
MERC	2	300	B&W CCZ	105,000	220	90	681,818
Elk River	1	600	B&W	176,000	399	125	630,147
SEMASS	3	900	Riley Stoker	280,000	600	140	666,667
PERC	2	350	Riley Stoker	133,400	294	200	648,202
Columbus	4	500	B&W	165,000	342	300	689,223
SPSA	4	500	CE, VU-40	180,000	399	400	644,468
Honolulu	2	890	CE, VU-40	244,000	396	100	880,230

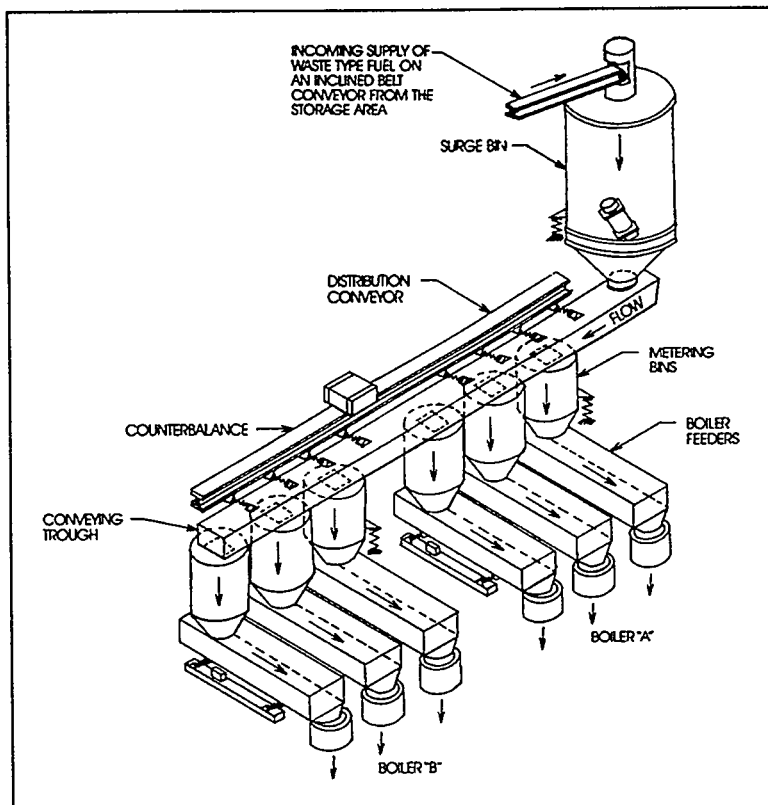


Figure 1

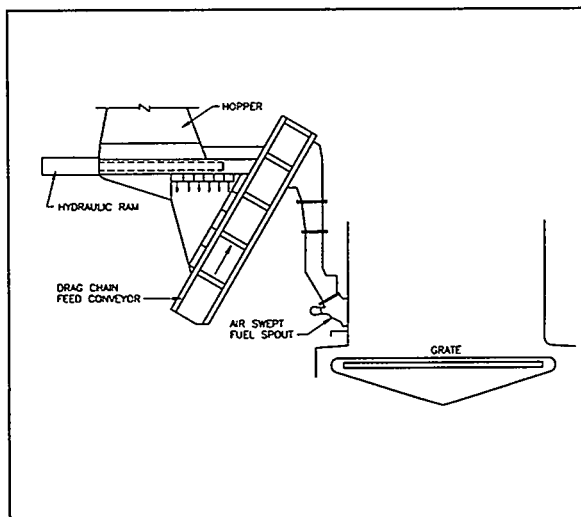


Figure 2

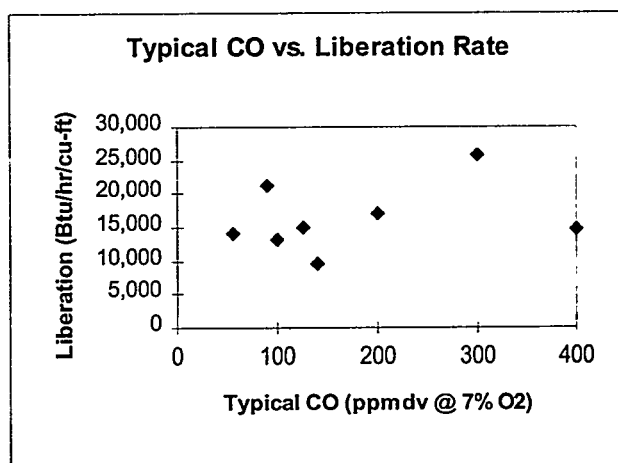


Figure 3

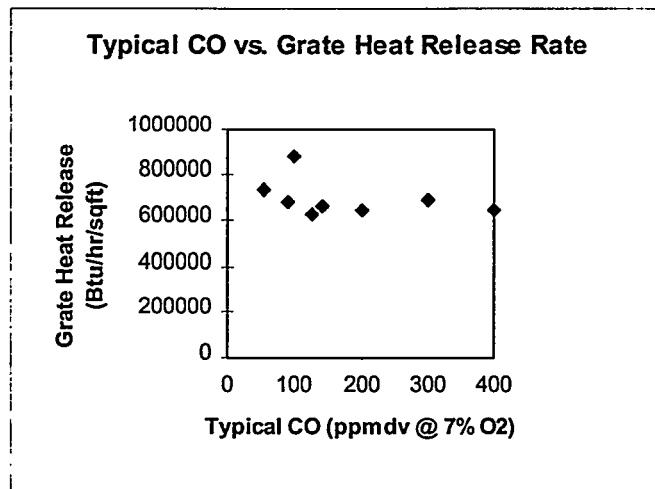


Figure 5

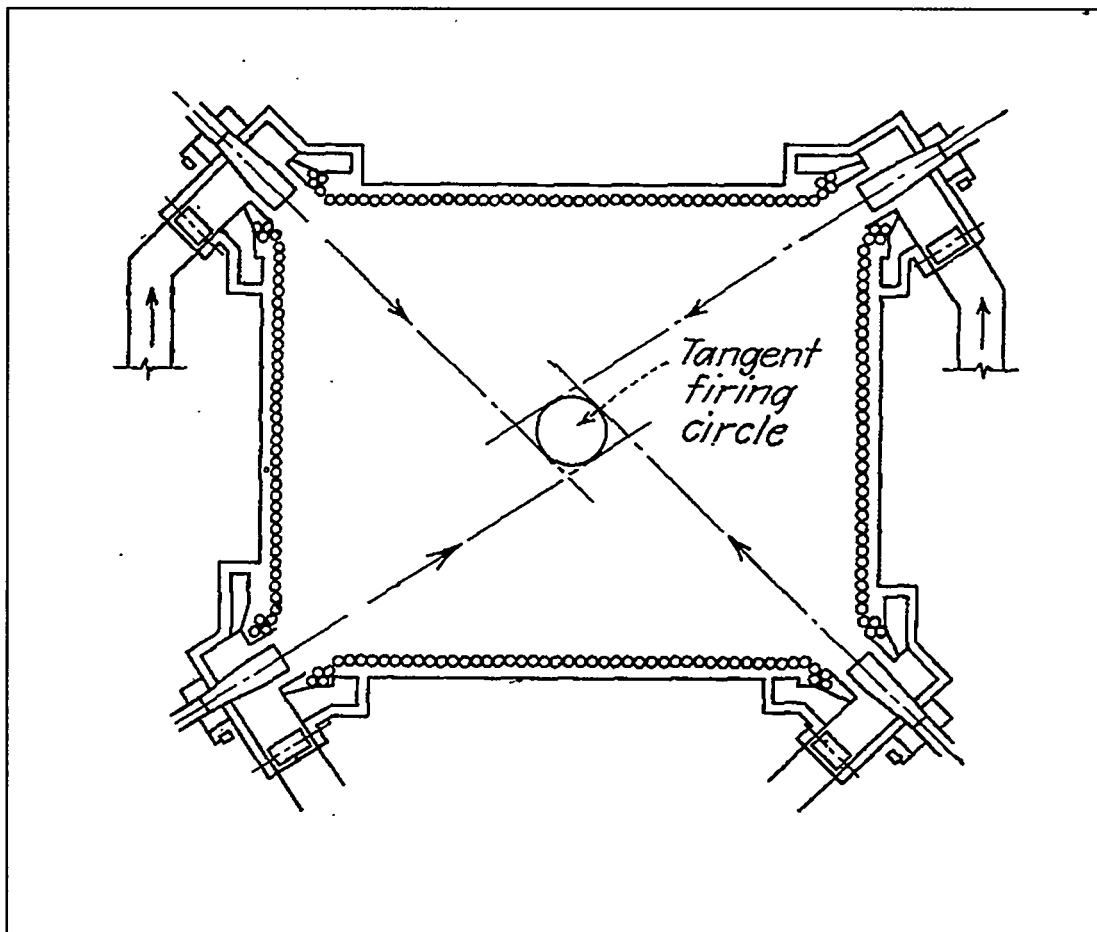


Figure 6

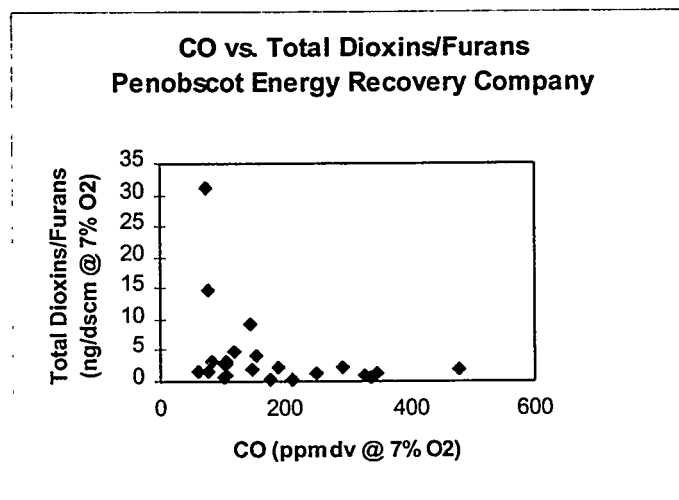


Figure 7

TECHNICAL SESSION II

Risk Communications

Promoting Positive Safety News -- The American Ref-Fuel VPP Experience

Lyle R. Hanna
American Ref-Fuel Company
777 North Eldridge Parkway
Houston, TX 77079

INTRODUCTION

American Ref-Fuel has a documented record of being a safety leader in our industry. In fact, American Ref-Fuel is only the third company of *any* industry to have all of its operating facilities designated as Voluntary Protection Program (VPP) Star worksites by the U.S. Occupational Safety and Health Administration (OSHA). While we're proud of our safety accomplishments, this has presented a whole new challenge -- namely how to promote this message to a media and public who may be largely indifferent to our safety practices unless there is a major problem. This paper examines the company's rationale for pursuing publicity of our safety record as well as detailing implementation of that strategy to date.

WHY THE 'SAFETY FIRST' PHILOSOPHY EXISTS

Providing safe working conditions for employees and instilling work habits to help employees protect themselves and others are the right things to do, period. The moral and ethical values of individuals and companies dictate that accidents and injuries can, and should, be avoided. From a business standpoint, the cost of safe work practices need only to be contrasted against today's spiraling medical and legal costs to see the positive impact safety can have on the bottom line. A third consideration -- which incorporates both the ethics and business sense of the company -- is image. If a company is perceived in its market and the community it serves as being extremely safe (or unsafe), there will likely be associations made between that and other attributes of that same company.

So if safety is such a universally accepted concept, why are there so few "good news" stories about it? Why does the notion of an OSHA visit bring sweaty palms? Why do companies who accept, or are forced to accept, blame for accidents, not aggressively promote that fact they often take extraordinary efforts to prevent accidents and injuries? Some of these answers lie in the conventions of safety reporting, the nature of the media and its customers, a shortsighted view of OSHA's role and an underestimated value of what public relations can mean on this topic.

AMERICAN REF-FUEL AND THE VPP

According to OSHA, the Voluntary Protection Program was created in recognition that compliance enforcement alone can never fully achieve the objectives of the Occupational Safety and Health Act. Good safety management programs that go beyond OSHA standards can protect workers more effectively than simple compliance. VPP participants are a select group of facilities that have designed and implemented outstanding health and safety programs. Being designated as a Star participant means a company has met all VPP requirements. In OSHA's own words, "The VPP application process is designed to be rigorous, to assure that only the best programs qualify." The numbers back up the agency's claim. Of the six million worksites OSHA is responsible for monitoring, fewer than 300 have been designated as Star sites. When American Ref-Fuel received the Star designation at our Niagara Falls, New York facility in March of 1996, we joined Mobil Chemical (19 sites) and Aurora Meat Packing (2 sites) as the only companies in America with all of its multiple operating locations as Star sites. In addition to having the first waste-to-energy plants named as VPP stars, we believe that we are the youngest company to ever attain the VPP Star and that our Southeastern Connecticut plant has the fewest employees of any VPP Star site.

American Ref-Fuel first became involved in VPP when Nancy Adam's OSHA's Long Island area director encouraged Hempstead plant officials to participate. After attending a conference hosted by the VPP Participant's Association, American Ref-Fuel representatives saw the benefits of the program and how well it dovetailed with our collaborative culture that encourages employees to "think like owners." The next step was to create a task force to perform a self-assessment of how the Hempstead facility stood with regard to OSHA requirements and determine actions needed to bring the plant to VPP standards. More than 100 items were identified. The plant manager and safety supervisor then organized a kickoff rally where they invited a representative from Hoechst Celanese, a VPP mentor company, to explain the benefits of the program. Among those benefits are improved employee motivation to work safely, yielding better quality and productivity; reduced workers' compensation costs; community recognition; and generally 60 to 80 percent fewer lost workday injuries.

The OSHA Region 2 office examined records, training plans and other documentation. An examination team toured the plant, interviewing employees from across the entire plant staff to determine management commitment and employee participation in the safety process. As James Stanley, deputy assistant to the Secretary of Labor explained, "We look at companies where the overall philosophy is that employees are an asset, not just a cost."

The Hempstead plant was designated as a Star site in October of 1994. We were then able to build on this success with subsequent Star recognitions at Southeastern Connecticut in May of 1995, at Newark, New Jersey in August of 1995 and Niagara Falls, New York in March of 1996. American Ref-Fuel has since acquired the SEMASS facility in Rochester, Massachusetts. Our goal is to apply our safety culture and the lessons learned at our other facilities to make that plant a Star facility as well.

One example of how this attention to safety is reflected on the bottom line is in the area of worker's compensation coverage. The National Council on Compensation Insurance, Inc. calculates an annual rating on behalf of the insurance industry. One statistic used is an experience rating modifier (ERM) where an average company in a given industry is given a factor of 1.0. A higher or lower factor results in a higher or lower premium. Based on our favorable history, American Ref-Fuel's ERM factor is .77, resulting in a 23 percent credit on our base premium. Translated into dollars, that one fact alone is worth an annual savings to our company of approximately \$155,000.

SPREADING THE NEWS -- WHY WE WANT PEOPLE TO KNOW WE'RE SAFE

Shouldn't we be satisfied that our people are returning home safely each day and that the company is saving money as a result? As someone who has spent his career in media and public relations, my answer is a definite no. There are several reasons to, in the parlance of the trade, "go positive" with this news. Among these are the opportunity it presents to report safety rather than lack of it, the chance to enhance relationships with your employees and other stakeholders, the ability to counteract other types of media attention, the concept of "success by association" and to help satisfy an overall "thirst" for information.

Safety is something we have done well throughout our company's existence. The difficulty has been finding a way to state that fact in a positive sense. The reality is that safety reports are most often quoted in injury statistics, time lost due to accidents or other quantifiable terms that measure the

exceptions to safety. As few as these incidents may be, they still don't present a positive message to an outside audience. Imagine a news release that begins, "XYZ company is proud to announce that only four people were hurt on its premises last quarter..." The elite nature of the VPP Star program, on the other hand, presents clear evidence that the company puts a high priority on safety, and delivers on that commitment.

In the evaluations American Ref-Fuel has received on our VPP applications, the OSHA personnel have always given us high marks for the level of employee involvement in the safety process. The employee input has been valuable in other ways as well. They are often the ones who present the image of our company. For instance, since our Hempstead plant began processing waste in 1989, more than 18,000 visitors have toured the plant. While there are more formal aspects of the tour, such as a video in the conference room, the more favorable comments usually have to do with how knowledgeable and friendly our crane operators and other plant personnel have been toward the guests. The VPP status gives these employees an extra sense of pride. This is further underscored by the fact that every time the company has been received a Star designation, there has been a big recognition dinner for all plant employees and spouses to gather and celebrate.

Our stakeholders extend beyond the realm of our employees. Community leaders attend our VPP events to congratulate our people and to share in the limelight of the positive image this casts on the community at large. In Connecticut, the state's Business and Industry Council has followed OSHA's lead in presenting its annual Safety Award to American Ref-Fuel's Southeastern Connecticut facility in Preston. Because American Ref-Fuel is a joint venture company of Browning-Ferris Industries, Inc. and Air Products, Inc., these two investor organizations have also been able to report our safety success to their stockholders and analysts who track their companies.

Garnering media attention has been more of a challenge. There certainly seems to be more "news" value to accidents and injuries than there is to prolonged periods of safe operation. As one television news reporter succinctly put it, "We don't cover airplanes that don't crash." We have, however, been able to "bridge" to our safety success and the VPP recognitions when talking to the media on other issues. For example, our Niagara Falls manager was a guest on a radio program where he had the opportunity to talk about safe disposal of citizens' discarded propane tanks. From an American Ref-Fuel perspective, the concerns about the tank disposal meshed well with a discussion of our safety culture and how this was a prime example of how that culture also looks after the best interests of the community.

We were able, with news releases and follow-ups, to get coverage of the Star site ceremonies in several local newspapers in the host communities of our plants. While the articles were not extensive, the benefit of getting positive news on file at a newspaper is that it tends to stay on file. In today's newsroom, the classic newsroom "morgue" of old clippings has been replaced by an electronic version where a reporter writing a story on any given company can retrieve previously written information with just a few keystrokes. Therefore, companies should make a conscious effort to see that newspapers' file information grows to be a more of a listing of accomplishments than a listing of instances where the company has been in the news for some form of violation or public controversy.

The "success by association" is a twist on the old phrase "guilt by association." The type of industrial safety covered by OSHA differs from what is usually meant when people ask, "Is this plant safe." The latter is usually a reference to environmental standards. Still, there is a natural tendency for people to link the two. They may be right. In both cases, a successful outcome is the result of competent design,

diligent attention to proper operation and overall atmosphere of pride of ownership. In both its organizational structure and its list of core principles, American Ref-Fuel links safety and environmental protection. Personnel in both departments report to the same vice president. Both criteria are also considered among the bonus calculations for all operations employees. The ripple continues outward beyond safety and environmental protection. Three of our VPP sites have received awards in the Solid Waste Association of America's Waste-to-Energy Excellence Awards competition, as well as capturing numerous other accolades.

A final point on our opportunity to publicize our VPP Star participation has to do with industry press. While we often hear about "information overload" and similar terms, modern communication capabilities have actually brought about a greater thirst for information to provide content for specialized or "niche" publications serving virtually every interest group imaginable. The waste and power industries are certainly no exceptions, with dozens of publications covering each. American Ref-Fuel has met with some success in promoting our VPP participation through these channels. We've then been able to compound this opportunity via reprints that we've used in our own promotional materials. These specialized publications also offer the benefit of reporters who are knowledgeable about our company and our industry, and who can produce articles in substantial detail. Their coverage is both a reward to our employees who deserve this tribute and a message to a broader audience who may sense a greater credibility when reading this information from a source outside of the company.

CONCLUSION

Certainly, safety is an issue that concerns us all. It's also an area where the small story can tell the big story in terms of conveying a company's attitudes and practices. American Ref-Fuel has parlayed our protection in the OSHA VPP Program into greater recognition for its employees, while attracting "good news" coverage of the waste-to-energy industry in a variety of publications. Industry opponents will continue to use the media as a forum and the more favorably inclined trade press will have ongoing needs for industry related story ideas. Given this scenario, it appears imperative that members of the waste industry consciously adopt strategies to promote positive events.

**Crisis Communications: Challenges For
The Waste-to-Energy Industry**

**Presented to the
1997 North American Waste-to-Energy Conference**

Karen D. Alexander
Vice President, Public Affairs
Ogden Energy Group, Inc.
40 Lane Road
CN 2615
Fairfield, NJ 07007-2615
April, 1997

COMMUNICATION FUNDAMENTALS

The communication process is comprised of four components: a sender, a message, a medium, and a receiver or audience. Effective communication requires us to understand the four components each time we communicate. We must understand ourselves--our bias, tone, even physical demeanor. We must understand the message--the words, pictures, and context. We must understand the medium--the bias of the written text or oral verse or video broadcast. Most of all, we must understand the receiver or audience--their bias, environment, experience, and education. Most of us take for granted that the meaning we give to our words will be accepted by the intended recipient. The existence of lawyers, counselors, and judges argues otherwise.

If you view communication as a process in which senders and receivers mutually influence each other by sending each other messages, you will strive to involve your audience before, during and after your interactions. with them in any one of the following communication situations:

- People in two person communication situations should be considered transceivers (transmitters/receivers) rather than communicator and communicatees. Each person simultaneously influences and is influenced by the other. We can also refer to those involved in this type of communication as both speaker/listener and listener/speaker because although the communication is going on simultaneously, one person usually initiated the contact.
- Three people can be called a small group. They get together and solve a problem, engage in a conflict, pursue common interests, or have a casual conversation. Our industry's organizations often engage in small group communication--in meetings with regulators, internal staff and colleagues, or community leaders. The uniqueness of the small group is that conflict occurs often in this relationship. Therefore, small group communication may demand more time to find common ground among the group if the goal is to build consensus or solve problems.
- The speaker-audience relationship demands the most preparation from those involved. The speaker who engages in formal presentations of issues must be prepared to research the issue, deliver the statement or speech, and attempt to make the audience feel and believe as she or he does. The audience, on the other hand, needs to develop good listening habits and be prepared to understand, if not agree with, the speaker's point of view.

During the course of any day, a public relations person engages in interpersonal (two persons, face-to-face) communication, small group (three or more), and speaker audience (formal presentations) situations. The importance of face-to-face communication is that feedback is immediate. Human communication, therefore, can be dynamic, with one communicative act influencing the next and change occurring in a continuous cycle as those involved strive to reach a common ground through immediate feedback.

Communication that is not face-to-face, does not have the luxury of immediate feedback. When sending our message by printed materials or through the electronic media, feedback most often is delayed. Interactive media in which feedback is delivered through a computer network strives to overcome the hurdle, but is as yet not as effective as face-to-face communication.

CRISIS COMMUNICATIONS AS A TOOL

Crisis communications is the ability to convey clear, concise, believable and caring messages to your organization's various publics or stakeholders when the unexpected negative event occurs. The event is usually, but not always, something catastrophic or of an emergency nature that adversely affects an organization directly, and/or adversely affects one or more of that organization's publics.

Crisis communications is a skill, a tool, a resource base and professional discipline upon which individuals and organizations can draw when confronted with an unexpected and potentially damaging event. It is a resource to draw upon to maximize the opportunity for positive outcomes even in the worst of situations. At a minimum, it can help an organization keep a bad situation from getting worse.

Successful crisis communications will require the use of all three modes of communication (two-person, small group and speaker-audience), with the latter tending to be the most common and crucial during a crisis (the typical press conference or press release format). At the same time, it is the communication form most likely to present the greatest opportunity for failed communication precisely because of the phenomenon of distance and delayed feedback described earlier.

Every person with access to mass media, whether newspapers, radio, television or the Internet, regularly witnesses, participates in and/or judges how well or not crisis communication skills are exercised. Crises within the memories of most in this audience that have tested the abilities and fortitude of organizations include:

- the Exxon Valdez oil spill;
- the Oklahoma City bombing;
- the Three Mile Island accident;
- the Tylenol product tamperings;
- the space shuttle Challenger accident;
- the as yet unexplained explosion of TWA Flight 200.

Each of us saw or heard these events reported by the media and, based upon the impressions we had of what we heard and how and when the information was imparted, we drew conclusions in our minds about cause, culpability and consequences. If you know of any of these events, they undoubtedly hold lasting impressions for you--both of the event and of the organization at the center of it.

Communication is a tool for managing a situation, any situation. When the situation is a crisis, however, that tool becomes all the more important because how well or not it is used can directly and irrevocably affect the reputation of your organization.

Every public relations guru begins his or her lecture to a corporate client by stressing the importance of trust. "If the public trusts you," the consultant promises, "you will be accepted." Or, "I can help you because the public (or the regulator, or the politician) trusts me." The formula seems simple: trust equals approval. Indeed, there must be an underlying acceptance that the person or entity sending the message is worthy of our attention. Trust, however, is only the beginning of effective communication.

There are numerous reasons why communication may not be effective even if the recipient of the message trusts the sender. Assume you are the receiver. You may trust and respect the sender, yet not believe her statements because you think she was misled. You may not like the message because it is disturbing or disruptive to your beliefs. You may not believe the medium, such as television, in which the message is delivered. You may not feel confident in your own experience or knowledge to trust your reactions to what you are hearing, reading, or viewing. Clearly, effective communication requires more than a simple formula.

Communication is most effective when trust, which is derived from the image of the sender, is combined with both empathy or rapport with the audience, and a message that seems logical to the receiver. To most communication professionals, image means developing "trust" and "credibility."

An important, although not exclusive, measure of successful crisis communications then is the degree of trust that you are able to instill in your audience. How well or not you are trusted, i.e., believed, can ultimately dictate not only the duration of the crisis but also whether you are judged by your publics to have brought it to a fair and responsible conclusion.

CRISES IN THE WASTE-TO-ENERGY INDUSTRY

Environmental protests.

Regulatory non-compliance.

Fire.

Corpse delivered to the pit.

Shredder or boiler explosion.

These are just some of the kinds of crises that have been faced within the waste-to-energy industry. The more tragic events--those where there was loss of life--while fewer, leave an indelible memory. Whether they leave an indelible scar has been a function of how the crisis was managed at the time.

Because the public and private sectors are involved in the waste to energy industry, the audiences are diverse. Critical to weathering any of these crises is to know your audience.

UNDERSTANDING YOUR AUDIENCE

Many of us make the mistake of thinking of the media as our exclusive audience. That is understandable because, when a crisis strikes, reporters often are the external people with whom we have the most contact.

But the media is not your only or ultimate audience. It is the vehicle through which your messages can be conveyed to your audience, but it is NOT in and of itself your sole audience.

Because the media can control or manipulate your message, they clearly are one audience. But also among your audiences are the various publics you serve or represent--employees, shareholders, authority board members, elected officials, clients, customers and the public at large. These are the people who are directly or indirectly impacted by the event and by how you manage that event.

Certainly, the media can influence the impressions of all of these publics. But if you know and understand all of your audiences, including the media, you can exercise a good degree of control over your message and how it is received. Properly performed, good media relations can provide the organization in crisis with infinitely more control than poor or no media handling skills.

It is important to remember that "The Media" as we call it, really is not one great monolith. It also is not the enemy. It is made up of competing organizations (most often, for-profit corporations) that are themselves made up of highly competitive people with as diverse backgrounds and predilections as those found in any other organization. The media have a job to do. They must tell **your** story to **your** publics. And it behooves you to help them do it well, because they can very easily and even unwittingly turn what should be your story into someone else's, if not their own. It is critical to understand whose story it is and to whom the story must be told before the crisis occurs.

WHOSE JOB IS IT ANYWAY?

Imagine that you are on the front lines of a major crisis being experienced by your organization. Who are you?

- A. The chief executive?
- B. The PR professional?
- C. The General Counsel?
- D. The Technical Expert?
- E. All of the Above?

The Answer is "E," All of the above.

Crises are best managed by a team with clearly established roles and responsibilities that have been planned and rehearsed in advance. Depending upon the nature of the event, your team might include all of the above people as well as others. Crisis communication is not, however, the exclusive domain of the communications professionals in your organization. Some of the most critical decisions with potentially lasting consequences will be made during a crisis. It is at this time, like no other, that the best and broadest thinking minds of your organization will be needed. But the higher up in the organization the manager, and the further away from the communications function, the more likely they are to be on the front lines of a crisis. So in addition to being smart and resourceful, those who are most apt to be your team leaders, also need to be trained.

It is rare that the communications professional will be the decisionmaker or team leader in a crisis. But they can, and should, be among the best and broadest thinking minds on your team. In the end, every decision made as to how the crisis will be managed and how those decisions are implemented will determine how well you weather the storm.

GETTING "IT" DONE

The "it" is ensuring that your reputation and credibility are intact after the smoke clears. There are some basic tools and guidelines that most communicators agree are fundamental to achieving that goal.

Which of the following tools do you think would be most critical to you in managing a crisis? (you may chose only 1)

- A. A PR Professional?
- B. A PR Firm Expert in Crisis Communications?
- C. An internal team knowledgeable and rehearsed in your organization's crisis plan and procedures?
- D. A plan tailor-made for your organization.
- E. A "How To" Manual

If you said "C," you are way ahead of the game. But why not the other answers?

In truth, if you have any desire to manage your reputation, not to mention crises, ideally you will have a combination of these resources, and a PR professional would tie or rank a close second. But, you were asked to chose only one.

What about answer "A?" Certainly a strong communications staff is a must in this industry. But staff without the guidance of a well thought out plan, rehearsed procedures and a team that works shoulder to shoulder for the common good of the organization will be of only minimal value to you. Because even if they (and you) come through that first crisis well enough, left without the right tools, they will eventually burnout.

Why not outside consultants? Again, as a supplement to your crisis management team, consultants can be helpful. But do you really want--more importantly, would you trust-- the exclusive advice of outside experts on how to do the right thing and preserve your organization's reputation? Probably not.

These are the people you want to call on before you have a crisis, when you and they have time to study and analyze your organization, its audiences, the kinds of crises you might confront, and sit down with you to develop your plan. It is the extraordinary executive who, in the throes of a crisis, will rely on what are probably never before heard principles of crisis communication which are being conveyed (perhaps for the first time, but for certain over and over again) by any PR expert worth their fee. This is especially true for industries like ours that are so often already under public

scrutiny. How many of you have been skeptical about the intuitive reasoning behind "getting out in front" of the issues, especially if it means publicity? Well, you are not alone.

Many of our public sector colleagues follow these principles of crisis communication either out of a commitment to and comfort with public disclosure or because in the past they've felt the wrath of political officials and public constituencies who have felt misled, uninformed or worse, lied to. Some, however, don't. And they too are excoriated in the press just as we in the private sector are for "mishandling, incompetence and bungling" of communications with their publics about the crisis. Oftentimes, public officials face even more immediate and dire consequences for botching crisis communications than does the private sector--after all, they are more directly accountable to their publics.

I chose "C" because, time and time again, experience has shown that the most valuable tool that your organization can have is a plan and a team that is well versed in and ready to implement that plan at a moment's notice.

CRISIS COMMUNICATIONS BASICS: THE PLAN

One can never over plan for a crisis. Because the most challenging test of public relations skills--and the fortitude of an organization--arises in times of crisis, preparedness is essential.

When an unexpected development that has the potential to alarm the public occurs, the credibility and decency of the organization experiencing the crisis come under intense scrutiny. Often the media is in hot pursuit of the facts surrounding the incident and as a consequence, the pressure on the organization's executives can be severe.

There are three general courses that organizations may choose in times of crisis. First, some organizations "stonewall," denying the crisis' existence. Inquiries are not answered and a "public-be-damned" image emerges.

Second, many organizations choose to "manage" the news by releasing partial or delayed information while concealing unfavorable facts. Ultimately, the facts slip out through insider "leaks" or government inquiries, and the disclosure shatters the organization's reputation. (How many of us wonder to this day whether there is any truth to the missile theory proffered by Pierre Salinger as the cause of the Flight 200 explosion? If we all trusted the U.S. Government based on its past performance and reputation, would there be such questioning and doubt? Probably not.) In either case, the media and the public learn not to trust the organization and subsequent communication--in crisis or day-to-day situations--grows ineffective.

The third and best course of action requires an open dissemination of information that explains the crisis while keeping the situation in perspective by providing background facts. This policy is the safest bet to preserve credibility.

The open door method of handling a crisis may offer the highest rewards, but it also requires the most extensive coordination and trust. In a crisis, your organization will not be the only source of information and therefore must keep abreast and keep others abreast of current events. Others both inside and outside of your organization may be called by an anxious media or community to learn more about what is happening at the facility. All of these sources, whether the public sector client, the regulatory body or those internal staff assigned as spokespersons, must be kept informed and know in advance how to coordinate the flow of information. A structured and rehearsed procedure translates into less risk of surprises and inconsistencies.

The goal of a crisis communication plan is assurance that all sources speak in one voice as they explain the full story within context. Implementation of a good plan means the public and the players remain calm. After the crisis is over, all parties better trust the other to tell the truth and tell it in a timely manner.

CONCLUSION

In summary, the following principles are key to successfully managing crisis communications.

First and foremost, **BE PREPARED**. There is no such thing as “it can’t happen to me.” While unexpected in its timing, the event can be anticipated and planned for. Here are some general preparedness tools:

- prepare and update a crisis communications plan, including designating your team;
- have the team rehearse and rely on the plan (and their common sense);
- designate (and train) a spokesperson (and an alternate) in both presentation skills and media handling;
- have on-hand factual information on your organization, your facility, and any other general materials that will provide a context and background for your audience.

Second, remember your audience and decide in advance what they will want and need to know and tailor your messages accordingly.

Third, treat the media as both an audience and a resource, a means of accomplishing your goal to maintain your credibility and reputation. When dealing with the media, whether through oral or written statements, abide by the following:

- don’t be defensive (they want a story, not your head);
- be clear and concise;
- be helpful (otherwise they might want your head);
- be honest and forthcoming: tell the truth about what happened and why without speculating, while acknowledging problems or mistakes;
- show you care;
- be calm and sober;
- avoid favoritism (TV vs. Radio vs. Print).

A badly managed crisis can cost you, dearly. What is at stake?

- 1) Your reputation--for honesty, acceptance of responsibility and caring.
- 2) The loyalty of your clients/customers/shareholders/employees--all of your various publics or constituencies. That loyalty is linked to your past performance and reputation, but also to each of your stakeholders’ perceptions of whether you can be trusted in this particular moment while the current crisis is underway.

- 3) Money.

and, of course,

- 4) Time.

Thank you. I would be glad to respond to any questions.

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After Flow Control: The Steps Taken by Dade County to Ensure Continued Operation of Its Solid Waste Management System

Paul J. Mauriello, AICP and Diana Ragbeer
Metropolitan Dade County
Department of Solid Waste Management
8675 N.W. 53rd Street, Suite 201
Miami, Florida 33166

ABSTRACT

In the wake of the U.S. Supreme Court decision in the *Carbone vs. Clarkstown* case striking down waste flow control as unconstitutional, Dade County, Florida, one of the most severely impacted communities in the nation, has managed to stabilize its waste stream and balance its solid waste department finances; although the road taken to restabilization has been a difficult one.

At its peak in 1995, Dade County experienced an annual loss of solid waste in excess of 1,000,000 tons, or over 40 percent of the waste stream normally handled by the County. This diversion of waste was accompanied by a net revenue loss of \$30 million per year. The County lost its ability to plan for future capacity needs, or to assure sufficient future waste flows to meet its put-or-pay obligation to the County's Resources Recovery plant operator. The County's solid waste management system bonds were downgraded by Moody's Investors Service and Standard and Poors.

With the help of a special solid waste management team, appointed by the County Manager, the department was able to rightsize its waste disposal operations to fit its reduced waste flows, stabilize its waste stream, and develop strategies to solve its long-term funding shortfall.

INTRODUCTION

Like many communities across the country, Dade County, Florida, has had to scramble to stabilize its solid waste management system (System) following waste diversion to disposal facilities in other jurisdictions. The U.S. Supreme Court's 1994 decision in the *Carbone vs. Clarkstown* case, striking down waste flow control (WFC) as unconstitutional, effectively foreclosed the use of WFC authority to solve Dade's waste diversion problem. The rapid and dramatic reduction in waste flow to County facilities forced the County to "rightsize" its disposal operations, find ways to stabilize its waste stream, and develop supplementary funding sources to fill the widening gap in its solid waste management budget. Understanding the Dade County experience in coping with waste diversion and lack of WFC authority may help other communities that are faced with similar challenges.

ORIGINS OF THE COUNTY'S SOLID WASTE SYSTEM

The Metropolitan Dade County form of government was established through amendment to the Florida State Constitution in 1956. Article 1, Section 9, of the Charter gave the Board of County Commissioners the power to provide and regulate, or permit municipalities to provide and regulate waste collection and disposal. At the time the Charter was adopted, solid waste disposal in Dade County was a sparsely regulated private and municipal activity. Commencing in the 1960's, federal, state, and local governments responded to the general public's increased environmental awareness, and concerns regarding the need for more aggressive efforts to protect the environment. The resulting regulatory climate left Dade County with over two dozen solid waste disposal facilities operating in an environmentally unacceptable manner

by 1970. Only the County's Northeast Incinerator was operating in full compliance with mandated environmental regulations.

This situation prompted the creation, by the county manager, of the Solid Waste Management Task Force to review solid waste disposal and collection practices in Dade County. While the Task Force was in the process of soliciting requests for proposals for a resources recovery facility, the 1974 state legislature enacted the Florida Resource Recovery and Management Act (Act) which required cities and counties in Florida to adopt local resource recovery and management programs for approval by the state. The Act promoted the use of interlocal agreements between cities and counties to define which local agency would administer the program. The Act required, however, that if no interlocal agreement had been effectuated or special act become law by December 1, 1978, the Board of County Commissioners would be responsible for, and administer the program. Moreover, the Act prohibited cities from withdrawing from programs if bonds had been issued to finance solid waste management facilities by the December date, in reliance on the Act.

The County's program was adopted by the Board in 1979 and approved by the state in the same year. The program was accompanied by a WFC ordinance which allowed the Board of County Commissioners to designate a geographical area contiguous to a County solid waste disposal and resource recovery facility, for the purpose of directing waste generated in such area to the facility, if deemed necessary by the Board. The program included two major waste disposal facilities, a 3,000 ton per day waste-to-energy facility (refuse derived fuel) in northwest Dade and associated 80 acre ash monofill, and a 2,100 ton per day garbage and trash landfill (Class I) in South Dade. Three automated waste transfer facilities would also to be developed in strategic areas of the County to enhance waste collection efficiency and reduce trips to disposal facilities. The program was financed by 1972 Decade of Progress Bonds (\$50 million) and 1978 State of Florida Pollution Control Bonds (\$137 million). The 1979 program was amended in 1984 to include reactivation of the County's North Dade landfill (Class III) to handle trash generated in the northern portion of the County.

The 1974 Act was later superseded by the 1988 Solid Waste Management Act. The 1988 Act delegated to counties the "Responsibility and power to provide for the operation of solid waste disposal facilities to meet the needs of all incorporated and unincorporated areas of the county." The Act also provided that "Any local government which undertakes resource recovery from solid waste pursuant to general law or special act may institute a flow control ordinance for the purpose of ensuring that the resource recovery facility receives and adequate quantity of solid waste from solid waste generated within its jurisdiction." Furthermore, the Act included a recycling mandate for counties of 30 percent of their waste stream by 1994.

Adoption of the County's Comprehensive Development Master Plan (CDMP) in 1988, pursuant to the requirements of the 1985 Local Government Comprehensive Planning and Land Development Regulation Act (Growth Management Act), coincided with passage of the 1988 Solid Waste Management Act by the state legislature. The County's vision of creating a single integrated solid waste management system in Dade County, first articulated in the 1979 Resource Recovery and Management Plan, and later incorporated in the 1988 CDMP, had been nearly realized. The single remaining private solid waste management facility in the County, the United Sanitation, Inc. landfill in the City of Medley, Florida, was subject to a phase-out agreement with the County due to environmental problems, and was scheduled to be closed by the end of 1990.

The System facilities have been enlarged and improved upon since 1988, but no new facilities have been added. The Medley landfill continues to operate under an amended phase-out agreement, and the majority of environmental problems at the facility have been remedied by the operator.

THE CHANGING SOLID WASTE MANAGEMENT ENVIRONMENT

The state of relative stability in countywide solid waste management that existed during the 1980's was short-lived. In 1991, two large waste-to-energy facilities (approximately 800,000 tons per year each) became operational, immediately to the north, in Broward County. The new facilities are owned and operated by Wheelabrator Technologies, Inc., a subsidiary of WMX Technologies, Inc. (previously Waste Management, Inc.). These facilities were built in response to the solid waste management needs of Broward County, one of the fastest growing counties in the country.

Since Broward County's charter did not specifically delegate the power to provide and regulate waste disposal to county government, the County entered into interlocal agreements with all but four of its municipalities to provide waste to Wheelabrator. In its agreement with Wheelabrator, the County pledged to provide a specified amount of waste, on a put-or-pay basis, for a period of 20 years. This contractual arrangement enabled Wheelabrator to secure financing for its facilities.

While the facilities were built to accommodate Broward's increasing waste stream over time, significant excess capacity would be present initially. Those municipalities participating in the agreement paid a tipping fee rate sufficient to cover the fixed costs of the facilities; \$76 per ton in 1995. Therefore, the excess or "merchant capacity" could be sold on the open market by the operator at "spot market" prices. Broward derives a financial benefit from the sale of merchant capacity, in that, to the extent the County is unable to satisfy its waste delivery obligation, fees from merchant tonnage offset its payment to Wheelabrator.

Wheelabrator substantially undercut Dade's \$59 per ton tipping fee, and rates as low as \$38 per ton were common. At the same time, other regional disposal facilities opened their facilities to waste from Dade County. At its peak in 1995, the diversion of waste from Dade County exceeded 1 million tons per year, or just over 40 percent of the County's normal disposed waste stream, and the potential existed for even greater waste diversion in the future (refer to figure 1).

FINANCIAL IMPACTS RESULTING FROM WASTE DIVERSION

The County's solid waste management system was sized to accommodate a waste stream of 2.3 million tons per year, and planning for capacity increases was an ongoing effort. The system was funded through the sale of revenue bonds as well as industrial development bonds, approximately \$300 million of which were outstanding when waste diversion began in 1991. The revenue stream from waste disposal fees was pledged for repayment of the bond debt.

Approximately half of this outstanding debt was used for landfill capacity, landfill closure, and waste transfer facilities. The remainder was set aside for construction projects at the County's Resources Recovery facility, such as, installation of a new air quality control system, stormwater management improvements, and expansion of plant capacity. Since the debt service cost on the bonds was fixed, declining waste tonnages were not directly offset by decreased expenditures.

The County's initial reaction to the waste diversion phenomenon was to take steps toward development of a means to fund the system's fixed costs that was not tied to waste flow. In August 1993, the County issued a request for proposals for development of a solid waste special assessment district. The County intended to levy special assessments on all improved properties that have the potential to generate waste for disposal. A consultant was hired to complete the project, however, due to strong popular opposition to the concept, only preliminary waste generation factors by land use type were developed; thereafter the project was abandoned. Although the County had a WFC ordinance in its solid waste management code, the pending U.S. Supreme Court case on WFC was a deterrent to active implementation of the ordinance.

By 1995, the County was forecasting an average annual budget shortfall in its department of solid waste management of \$30 million. Moody's Investors Service downgraded the County's solid waste revenue bonds from A to Baa1 and Standard and Poors downgraded the bonds from A to BBB+. At this point, a Special Solid Waste Management Team, appointed by the County manager, consisting of the most senior Assistant County Manager and the County's Deputy Budget Director, was assigned to the department of solid waste management to "rightsize" the department and develop strategies to solve the long-term funding shortfall.

RIGHTSIZING AND STRATEGIC PLANNING PHASE I

In March of 1995 the Department eliminated 225 positions, primarily in disposal operations, support functions and administration. All non-essential capital projects were either deferred or eliminated. In April 1995, the Board of County Commissioners gave conceptual approval to the Phase I Strategic Plan for Dade County Solid Waste Management, identifying additional rightsizing initiatives, revenue enhancements and major business options. The key elements of the plan included restructuring of the department's debt to levelize debt service payments (refer to figure 2), renegotiation of the operations and management agreement with the County's Resources Recovery facility operator, and establishment of two additional sources of revenue to the department to pay fixed System costs.

Restructuring of the department's debt was accomplished in 1997. The County's existing Utility Service Fee, used to fund groundwater protection activities charged on the water and sewer bill, was increased by from 4% of user charges to 7.5%, with the additional revenue going to fund landfill closure and related activities. The additional 3.5% generates approximately \$13 million annually. A Disposal Facility Fee program was also developed in which private solid waste haulers operating in unincorporated Dade County must pay a percentage of gross receipts (currently 10%) to the County to cover the costs of disposal capacity availability at County facilities. The Disposal Facility Fee generates approximately \$5 million annually.

Renegotiation of the Resources Recovery Agreement

In 1990, \$190 million in industrial development revenue bonds were issued for retrofit and expansion of the County's Resources Recovery facility. Installation of a new air quality control system (gas scrubbers and bag house) and a 50 percent capacity expansion were planned (2 additional boilers for a total of 6). Community concerns over the appropriateness of the expansion delayed the project to the extent that waste diversion became an issue as well. Along the way, the planned expansion was transformed into a planned trash-to-fuel facility whereby 270,000 tons of trash annually would be converted to a biomass fuel for energy production off-site. The trash-to-fuel project was much less objectionable to the surrounding community than the outright expansion of combustion capacity at the site.

The County then faced a situation where a facility valued in the hundreds of millions of dollars would have to be upgraded to meet federal air pollution control standards or be shut down, and the County had no means to assure adequate waste flow to the facility in the foreseeable future. Meanwhile, the plant operator, Montenay-Dade, Ltd., having been successful, along with the County, in convincing the community of the merits of trash-to-fuel over on-site combustion had entered into its own fuel delivery agreement with Okeelanta Corp. Okeelanta is a sugar producer in south central Florida that was building a waste-to-energy facility that would burn biomass fuel to create electricity for on-site use and export.

A grand compromise was struck between the parties that would allow for both retrofit of the Resources Recovery facility and development of trash-to-fuel. The new agreement, dated September 1, 1996, requires the County to deliver all the garbage available in the System, up to 936,000 tons, but no less than 572,000 tons. The County must also deliver a minimum of 400,000 tons of trash for trash-to-fuel and

on-site combustion, the on-site portion of which may be displaced by garbage (130,000 tons). The result is an overall annual minimum waste delivery requirement of 972,000 tons and a maximum of 1,206,000 tons depending on waste flow (refer to figure 3). The County's previous minimum annual waste delivery obligation was 936,000 tons. On the retrofit side, Montenay agreed to lower its processing fee for waste processed through the fourth boiler (for tons processed over 702,000), from \$25.19 per ton to \$21.33 per ton, as a concession for allowing the boiler to be retrofitted without assurance of waste flow.

STRATEGIC PLANNING PHASE II

Phase II of the strategic planning process involved two key elements: (1) long-term waste disposal agreements with municipalities and private waste haulers for disposal at County facilities, at a reduced \$45 contract tipping fee rate, and (2) long-term, low-cost, waste disposal agreements with regional waste disposal companies, to ensure disposal capacity availability for System waste without future capital outlays by the County.

Phase II - Part 1

Throughout the summer of 1995, the County engaged representatives of the Dade League of Cities, representing most of Dade's 26 municipalities, in a dialogue on a wide range of solid waste management issues. It soon became clear to County representatives that the municipalities, once captives of the System, had become somewhat hostile customers. The discussions, which proved healthy for all concerned, ultimately led to development of a standard interlocal agreement for use of the System by municipalities. The agreement was adopted by the Board of County Commissioners on September 14, 1995.

The standard interlocal agreement provided that each participating municipality would commit its waste stream to the System for a period of 20 years. A provision was included that allowed municipalities that had already contracted on a short-term basis with other waste disposal providers, to fulfill the terms of those contracts and then return to the System. The County pledged to provide sufficient capacity to meet the growth management needs of each participant at a per ton fee of \$45, with no increases in the Consumer Price Index until October 1, 1998, which increases would then be capped at 5 percent per year for the duration of the agreement. In order to address the possibility that certain of the System facilities may be phased-out, the agreement established the right of the County to direct municipalities to particular facilities; provided that no municipality would have to deliver its waste to a facility that was farther than 20 miles from its nearest boundary. To date, 18 municipalities have entered into interlocal waste disposal agreements with the County, including Dade's two largest municipalities, Miami (180,000 tons annually) and Hialeah (70,000 tons annually). The total annual waste committed to the System under these agreements is approximately 420,000 tons (refer to figure 4).

In addition to securing waste commitments from municipalities, the County pursued its largest waste hauler, Browning-Ferris Industries, Inc. (BFI). BFI controlled approximately 520,000 tons, or 23% of the waste generated in the County. In 1995 approximately 175,000 tons of BFI's waste was being disposed of at County facilities, however, BFI was under no obligation to continue to deliver this waste to the County. The remainder of BFI's waste, approximately 345,000 tons, was being diverted to other facilities. BFI was eager to discuss a waste commitment to the County, provided the County would allow BFI to construct its own waste transfer facility. Without such a facility, BFI could not take advantage of transportation efficiencies that accompany the use of large capacity long-haul vehicles.

The County maintains countywide authority for environmental permitting through its department of environmental resources management, which acts as the local regulatory agency for the state department of environmental protection. The solid waste department is a review agency for resource recovery and management facility permits, as stipulated in the County Code. The department reviews each application

for its anticipated impacts on the system from contractual, financial, and regulatory perspectives consistent with County bond ordinances and the County Charter. Through a process of negotiation between the County and BFI, a waste commitment scenario was arrived at that would mitigate the potential adverse impacts of the transfer facility on the System.

On October 17, 1995, BFI and the County entered into a 20 year waste disposal agreement. The agreement requires BFI to deliver 300,000 tons of waste to County facilities annually, a 42 percent increase in tonnage, all of which is committed to the system (refer to figure 3). The agreement also requires that 100,000 tons of the waste be delivered to County transfer facilities. The transfer facility delivery requirement enables the County to optimize the use of its existing transfer facilities. BFI's waste transfer facility was approved by the County and is currently in operation.

Phase II - Part 2

Part 1 of the Phase II strategic planning process has resulted in stabilization of the County's waste stream at approximately 1.6 million tons annually. Figure 3 shows the committed portion of the waste stream and its sub-components. The largest committed component is waste collected from the area of unincorporated Dade served by the County's own forces (613,000 tons annually). Other committed tonnages include: municipalities (417,000 tons annually), Browning-Ferris Industries (300,000 tons annually), Waste Management Inc. of Florida (88,000 tons annually under a 1987 agreement), and County agencies (87,000). The remainder of the 1.6 million tons consists of waste delivered by private haulers and others that is uncommitted (100,000 tons annually). The County's tipping fee for uncommitted waste is \$59 per ton; \$14 higher than the fee for committed waste.

Part 2 of the phase II strategic planning process focused on the County's transition from development of County owned facilities to fulfill future capacity needs, to contracting for this capacity with large waste disposal companies in the South Florida region. This fundamental change in the County's waste management philosophy is a practical outcome of the lack of WFC. The change allows the County guaranteed access to large volumes of waste disposal capacity, at low cost, without having to take on the debt required to construct, staff, and maintain a facility. The County can also preserve its existing landfill capacity for contingency purposes, and as leverage when negotiating future waste disposal agreements.

On October 27, 1995, the County entered into a 20 year waste disposal agreement with Waste Management Inc. of Florida at a tipping fee of \$24.50 per ton. The agreement allows the County to dispose of up to 500,000 tons of solid waste annually at Waste Management's two regional landfills. The County must deliver a minimum of 100,000 tons of waste annually under the terms of the agreement. The agreement contains two five year options to renew upon mutual consent.

On December 29, 1995, the County entered into a one-year agreement with Wheelabrator South Broward, Inc. at a tipping fee of \$26.50 per ton. The agreement contains six one year options to renew at the sole discretion of Wheelabrator, and three additional one year options to renew upon mutual consent. If Wheelabrator desires, the County must deliver up to 100,000 tons of waste annually. The unusual structure of this agreement is due to the fact that the Wheelabrator facility is a waste-to-energy facility, which may or may not require additional waste from Dade depending on market forces. Since the County's tipping fee rate with Wheelabrator is low, Wheelabrator has an incentive to attract other waste streams that are willing to pay higher fees, therefore displacing Dade's waste.

Conclusions

As the most populous county in Florida (over 2 million people), Dade County has always tried to take a leadership role in its approach to fulfillment of state and federal solid waste management initiatives. The solid waste management system built by Dade County is second to none in this regard. Environmental

protection and community awareness of fundamental environmental issues such as groundwater protection and air quality have been primary objectives of the County's solid waste program since the 1970's.

Converting from disposal fee based funding to other sources is extremely difficult for local government, and its degree of difficulty should not be underestimated or simply ignored. Quilting together long-term waste commitments through interlocal agreement or contract is also a long and arduous process. Moreover, while providing encouragement, bond rating agencies have been unwilling to raise ratings based on Dade's newly implemented funding and waste stream stabilization program.

The County dutifully accepted its responsibility for countywide solid waste management, and has had to find creative ways to pay for facilities that were built in sole reliance on a revenue stream based on waste flow control. The level and scope of the County's investment in solid waste disposal facilities was driven by state and federal mandates. And let's not forget the U.S. Environmental Protection Agency's hierarchy of waste management methods which touts combustion over landfilling as a more desirable waste management option.

The fact that the U.S. Supreme Court decided against the interests of local government in the *Carbone vs. Clarkstown* case is no one's fault. But that does not mean that no one has a responsibility for properly managing the impacts of that decision. Just as local governments step up to the plate to fulfill state and federal mandates, the higher levels of government should ensure that appropriate legislation is passed to protect local governments when they are hurt as a result of their participation in furthering a larger social agenda.

Many point to Dade County's experience in coping with the loss of waste flow control as evidence that no action by Congress is needed. But in fact, Dade County faces two potential threats to the stability of its solid waste management system without WFC flow control:

1. Dade County is experiencing a watershed of incorporation and annexation activity. Most incorporations are on hold pending further study by the County of their potential effects on the remainder of the unincorporated area. In February 1996, the County passed an ordinance which allows the County to maintain control over waste generated in newly incorporated municipalities. The waste collected from within the unincorporated area of Dade County is the single largest component of committed waste tonnage to the system.
2. By ordinance, the County does not allow the development of private solid waste management facilities in Dade County in instances where a facility's operation would have an adverse impact on the System.

While the County Attorney's Office has found both of these ordinances to be legally sufficient, a successful legal challenge to the County's authority in these areas remains a possibility. The County endorses Congressional legislation establishing WFC to the extent necessary in order for any municipality or county to retire debts incurred based on a state solid waste management act, or other state or federal laws, or regulatory requirements regarding local government solid waste management responsibilities.

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5. Interlocal Agreement Between Metropolitan Dade County and Contract Cities for City Use of the County Solid Waste Management System, Adopted by Board of County Commissioners, September 14, 1995; Resolution number R-1198-95.
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7. Non-Exclusive Agreement Between Metropolitan Dade County, Florida and Waste Management Inc. of Florida for Provision of Municipal Solid Waste Disposal Services, October 27, 1995.
8. Non-Exclusive Agreement Between Metropolitan Dade County, Florida and Wheelabrator South Broward, Inc. for Provision of Municipal Solid Waste Disposal Services, December 29, 1995.

DEPARTMENT OF SOLID WASTE MANAGEMENT DISPOSAL REVENUE TONS (BY THOUSANDS)

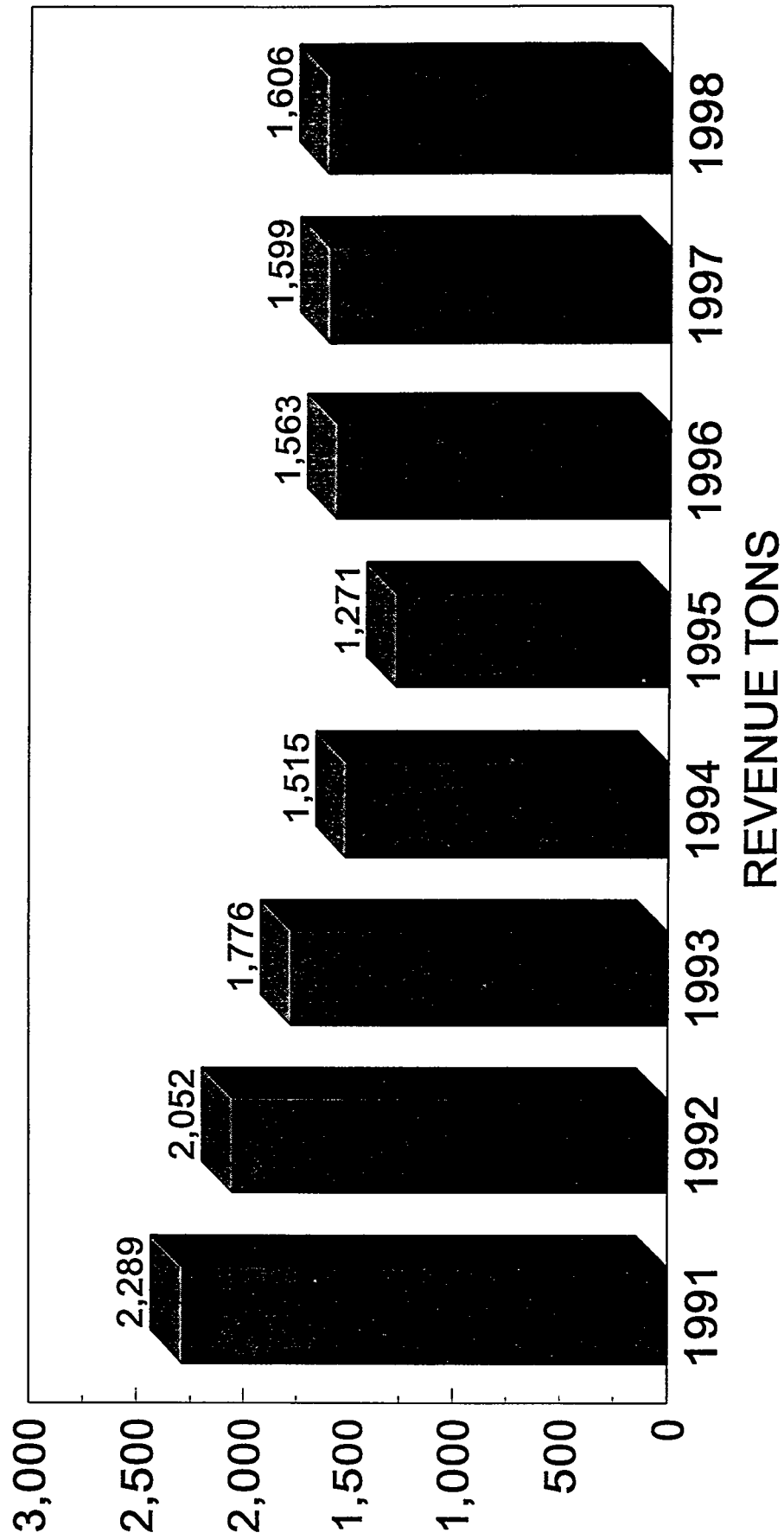


Figure 1

DIRECT OBLIGATION DEBT REFINANCING Impact On Cash Requirements

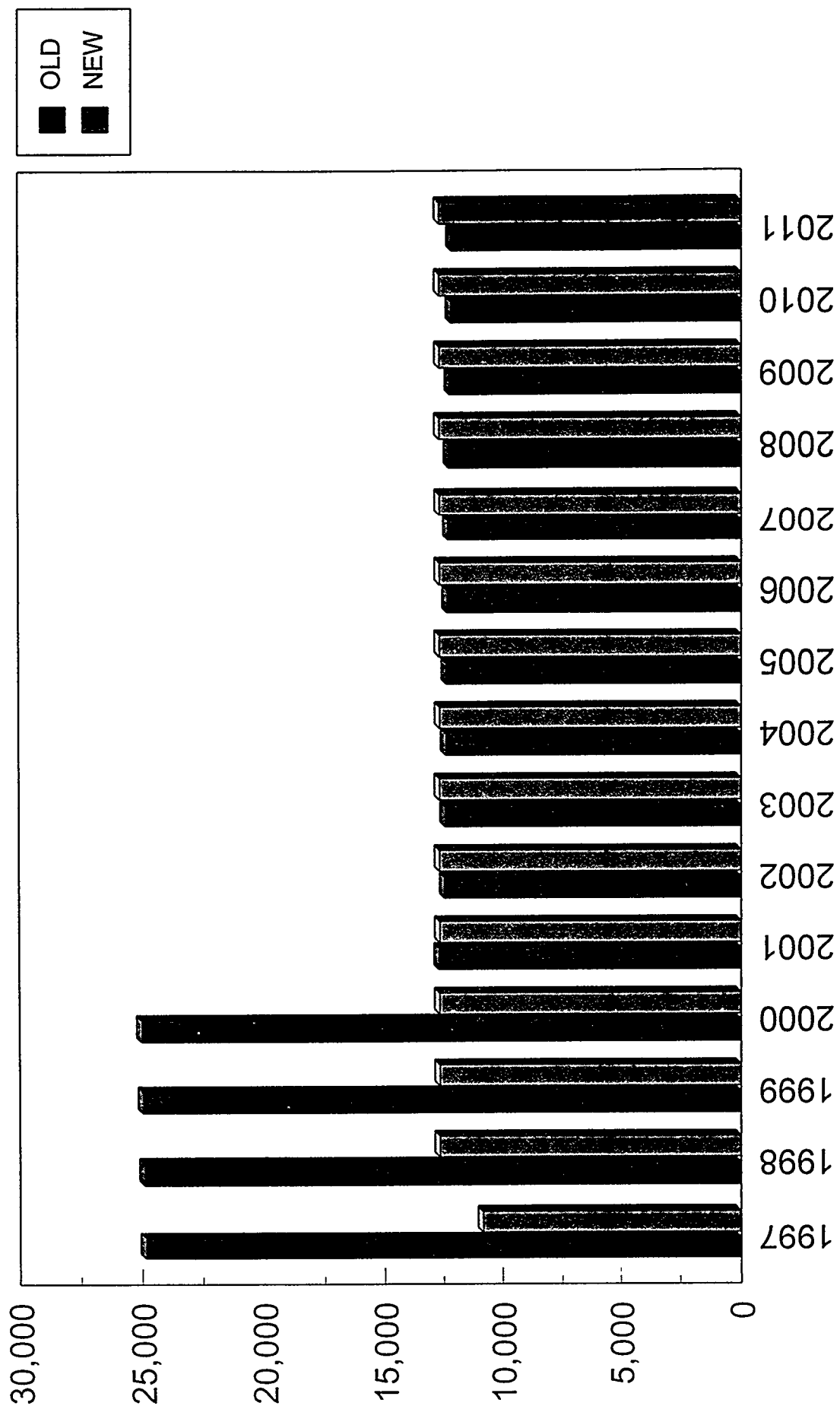


Figure 2

**DADE COUNTY, FLORIDA
RESOURCES RECOVERY FACILITY
GARBAGE AND TRASH COMMITMENTS**
September 1, 1996

From:
September 1, 1996

AOSWGT	Garbage Minimum	572,000
	Trash Maximum	364,000
Total		936,000

After:
RTIAPCD**

AOSWGT	Garbage Minimum	572,000
	Trash Maximum	130,000
	Subtotal	702,000

ARTGT***		270,000
----------	--	---------

Total **972,000**

345

MAXIMUM WASTE DELIVERY AMOUNTS	
If garbage is available for delivery, County must deliver up to -	936,000
ARTGT -	270,000
Maximum Waste Delivery Amount -	<u>1,206,000</u>

*AOSWGT - Annual On-site Waste Guaranteed Tonnage
 **RTIAPCD - Recyclable Trash Improvements Actual Performance Completion Date
 ***ARTGT - Annual Recyclable Trash Guaranteed Tonnage

Figure 3

DEPARTMENT OF SOLID WASTE MANAGEMENT COMMITTED TONNAGES

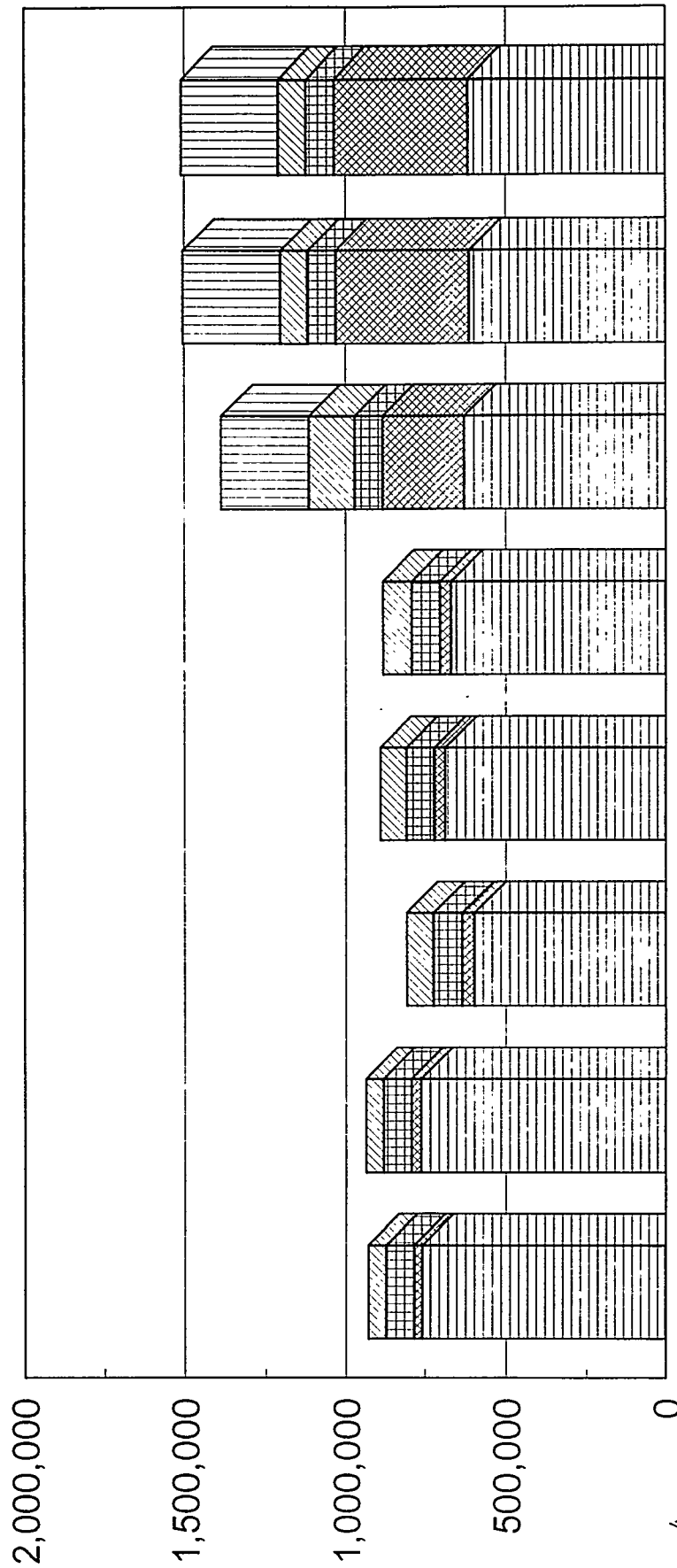


Figure 4

TECHNICAL SESSION II

***Emissions Measurement &
Monitoring***

Dioxin Surrogates — Are There Any Meaningful Ones?

H. Gregor Rigo
Rigo & Rigo Associates, Inc.
1 Berea Commons, Suite 211
Berea, Ohio 44017

INTRODUCTION

A number of easily measured pollutants have been offered up as dioxin surrogates—easily measured pollutants or process variables that consistently parallel dioxin emissions. Surrogates are a very attractive concept because the expense of direct dioxin measurement could be avoided. Also, the public can be assured that as long as easily and potentially continuously measured surrogates are within acceptable limits, people are not being exposed to excessive amounts of pollution. The question remains, however, is there a meaningful surrogate at conventionally regulated levels? Or, perhaps more importantly, at elevated levels that provide a comfortable margin of safety between normal operations and the conditions likely to represent elevated dioxin emissions?

For example, the preamble to the April 16, 1996 proposed Hazardous Waste Combustor Rule, states that particulates are a surrogate for trace organic HAPs, yet the supporting documents in the docket pronounce that “the plots between organic emissions and PM... show no apparent trends for cement kilns or other systems...”¹ U.S. Environmental Protection Agency (EPA) found no statistically significant correlation between particulates and trace organics. Further, EPA’s surrogate analysis concludes that “...PM are not good surrogates” (for SVOC and VOC)². As the following analysis shows, MWC data buttresses EPA’s supporting documentation, not the rhetoric in the Preamble. The suppositions provide a good starting point for evaluating the efficacy of various surrogates. However, in the course of developing the regulations or providing public assurance, peer-reviewed hypothesis and not unproved theories should be the basis of surrogate selection. It is particularly discouraging to realize that surrogates are sometimes offered even though the EPA has test data that can be used to test hypothesized relationships.

APPROACH

The following steps were undertaken to perform the analysis:

- Express all concentrations in common units and at the same diluent concentration.
- Check the database against laboratory and field data sheets to minimize errors and examine the database to identify outliers which much be corrected or flagged for inclusion and exclusion in the analysis.
- Use only values that exceed the reference method practical quantitation limit (RMPQL) in statistical procedures —relationships between values less than the RMPQL and higher values are meaningless since RMPQL results have an uncertainty of ± 30 percent. Relationships between pairs with at least one concentration below the analytic (laboratory) detection limit equivalent concentrations (ADLE) or the RMPQL concentration are simply due to chance. Table 1 is a summary of the results of a recent methods validation study conducted as an add-on to the DOE/NREL sponsored performance demonstration test at EAC/Pittsfield³. In this test, reference method testing was conducted using a quad-train. 40 CFR 63 Method 301⁴ method validation criteria were used to calculate the method’s practical quantitation limit, “the lowest concentration which can be accurately measured”⁵.
- Use International Toxic Equivalent (ITEQ) dioxin concentrations. The general linearity of tetra-through octa-dioxin and furan homologue totals and ITEQ has been established⁶. Given the international interpretability and trend toward summarizing complex dioxin and furan mixtures as an equivalent amount of 2,3,7,8 tetrachlorodibenzo-p-dioxin using the international weighting scheme, this approach has been selected even though it is at variance with current EPA MWC regulations.

- Use localized regression (loess) curves to identify the potential for relationships between paired variables. Loess curves are good for identifying the general shape of a trend through data. They are calculated, in this case, using the 30 or 50 percent of the data that surrounds each point and represent the curve drawn through the center of what is effectively a rolling average. When there are two or more underlying relationships in the data, the loess curves are shaped like hockey sticks. Forcing a straight line through such data is incorrect. A trial and error approach can be used to establish the breakpoint between various segments or splines. Absent such an extensive effort, statistical significance cannot be assigned to any particular inflection point or curve segment.
- Employ Spearman Rank-Correlation techniques when the use of individual scattergrams becomes unduly burdensome (such as in the analysis of the relationship between particulates and a plethora of trace organic HAPs) so that the underlying form of the distribution does not affect the comparisons of data above the RMPQL. Also, since this is really an exploratory data analysis — we cannot assume any specific hypothesis is true before analyzing the data — use multiple comparison statistics to identify significant results.

ANALYSIS OF POTENTIAL SURROGATES

A number of potential dioxin surrogates have been suggested. The relationship between air pollution control system (APCS) operating temperature, carbon monoxide and total hydrocarbons and dioxins are explored. Additional relationships between trace contaminants that may be less expensive to monitor, such as chlorobenzenes and dioxins, are explored. Surrogate relationships between dioxins, particulates and a host of additional trace organics that EPA has hypothesized are associated with particulates are also investigated using the techniques just described.

Dioxins Versus APCS Operating Temperature

Figure 1 is a plot of the ITEQ dioxin data collected from more than 150 MWCs since 1976. The loess line shows that there is no meaningful relationship between dioxins and APCS operating temperature below about 300 °F. Above that temperature, there is a generally linear relationship showing increasing dioxins with increasing APCS operating temperature. This supports EPA's finding underpinning the regulatory requirement to keep APCS temperature at no more than 30°F above the highest temperature demonstrated during the most recent compliance demonstration. Looking at the detailed data underlying this scattergram, it becomes apparent that the slope of the ITEQ dioxin — APCS operating temperature line for each facility is generally similar as long as emitted concentrations are above the RMPQL. That is, they are measured with reasonable precision. There is considerable scatter among plants indicating that more than APCS operating temperature is involved in determining dioxin emissions from MWCs.

Dioxins Versus Carbon Monoxide

Figure 2 is a scattergram relating dioxin emissions and carbon monoxide. Again the loess plot displays the hockey-stick pattern characteristic of emissions that are unrelated below a trigger concentration and linearly related above that level. Carbon monoxide (CO) becomes a meaningful surrogate for dioxins when its concentration exceeds 200-400 ppm_{dv} @ 7% O₂. Below that level, there is no meaningful relationship. Consequently, a facility that exceeds EPA's CO emissions standard of 100 ppm_{dv} @ 7% O₂ <4-hr average> for MWCs or up to 250 ppm_{dv} @ 7% O₂ <24-hour average> for other sources is unlikely to emit increased dioxins until sustained levels above 300-500 ppm_{dv} @ 7% O₂ are realized.

This finding is generally consistent with the mid-1980's data underpinning EPA's Good Combustion Practices. Back then, sustained operation under furnace conditions conducive to comparatively elevated dioxin emissions were standard, although rapidly becoming antiquated. Modern facilities generally operate at much lower sustained CO concentrations. Environmental impairment is not indicated when EPA's regulatory levels are exceeded for most plants. Only when emissions approach two to three times the permitted levels for sustained periods of time does the potential for a problem appear.

Note that these data were not analyzed using statistical techniques that account for confounding factors such as design and operating differences. If a surrogate is to be generally useful, it must be robust. That is, it must represent what it is supposed to be true in general and not just in special cases or under specific conditions. Examination of the loess curve and data points in Figure 2 indicate that when the curve breaks upward, the dioxins are generally below the levels found to produce theoretical multi-pathway health risk levels that trigger superfund site cleanups.

Dioxin Versus Total Hydrocarbons

Figure 3 is a scattergram showing the relationship between dioxins and total hydrocarbons. Interestingly, the loess line is essentially horizontal indicating no relationship for all the data. When the dioxin data are trimmed to eliminate concentrations below the RMPQL, the loess line is again a clear hockey stick with an inflection point in the vicinity of 10-20 ppm_{dv} @ 7% O₂. In fairness, it must be pointed out that THC data are available over a comparatively restricted range and a stronger relationship might exist at higher THC concentrations. On the other hand, these results are from operating facilities, and even with the operational abuse imposed on some of them during research efforts and performance demonstrations, it is unlikely that higher concentrations will be observed at commercial installations.

Carbon Monoxide Versus Total Hydrocarbons

Since both CO and THC monitors are commercially available (although some would quickly point out that THC monitors are unreliable without extraordinary care), the question arises which analyzer should be employed. Figure 4 is a scattergram showing the relationship between CO and THC. The loess curve displays the same hockey stick pattern that characterizes the relationship between dioxin and CO. In fact, the break point is the same CO concentration. This indicates that either CO or THC could be used as a dioxin surrogate at "high" emitted surrogate concentrations.

Dioxins Versus Chlorobenzenes

For many years, researchers have been using chlorobenzenes as a surrogate for dioxins, arguing that when they affect a change in chlorobenzenes they affect a similar change in dioxin emissions. Figure 5 is a scattergram relating dioxins and total chlorobenzenes (homologue totals — mono- through penta-chlorobenzenes). Once again, the loess curve shows the hockey-stick pattern that characterizes a change in formation mechanisms, or simply a shift from highly uncertain data to comparatively accurately known concentrations. In this case, below about 2,000 µg/dsm³ @ 7% O₂ of chlorobenzene, there is no co-trending. Above that level, a relationship begins to emerge.

Additional insight can be obtained by looking at the simultaneous dioxin and chlorobenzene data collected during the recent EAC/Pittsfield testing, the testing conducted at Davis County⁷ and the ongoing compliance testing performed at the Peel Resource Recovery Incorporated (PRRI) facility in Brampton, Ontario, Canada. Each of these test programs involved splitting the Method 23 catch at the analytic laboratory and analyzing dioxins and chlorobenzenes in the parent samples. Also, these samples

were all taken by the same field teams and analyzed by the same analytic laboratory so that between-team and between-laboratory variance sources are eliminated.

Figure 6 shows that EAC/Pittsfield and PRRI display no relationship between dioxins and chlorobenzenes. At Davis County, however, a relationship becomes apparent when the total chlorobenzene concentration exceeds 6-8,000 $\mu\text{g}/\text{dsm}^3$ @ 7% O_2 . Interestingly, the chlorobenzene concentrations at Davis County are characterized by a single normal distribution, but the dioxins fall into two groups. This is not surprising since activated carbon was used to reduce dioxin and mercury emissions during the Davis County demonstration test. The lack of change in chlorobenzenes is an indication that activated carbon does not affect chlorobenzene emissions. Also, when the simultaneous data from these three plants are considered as a single group as in Figure 7, the same 2-4,000 $\mu\text{g}/\text{dsm}^3$ @ 7% O_2 inflection point that characterizes the entire data set is indicated by the loess curve. This indicates that chlorobenzenes may be a good surrogate at high dioxin concentrations, but the relationship has no utility at the below MDPQL levels that characterize today's MWCs and probably is non-existent at facilities using powdered activated carbon to reduce dioxin concentrations. It also issues the caution that laboratory studies analyzing chlorobenzene levels are reached and conclusions drawn by such studies must be taken as tentative.

Dioxins and Other Trace Organic HAPs

Because of the number involved, the relationship between dioxins and a plethora of other potential surrogates and less exactly measurable parameters was investigated using multiple Spearman Rank-Order Correlation techniques. The following statistically significant relationships between ITEQ dioxins greater than the RMPQL and the potential surrogates were identified:

- Hexachlorobenzene
- Pentachlorophenol
- Total PAHs (California list)
- Acetanaphthylene
- Total Chlorobenzenes
- Phenanthrene
- Particulates
- Carbon Monoxide
- Total Hydrocarbons

Only hexachlorobenzene accounts for more than 50 percent of the simultaneous change in dioxin concentrations. That is, even though there is a statistically significant relationship between dioxins and the other listed parameters, the amount of change in dioxins explained by a change in the other is too small to be practically significant and explain an important amount of the variability.

Below RMPQL dioxin data were eliminated from this analysis, so the above correlations are for concentrations that are likely to be representative of actual emissions. Analysis of the scatter plots for CO, THC and Total Chlorobenzenes demonstrate that there is a critical level below which no meaningful relationship exists. Further analysis and exclusion of low level concentrations without apparent relationships might produce stronger correlations. For example, for CO concentrations above 250 ppm_{d} @ 7% O_2 , the amount of dioxin change explained rises from 7% to 26%. Further improvement could be realized by optimizing the breakpoint. The result of this sort of analysis is identification of concentrations above which a meaningful surrogate relationship exists so that exceedances are indicative of an increase in dioxins.

Particulates With Organic HAPs

During the development of the proposed HWC Rule⁸, EPA suggested that particulates were a surrogate for dioxins and other trace organic HAPs. The following statistically significant correlations were found with particulates for all data sets characterized by dioxin concentrations above the RMPQL:

- Phenanthrene
- Naphthalene (a contaminant in Method 23 recovery chemicals)
- Pentachlorophenol, and
- Acenaphthylene

Interestingly, the vast majority of the trace organic HAPs investigated, another 48 Section 112 organic HAPs for which we also have simultaneous particulate data, show no relationship with particulates. Consequently, having low emitted particulate concentrations does not provide assurance that trace organic HAPs emissions are also low; there is no obvious relationship.

CONCLUSION

A statistical review of more than 1000 dioxin test runs conducted at MWCs indicates that conventional regulatory and permitted levels of surrogates like CO and THC are not associated with increased dioxin emissions. The variables identified by EPA's good combustion practice strategy (CO and THC) are sufficiently related that keeping CO below say 250-500 ppm_{dv} @ 7% O₂ <4-hr average>, and THC below 20 ppm_{dv} @ 7% O₂ <4-hr average>, provides reasonable assurance that dioxin emissions are not increasing.

An increase in dioxin emissions begins to occur when the APCS operating temperature rises above 300-400°F; but below that operating temperature window, dioxin emissions are below the RMPQL. So, imposing an incremental temperature restriction on low temperature systems is not environmentally beneficial. Whatever relationship that might be found is likely the result of chance relationships among variables. At the upper limit of the available data, however, a meaningful relationship probably exists.

The surrogate relationship is not apparent, or even necessarily incipient, at current regulatory levels. Consequently, it is incumbent upon regulators, operators and the public to realize that violating extremely restrictive combustion-related emissions restrictions is not equivalent to belching unregulated pollutants.

Particulates are not good surrogates for dioxins or other trace organic HAPs emissions. Consequently, monitoring particulates with a continuous particulate monitor would not provide any additional assurance that these emissions are being minimized.

Public assurances of continuous compliance can be provided, however, by a second, much higher limit for the surrogates. Arbitrarily restricting surrogates to low levels simply does not enhance environmental protection. Concentration limitations for surrogates should be based on the potential of each pollutant to do environmental harm.

Annex A - Statistical Considerations

When multiple comparisons are done in an exploratory effort, there is a great risk of chance findings. When working at the 95% statistical confidence level (α , the statistical significance level, is 0.05), 5 percent or one out of 20 comparisons, are expected to be "statistically significant" when there is nothing significant to be found. To get around this problem, multiple comparison techniques are used. There is

little dispute that if the significance level is greater than the Bonferroni significance level of $\alpha/\{n(n-1)/2\}$ for the n variables being compared, then a significant finding has been uncovered. For significance levels between α and the Bonferroni level, individual critical levels for each comparison should be based on the False Discovery Rate (FDR) level of $i\alpha/\{n(n-1)/2\}$ where i is the rank order from least to most significant of the comparison.

Dual-train calibration type analysis to establish the RMPQL is slightly complicated because the RMPQL is established by comparing two simultaneous, but unknown results. Unlike the implicit assumptions in Method 301 that the average of a pair of results is its true value, the field testing cannot achieve that goal because there is no "reference method" known to produce true values and no way to guarantee that slight spatial deviations do not produce real differences. Consequently, either member of a twin pair of results could be considered first and the other second. Fisher's symmetrical table approach aligns each pair first with one member to the left and then again with it to the right in a duplicate pair used, an upper bound for the RMPQL is produced. If the data are aligned with the largest of each pair on the same side, the minimum residual variance lowest likely RMPQL is produced. EPA's Method 301 method of calculating data variability produces a number between the two limiting values.

Given that the underlying experiment used the same sampling team and analytic laboratory, the upper limits are probably more representative of the true RMPQL than the lower limit. So, concentrations larger than the RMPQL calculated using Fisher's symmetrical table were taken as probably exceeding the RMPQL and accurately measured in this assessment.

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Table 1. Reference Method Practical Quantitation Limits for Method 23,26 and 29 measurable parameters.

pollutant	units	nominal sample volume (dsm ³)	Analytic (Laboratory) Detection Limit Equivalent Concentration ADLE	Reference Method Quantitation Limit RMPQL
HCl	ppm _{dv} @ 7% O ₂	1.800	0.006	126 to 218
Cl ₂	ppm _{dv} @ 7% O ₂	1.800	0.003	9 to 11
HBr	ppm _{dv} @ 7% O ₂	1.800	0.016	0.4 to 0.7
HF	ppm _{dv} @ 7% O ₂	1.800	0.005	5 to 15
Particulates (Front-Half)	gr/dsft ³ @ 7% O ₂	3.714	0.001	0.11 to 0.058
Cd	µg/dsm ³ @ 7% O ₂	3.714	0.5	46 to 77
Hg	µg/dsm ³ @ 7% O ₂	3.714	0.008	47 to 74
Pb	µg/dsm ³ @ 7% O ₂	3.714	5	825 to 1,700
ITEQ	ng/dsm ³ @ 7% O ₂	3.714	0.19	0.22 to 0.47
Dioxins			(0.03)	
Total	ng/dsm ³ @ 7% O ₂	3.714	0.84	10.9 to 19.6
Dioxins			(0.03)	

Note: The ADLE is based on the laboratory DL and the stated sample size. The upper two tailed tolerance limit provides 99 percent coverage of future tests at the 95 percent statistical confidence level within 30 percent for the measured value. The duplicate Method 23 and 29 results and quadruplicate Method 26 results were analyzed using statistical calibration techniques. Given that this testing was done by one field team, at one site, using one analytic laboratory, the upper bound of the RMPQL is probably most representative.

Figure 1. Scatter plot displaying the relationship between dioxins and APCS operating temperature.

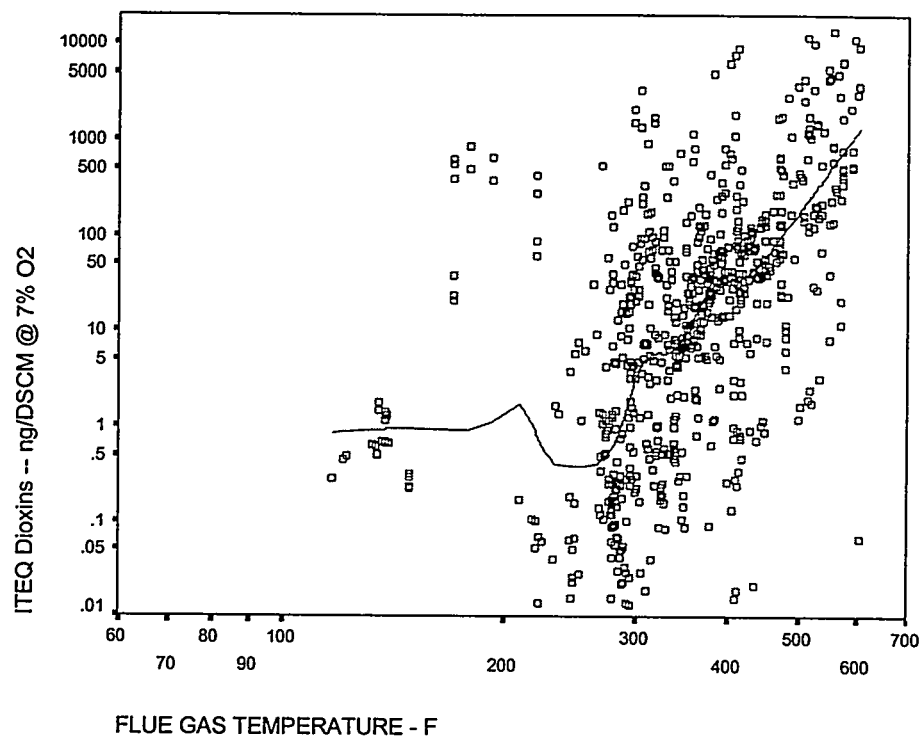


Figure 2. Scatter plot displaying the relationship between dioxins and CO.

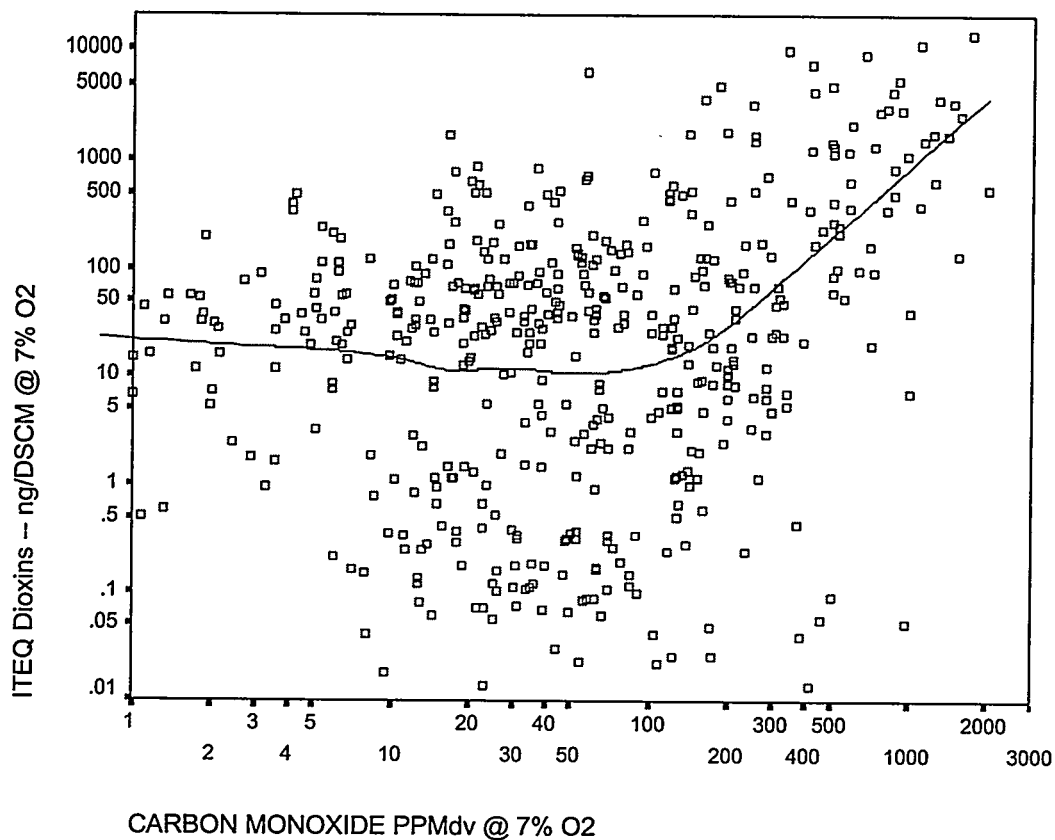


Figure 3. Scatter plot displaying the relationship between dioxins and THC.

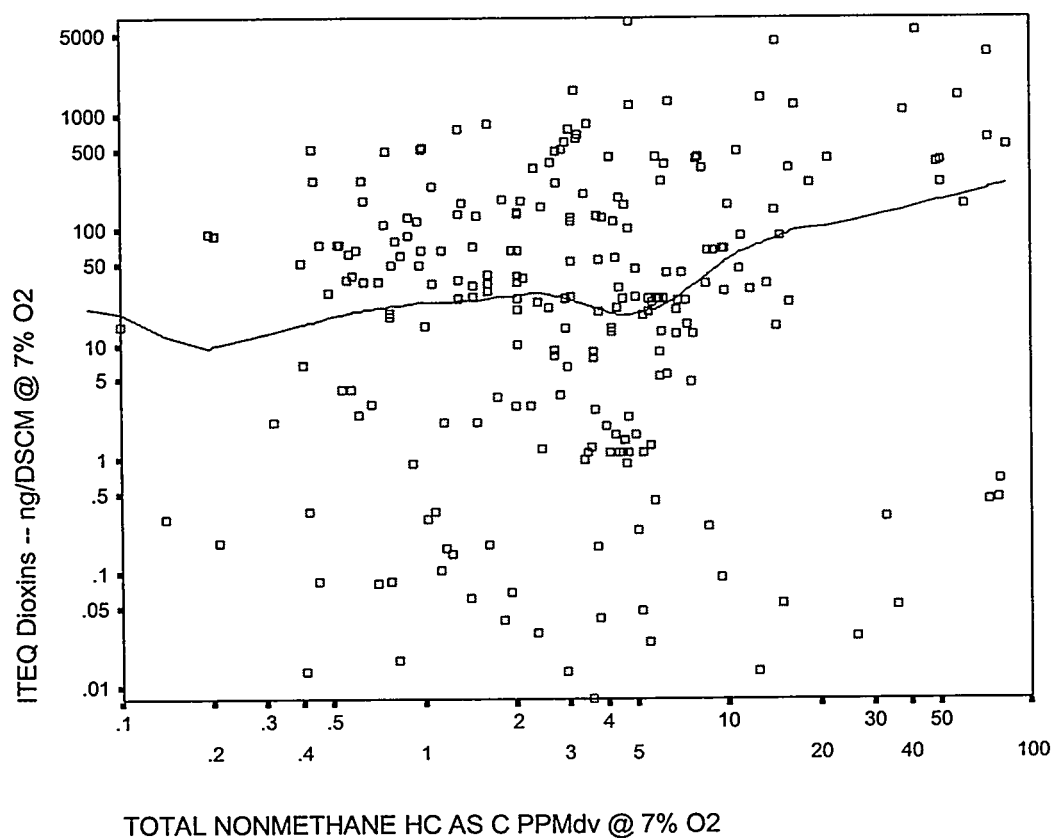


Figure 4. Scatter plot displaying the relationship between CO and THC.

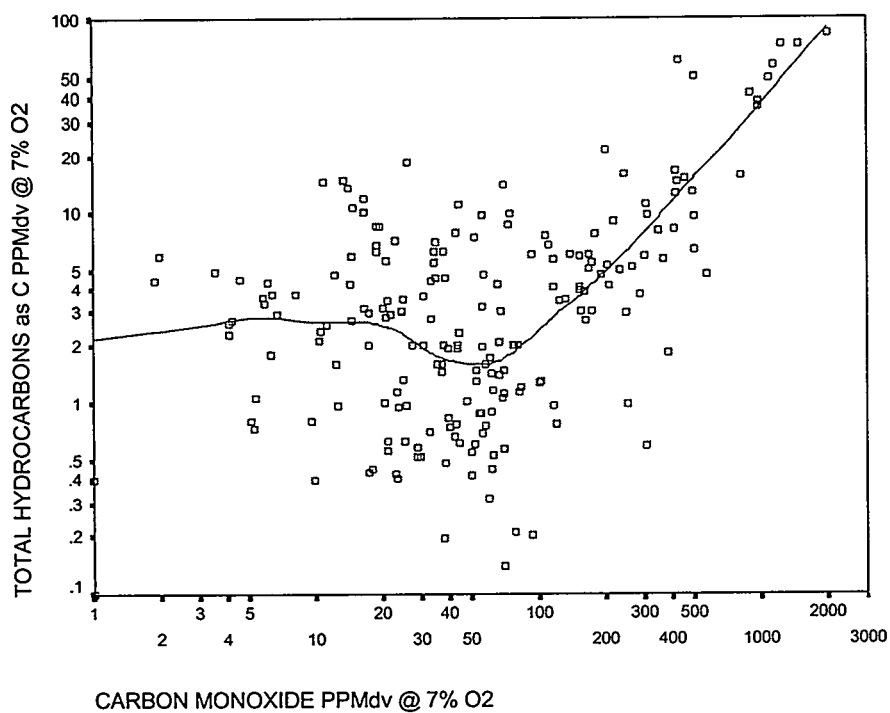


Figure 5. Scatter plot displaying the relationship between dioxins and total chlorobenzenes.

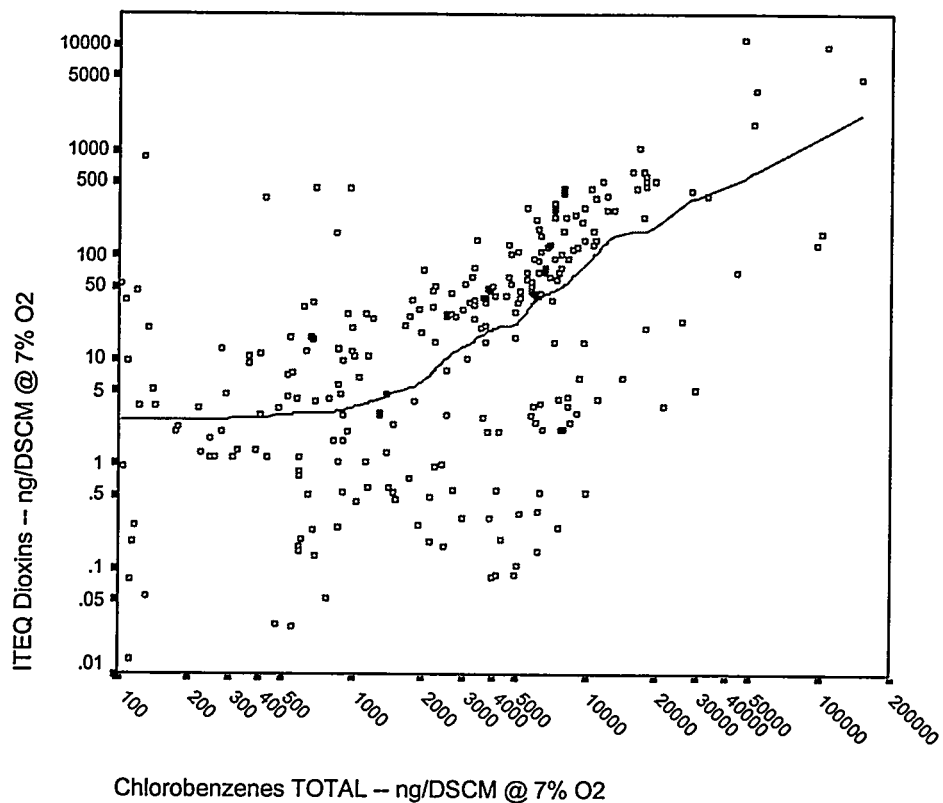


Figure 6. Scatter plot displaying the relationship between dioxins and total chlorobenzenes for three simultaneously measured facilities.

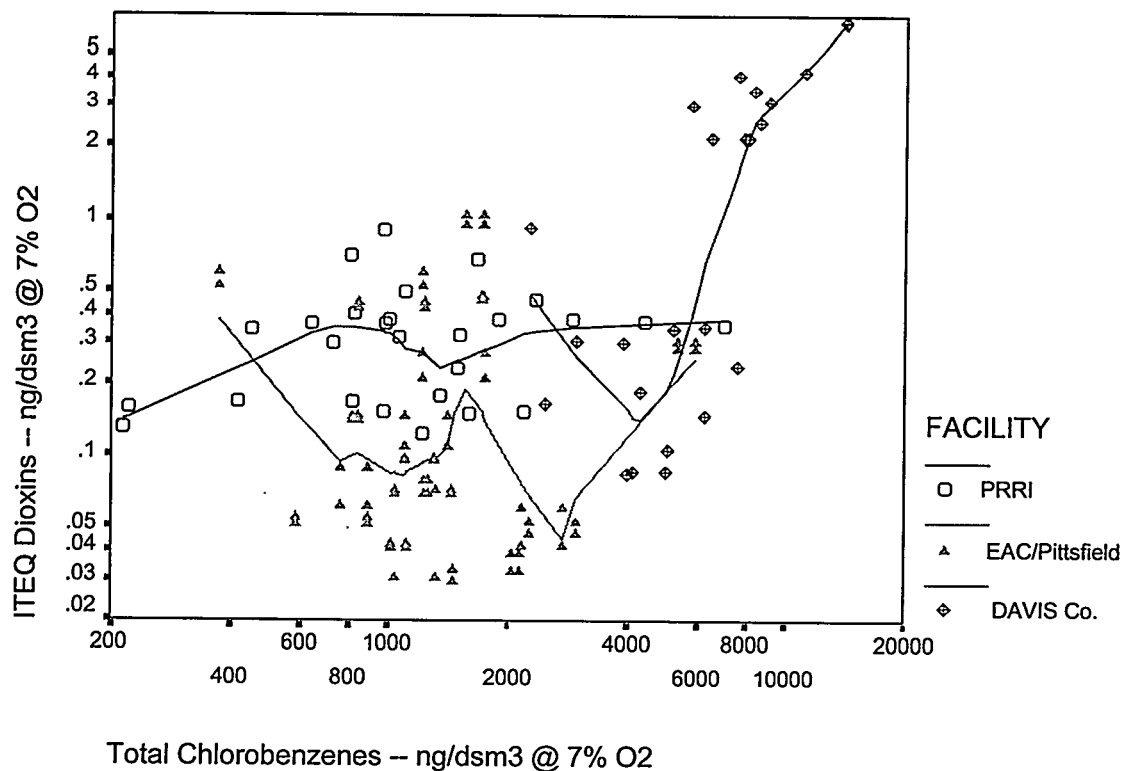
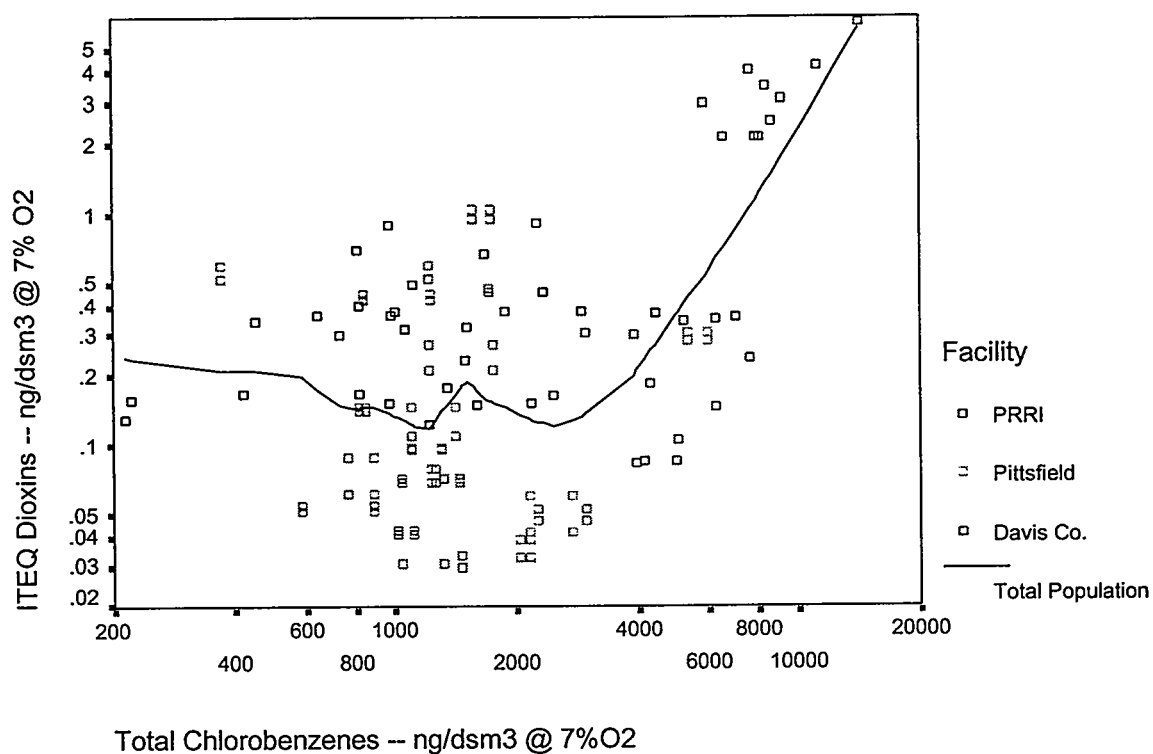


Figure 7. Scatter plot displaying the relationship between dioxins and total chlorobenzenes for three simultaneously measured facilities treating the data as a single group.



Continuous Monitoring of Metals Emissions

Robert G. Barton, Gary D. Hinshaw, Brian Cage, and Paul Gorman
Midwest Research Institute
425 Volker
Kansas City, MO 64110

INTRODUCTION

Continuous monitoring of emissions can assure the public of the safe operation of combustion facilities. Because of this, continuous monitors for many materials that have not been previously subjected to continuous measurement are being developed. Trace metals are one such material. A novel concept for the continuously monitoring toxic metals emissions, in gaseous and particulate form, has been developed and is being tested at Midwest Research Institute (MRI). The concept is based on the use of the SpinCon[®] gas-liquid contactor with an inductively-coupled argon plasma emission spectrometer (ICAP) or an ion chromatograph. This combination of technologies is called SPICAP. The SpinCon[®] uses a high-velocity cyclonic gas-flow to transfer both soluble gases and particles from a contaminated gas stream to a concentrated liquid medium. The liquid medium can be transported to an appropriate analytical device on a continuous, semi-continuous or batch basis.

As described by French and Durham¹, the most common approaches used to continuously measure concentrations of multiple metals are based on the measurement of emissions spectra generated when stack gas samples are subjected to strong excitation sources. The SPICAP system may be operationally more complex than these competing systems due to its requirement for a liquid medium. However, it is capable of concentrating metals in the liquid stream yielding lower detection limits. In addition, the SPICAP is currently the only system that is capable of collecting samples that can be used to continuously measure hexavalent chromium (Cr⁺⁶) emissions.

MRI's development program consists of three concurrent tasks. In the first, a computational model of the capture processes is being developed and refined. This model was used to predict the capabilities of the device and suggest new areas of development. In the second task, a series of controlled laboratory experiments were conducted to evaluate system operation and performance. The final task involves conducting field tests using prototype units.

EQUIPMENT

The CEM developed by MRI is based on the patented SpinCon[®] gas sampling system². This device transfers contaminants from a gas and concentrates them in a liquid. A simplified schematic of the device is shown in Figure 1. Gas samples are drawn from a stack through a Teflon line at a controlled rate. The line can be continuously rinsed as in the standard Cr⁺⁶ method³. Gas samples can then be passed through a saturation tower equipped with an air-atomized spray nozzle to cool and saturate the gas. The saturation tower is only used when sampling gases that are not saturated with moisture and are above approximately 200°C.

Gas samples then flow into a transition chamber from which they are drawn through a slit in the wall of the SpinCon[®]. The slit is cut tangentially into the wall of a cylindrical collection chamber forcing the gases that enter to flow horizontally around the interior circumference of the chamber. After one revolution the gases exit up the center of the cylinder. Liquid is introduced through a small hole in the wall of the collector. The cyclonic air flow forces the liquid to form a thin film on the wall of the collector. When the film encounters the slit, it is atomized to form a jet of fine droplets. The droplets move with the entering air across a chord of the collector and collide with the wall. After the collision, the film is reformed. The air flow is induced by a pump downstream of the collector. Air and liquid

flows are controlled independently. Decreasing the liquid flow relative to the air flow allows the device to reach lower detection limits at the expense of longer response times.

Figure 2 illustrates the mechanisms that control the capture of material in the device. As the particle laden air enters the device, it encounters a cloud of slow-moving drops that have just been formed by atomization of the film. Particles are transferred from the gas stream to the liquid by inertial impaction with these drops. The drops rapidly accelerate to the speed of the air jet. Within the cloud of drops, very small particles, those with diameters less than about $0.1\text{ }\mu\text{m}$, move to the droplets due to Brownian diffusion and are collected. When the drops collide with the wall of the collector, the gas and liquid are separated and the film is reformed. The gases then move around the inner wall of the collector in a thin layer near the wall. Particles move outward toward the wall due to the centrifugal forces. Any particles that reach the wall of the collector or the liquid film will be removed from the gas stream.

The collection of vapors occurs primarily in the cloud of droplets. Any soluble vapors diffuse to the droplets and are absorbed into the liquid. The mechanisms are enhanced by the large quantity of available liquid surface area in the droplet cloud. Once the liquid reforms the surface film, the available surface area decreases significantly and little additional removal of gases occurs.

MODELING

A computational model based on the mechanisms described above has been developed. All of the mechanisms except Brownian diffusion are accounted for. Table 1 summarizes major components of the model and the associated computational approaches. The model was used to predict the effect of several operational parameters on the predicted collection efficiency of the device. Two parameters found to exert a strong influence on the collection efficiency were particle size and slit coverage.

Figure 3 illustrates the predicted capture of particles and gases at the baseline conditions summarized in Table 2. The zone where particles collide with stationary droplets captures 67 percent of the particles initially in the gas stream. Centrifugal forces resulted in the capture of an additional 27 percent of the particles initially present. The predicted overall particle collection efficiency for the baseline conditions was 94 percent on a mass basis. Significant collection of soluble vapors is predicted to occur only in the cloud of droplets. Baseline vapor collection is predicted to be 40 percent by mass.

Figure 4 illustrates the impact of particle diameter on the predicted collection efficiency. The calculated efficiency was close to 100 percent for particles greater than $3\text{ }\mu\text{m}$ in diameter and decreased rapidly for smaller particles. The collection of particles less than $0.1\text{ }\mu\text{m}$ in diameter is the device will probably be much greater than predicted due to the influence of Brownian diffusion.

The fraction of the slit covered by the liquid film was thought to be an important operating parameter. When the film completely covers the slit, 90 percent of the particulate mass is captured by impaction in the spray and another 7 percent is captured in the centrifugal zone. When the fraction of the slit covered is decreased, the fraction of the material captured in the spray decreases proportionally. However, the relative quantity captured in the centrifugal zone increases. The overall capture efficiency decreases only slightly as the fraction of the slit covered by liquid decreases. Because most gas capture occurs in the droplet cloud, the capture of vapors is a strong function of slit coverage.

LABORATORY TESTING

The system's ability to collect hexavalent chromium has been tested in the laboratory⁴. Hexavalent chromium was selected as the target metal for these tests for three reasons. First compounds containing hexavalent chromium are often much more volatile than compounds containing the more common trivalent chromium. In combustion systems, compounds containing hexavalent chromium will vaporize in the high temperature regions and then condense as the gases cool. These processes result in the formation of particles typically about 0.2 μm in diameter. Particles in this size range are the most difficult to capture in most collection devices. Second, none of the multiple metals CEMs under development are capable of determining chromium speciation. Third, hexavalent chromium is a potent carcinogen and of significant environmental concern.

A DeVilbiss nebulizer was used to generate an aerosol consisting of particles composed of CrO_3 . The aerosol was sampled using the SpinCon[®], the standard EPA method for hexavalent chromium³ and an inertial impactor. The collected material was analyzed for Cr^{+6} using ion chromatography. The results of these tests are summarized in Figure 5. The concentrations of Cr^{+6} found in the SpinCon[®] solutions were within 11 percent of those in the solutions produced by the standard method.

FIELD TESTS

Two series of field tests have been conducted using prototype sampling units. In both test series, samples of the collection liquid were obtained and shipped to an off-site laboratory for analysis. The tests were conducted at a hazardous waste incinerator and a mixed waste incinerator.

Hazardous Waste Incinerator

In these tests, the SpinCon[®] sampler was used concurrent with a standard EPA hexavalent chromium sampling train at a hazardous waste incinerator. Figure 6 summarizes the results of the tests. Much variation was observed because the emitted concentrations were close to the detection limits of the testing methods used. The detection limit of the SpinCon[®] system can be lowered by retaining the liquid in the collector for a longer period. However, that approach was not used in the field tests. No particle size analysis was performed. Due to the mechanism described previously, the particles containing the hexavalent chromium probably ranged in size between 0.2 μm and 1 μm .

The relative accuracy of MRI's approach was assessed using draft EPA performance specifications for multi-metals continuous emissions monitoring systems⁵. The documents specify two criteria for assessing the relative accuracy of an experimental CEM. The relative accuracy of the experimental method must be:

- Within ± 20 percent of the mean value of the EPA reference method
- Within ± 10 percent of the applicable standard.

The relative accuracy obtained using the SpinCon-based approach varied from that for the EPA reference method by 27 percent. However, the relative accuracy was calculated to be 7.1 percent of the applicable standard. Thus, the system conformed to the second criteria.

Mixed Waste Incinerator

The second series of tests were conducted at the U.S. Department of Energy Oak Ridge Reservation, located near Oak Ridge, Tennessee. A mixed waste incinerator designed and permitted for thermal destruction of radioactively contaminated polychlorinated biphenyl (PCB) and other hazardous compounds. Emissions were measured using the SpinCon-based system and EPA Method 29 simultaneously. Thirteen metals were targeted—antimony, arsenic, barium, beryllium, cadmium, chromium, lead, silver, manganese, cobalt, nickel, selenium, and uranium.

Figure 7 summarizes the results of the testing. The data show that the SpinCon-based unit generally indicated lower metals concentration than Method 29. However, the concentrations of all but four metals were below 10 µg/dscm. As these low levels, small variations in measured concentrations result in large relative errors.

For the four metals present at concentrations above 10 µg/dscm (Ba, Pb, Sb, and U), the EPA Method 29 results are higher than the CEMs results by a factor ranging from 1.1 up to 3.0. This difference may be caused by carryover of liquid from the sampler which removes some of the metal analytes. More recent improvements in the collector's level control system have reduced this problem.

CONCLUSIONS

The development of the SpinCon® sampler is an ongoing project at MRI. Testing and modeling work indicate that the CEMs is promising and has several unique capabilities. These include:

- Efficient collection of fine particles and soluble vapors.
- High gas sampling rate
- Low liquid volume and flow rate
- Adjustable concentration ratio (i.e., the ratio of the concentration of the component captured in the liquid to the concentration of the component in the gas being sampled).
- Capable of detecting hexavalent chromium

However, additional development is needed before the device can be commercially available.

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Table 1. Modeling approaches used to investigate behavior of the SpinCon®.

Process	Approach
Atomization	Twin fluid atomizer (after Lefebvre ⁵)
Particle-Droplet Inertial Impaction	Modification of venturi scrubber model (after Wark and Warner ⁷)
Capture due to Centrifugal Forces	Force balance (similar to cyclone analysis)
Vapor Absorption in Film	Diffusion limited rate. Turbulent boundary layer (after Geankoplis ⁸)
Vapor Absorption in Cloud	Diffusion limited rate. Droplets and vapor have same velocity (after Geankoplis ⁸)

Table 2. Baseline conditions used in the model.

Parameter	Value	Units
<i>Liquid Properties</i>		
Surface Tension	72.12	dyne/cm
Density	0.9965	g/cm ³
Viscosity	0.8532	centipoise
Heat of Vaporization	2.26×10^6	J/kg
Average Molecular Weight	18	g/mol
<i>Solids Properties</i>		
Density	2.28	g/cm ³
Particle Loading in Gas	100	µg/m ³
Mean Particle Diameter	2	µm
Standard Deviation of Size Distribution	1	µm
<i>Gas Properties</i>		
Density	1.179×10^{-3}	g/cm ³
Viscosity	1.97×10^{-5}	centipoise
Vapor Contaminant Concentration	100	µg/m ³
Diffusivity of Vapor in Bulk Gas	0.288	cm ² /s

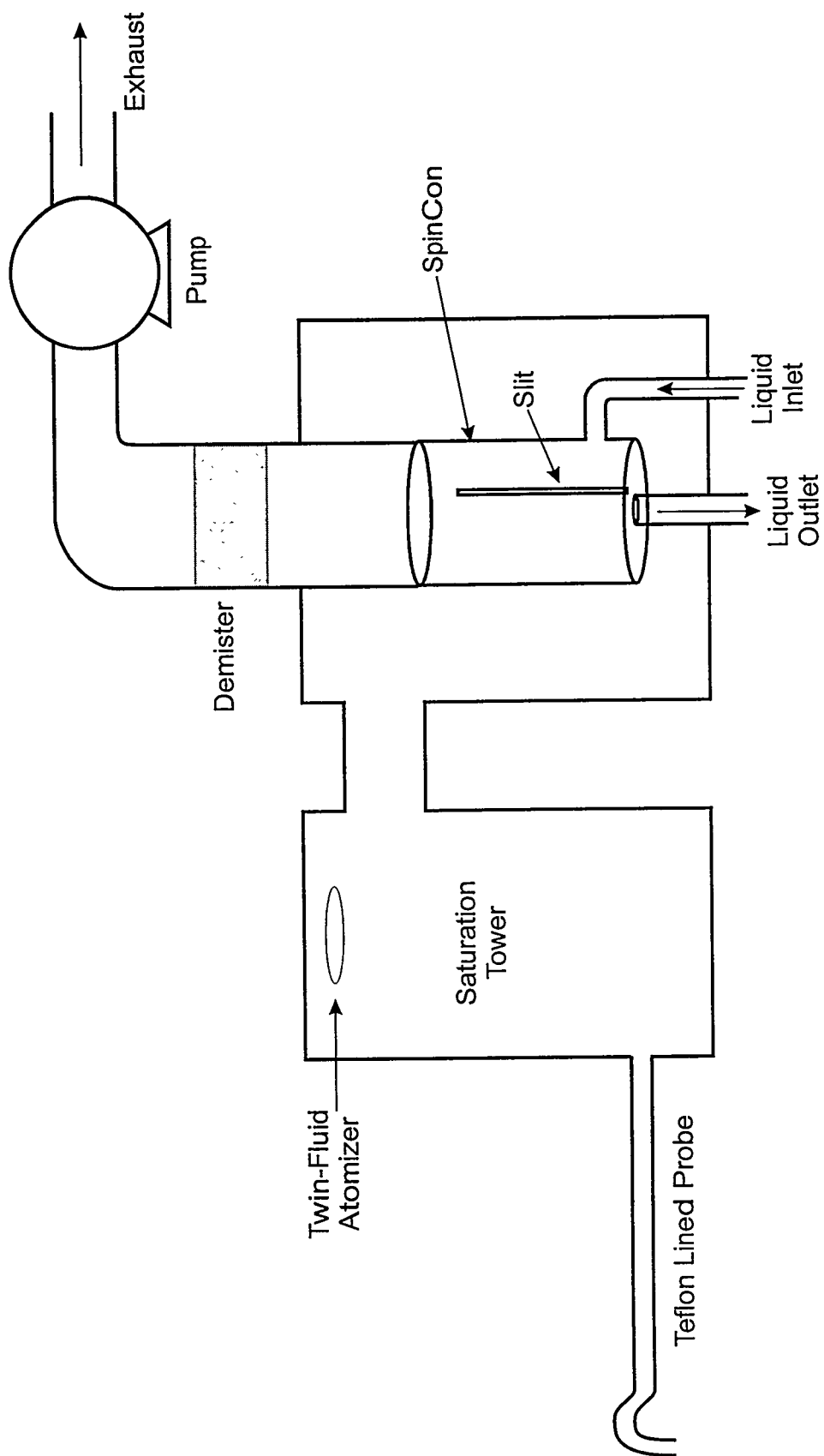


Figure 1. Schematic diagram of the SPICAP system.

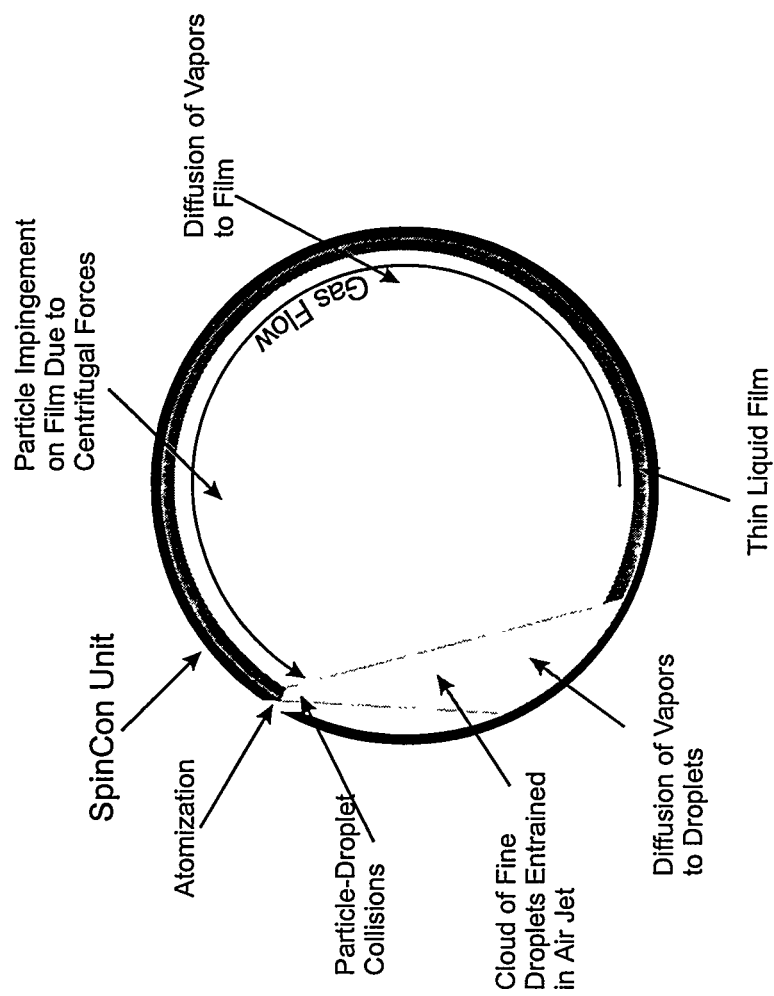


Figure 2. Mechanisms that control the collection of metals in a SpinCon collector.

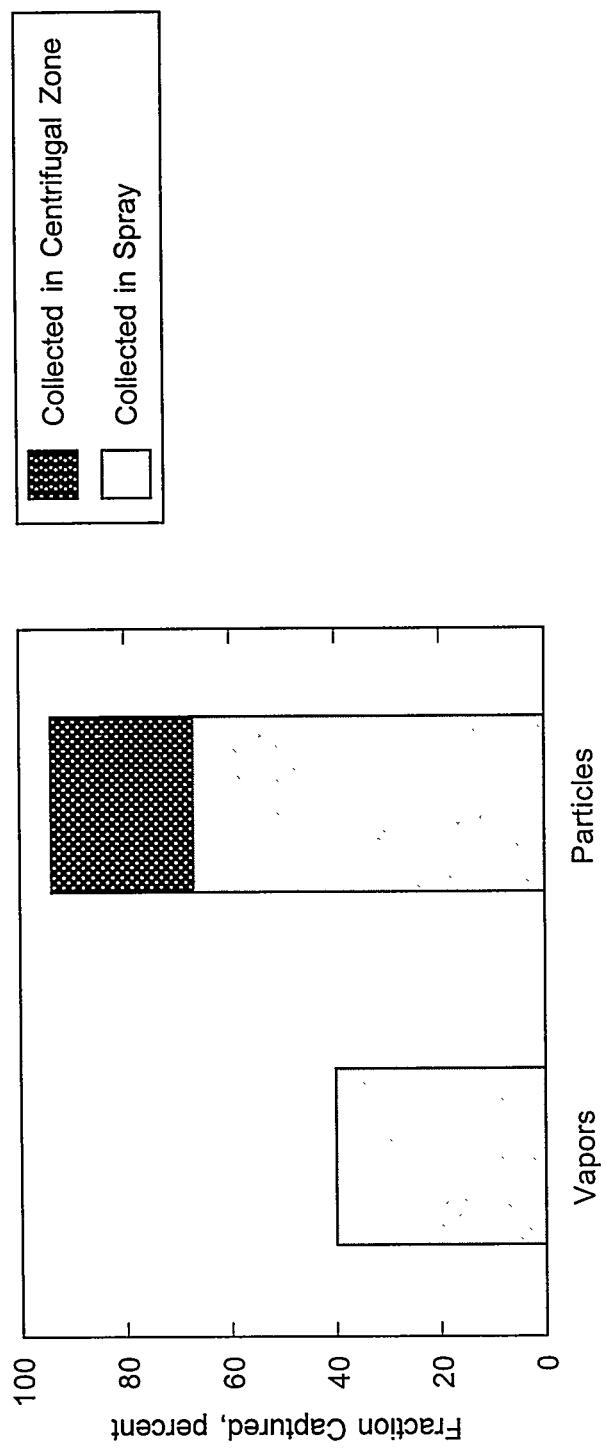


Figure 3. The predicted fraction of vapor and particle contaminants remaining in gas samples at two locations in the SpinCon collector.

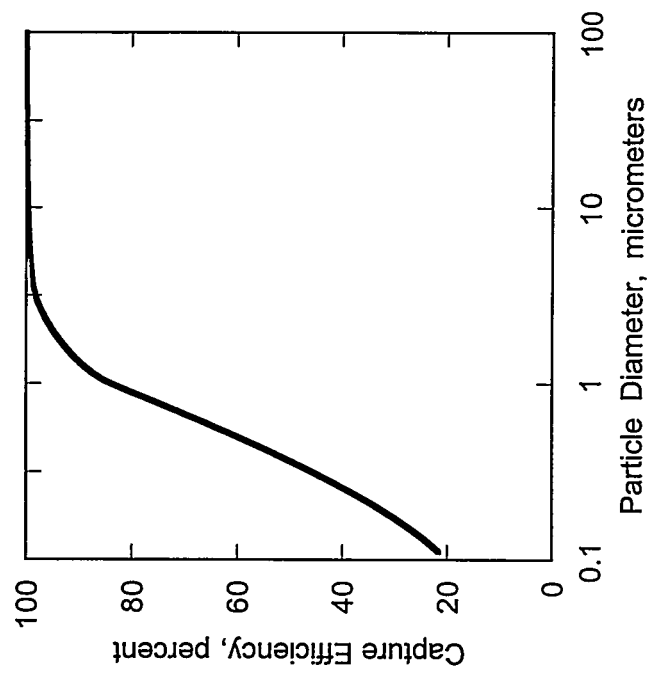


Figure 4. The predicted impact of particle size on capture efficiency.

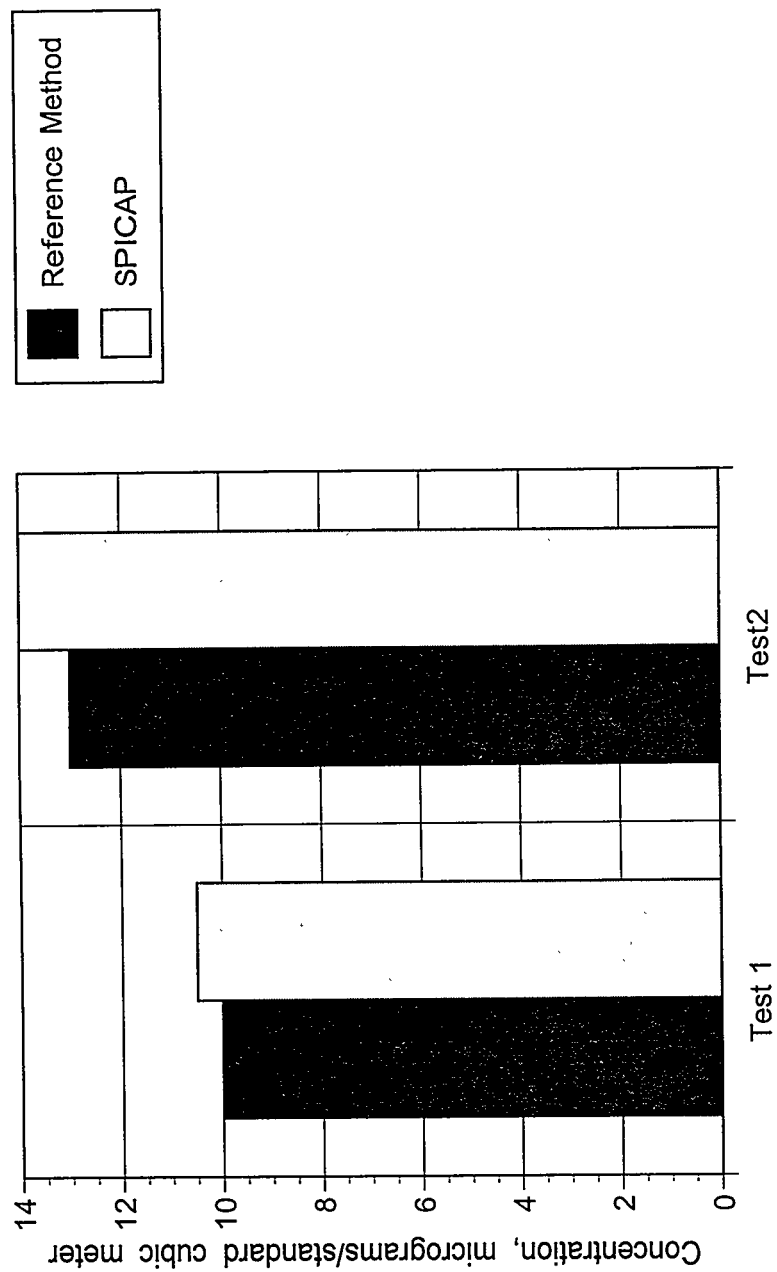


Figure 5. Hexavalent chromium concentration measured in laboratory system using the SPICAP and the EPA reference method.

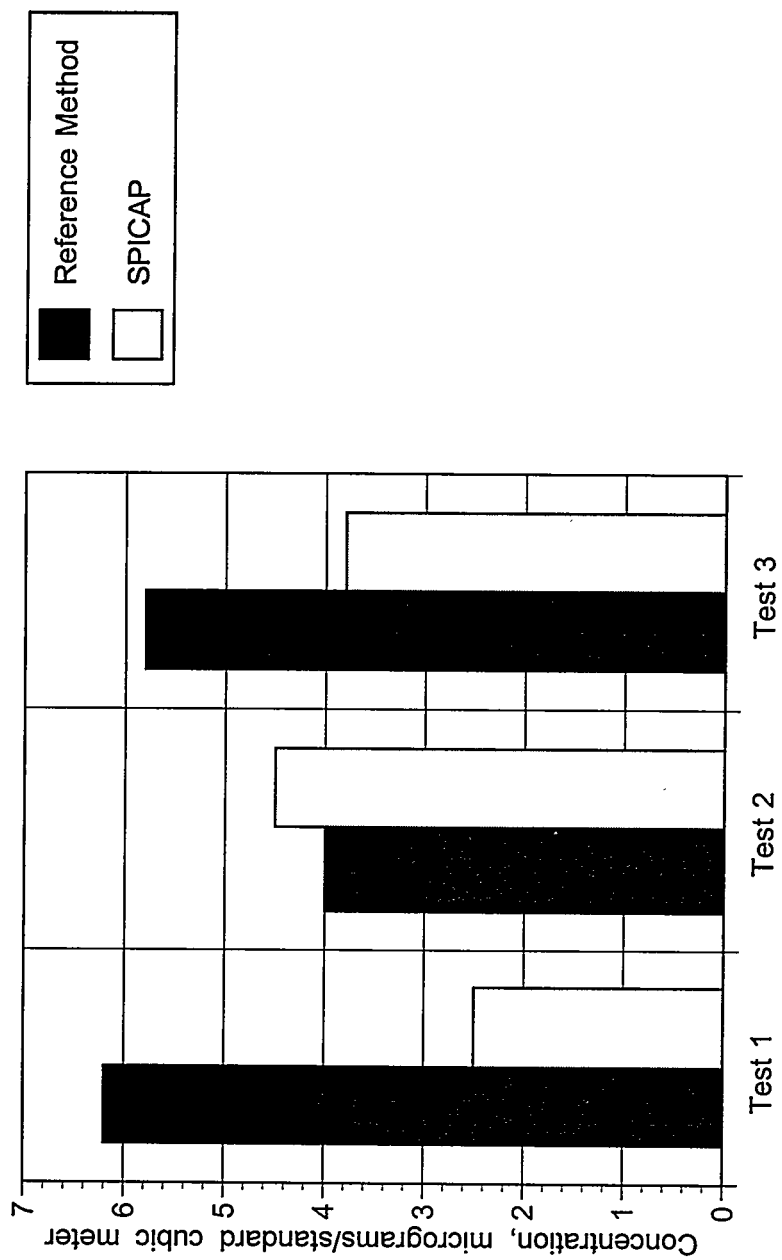


Figure 6. Hexavalent chromium concentration measured in incinerator exhaust gas using the SPICAP and the EPA reference method.

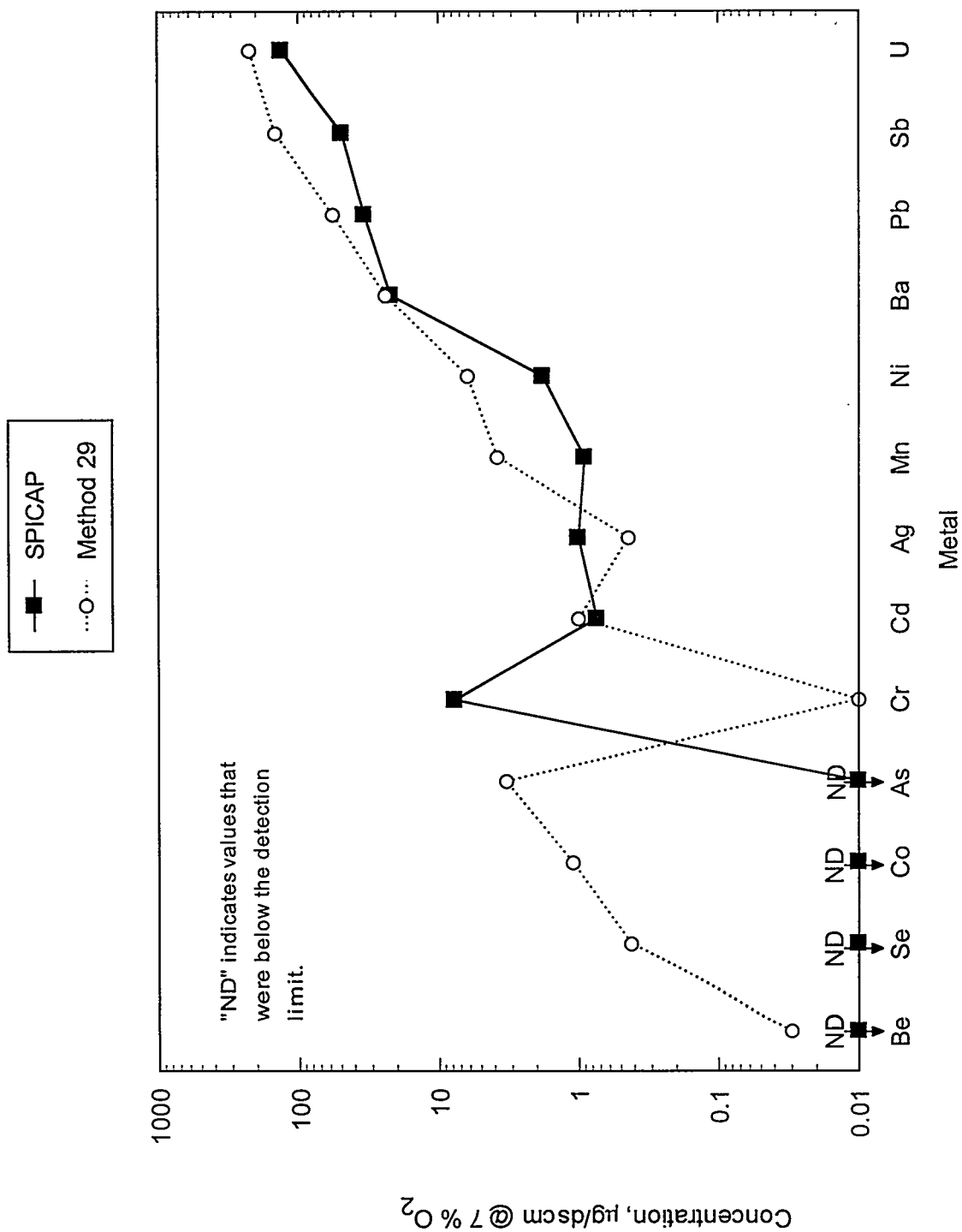


Figure 7. Results of sampling the exhaust gas of a mixed waste incinerator using SPICAP and the EPA reference method.

Establishing Data-Derived Emissions Limitations

H. Gregor Rigo
Rigo & Rigo Associates, Inc.
1 Berea Commons, Suite 211
Berea, Ohio 44017

and

Gary Liberson
Environmental Risk Sciences, Inc.
1000 Thomas Jefferson St., NW, Suite 506
Washington, D.C. 20007

INTRODUCTION

The emissions limitations found in regulations and permits have traditionally been set using engineering judgment, commercial considerations and public perception of potential harm and achievability. Given the restricted list of pollutants in Section 129 of the Clean Air Act (CAA) and EPA's decision to base municipal waste combustor (MWC) Maximum Achievable Control Technology (MACT) Floor determinations on limitations in enforceable permits, the need for determining these values from test data seems to be past. However, this does not stop local jurisdictions from imposing additional requirements. Local regulatory bodies and concerned citizens frequently want to regulate pollutants that are not addressable using EPA's permit limit procedure; too few permits include limitations on specific emissions. The need to correctly calculate achievable emissions remains. At the very least, it is imperative that correctly calculated limitations be placed in the administrative record supporting a permit so that if a problem occurs, a facility retains the ability to defend itself. Fortunately, emissions limitations can be calculated using statistical techniques that consider both regulatory constraints and source variability. These procedures provide a deterministic, objective link between test results and a lower limit that bounds achievable, data-derived regulatory and permit restrictions.

PHILOSOPHICAL FRAMEWORK

EPA set the MACT floor for MWCs by ranking individual pollutant limitations from existing permits from lowest to highest and selecting the 12 percent that were lowest based on the number of incinerators in a category. This group of permitted limits was then averaged. EPA's approach presumes that the permit limitations were being achieved and that the arithmetic average is routinely achievable. Averaged emissions limitations simply imply that some values are larger than the average and some are smaller. Consider, for example, averaging: 20, 20, 20, 20 and 10 to get 18. For this group, only one would be in compliance with the arithmetic average of the emissions limitations even when all five are operating at their permitted level. This points out an obviously unintended consequence of reading the adjective "average" (meaning "typical") in the CAA as the verb or noun meaning "arithmetic average". To establish an emissions limitation using the data average is clearly wrong.

To address this problem, a number of different approaches have been posited by the EPA and industry. The balance of this paper presents these approaches, along with a couple of additional conceptual approaches that could prove useful when faced with the problem of establishing permit limitations for previously unregulated pollutants.

STATISTICAL CONSIDERATIONS

Average emitted concentrations and variance estimates are derived from test data. Figures 1 and 2 show the theoretical statistical effect of uncertainty on the expected distribution of the sample average compared to the true value. The true distribution may be shifted to the left or right of the calculated average; it may also be flatter or more peaked because of the uncertainty with which the standard deviation is known. We can be reasonably certain, however, that the true mean is within the 95 percent statistical confidence level confidence limit for the average and the population standard deviation (the true variability of the sample) is similarly bounded by the 95 percent statistical confidence level confidence limit for the standard deviation. When these two sources of uncertainty are combined, the emissions limitation is correctly determined by the 95 percent statistical confidence level, percent coverage tolerance limits that contain a specified percentage of future tests at a given statistical confidence level result. The errors are incorporated by K -statistics^{1,2}.

Inherent Limitations of a Statistical Bound

Regardless of the quality of data and validity of the statistical procedures employed, there is a known chance that a well-operated plant will exceed the average. This is inherent in the statistical procedure. When working at the 95 percent statistical confidence level, there is a 5 percent chance that a valid measurement will be outside the calculated bound. Similarly, when limits are calculated to contain a specified percentage of future measurements, say 99 percent, there is still a one percent chance that a valid measurement will not be included when the plant operates as it did when tested to set the limits!

Consider the implications of these errors to a well-operated MWC with three units being tested for six reference method pollutants every year—a combined total of 18 tests per year must be passed. At the 95 statistical confidence level, one exceedance would be expected virtually every year when statistically perfect emissions limitations are promulgated since 1 out of 20 tests under the same conditions should result in a violation at the 95 percent confidence level. Similarly, if the limits are designed to contain 99 percent of the future test values at the 95 percent statistical confidence level, more than one violation of a set of consistently tight, but perfectly derived, emissions limitations can be expected.

Sources of Error

Characterizing stack emissions involves field sampling and recovery, sample handling, laboratory analysis, data entry, results calculation and interpretation. When three runs make up a performance test³, the results are never exactly alike due to normal variability (random errors) introduced at each step of the characterization process. Analyzing emissions from different test conditions introduces another source of variability due to changes in the fundamental performance of the system. All the foregoing assumes that the same team and laboratory do all the testing. Different field teams, laboratories and chemical supply houses introduce additional sources of variability during retesting.

From a global perspective, available test data can be said to contain two broad types of error:

- within-test error—this characterizes the differences between the three runs or repeated measurements made close together in time to characterize a single test condition.
- between-test error—this characterizes the differences between the average obtained from a number of different tests taken under different conditions and at different times.

Each error source must be accommodated when emissions limitations are calculated. Just as performance is characterized by the average of the individual test runs, within-test error is characterized by the standard deviation of those same runs. Between-test variability is estimated as the standard deviation of the individual test condition averages for an individual plant. When these are combined, the overall source variability, including the effects of different test teams, laboratories, operating conditions and normal performance changes, are characterized. Combining either the between- or within-test variability from several test series or sources is known as pooling. This is a valid technique for maximizing the information.

Statistical Outliers

Even the best laboratories and field teams sometimes produce aberrant data. When there are enough replicates, a number of statistical tests can be employed to identify unusually large and small values. Leaving such values in the analysis bias the average and inflates the standard deviation. Removing such values leaves a facility exposed to exceedances for normal occurrences. This is an issue that requires careful attention and balance. Those interested in tight regulations will want outliers excluded. Those

interested in not being penalized for chance occurrences will want them included. Agreement on outlier identification and handling should be reached prior to applying any statistical treatment of the data.

Combining (Pooling) Data From Several Tests

Unless the overall variability (both the between- and within-test variability) are properly incorporated, the expected range of future test results cannot be characterized. Facilities that comprise the MACT Pool could routinely fail future tests even when tested under identical conditions if the emissions limitations are not properly set.

Emissions data sets typically contain results for a number of test conditions and units. Determination of the statistics for the pooled standard deviation and the effective number of runs for both the within- and between-test conditions can be accomplished with the same basic equations.

The data from individual test conditions are used to estimate within-test variance. Our review of the data indicates that the within-test standard deviation — estimated for each run using the natural logarithms of the data since the data are lognormally distributed⁴ — can be treated as coming from an equal variance population.

Under this assumption, the pooled standard deviation (S_p) and effective number of runs (N_p) which characterize all test conditions (C), not just an individual test series, are defined by the following equations:

$$S_p = \sqrt{\frac{\sum (n-1)s_c^2}{\sum n - C}} \quad (1)$$

$$N_p = \sum n - C + 1 \quad (2)$$

Estimating the overall test condition standard deviation (S_o) and effective number of runs (N_o) by pooling the between- and within-test condition variability (S_b and S_w , respectively) is more complicated than simply pooling either of these two variability sources alone. Review of the available data indicates we cannot assume that the variances are equal. The pooling is done by using the following equations for combining two standard deviations when they cannot be assumed⁵ equal:

$$S_o = \sqrt{\frac{(N_w - 1)S_w^2 + (N_b - 1)S_b^2}{(N_w + N_b - 2)}}, \quad (3)$$

$$N_o = 1 + \frac{(N_b\theta + N_w)^2}{\frac{(N_b\theta)^2}{N_w - 1} + \left(\frac{N_w}{N_b}\right)^2}, \text{ and} \quad (4)$$

$$\theta = \left(\frac{S_w}{S_b}\right)^2 \quad (5)$$

Ranking Test Series Averages

Before selecting best performance, the results of emissions testing have to be ranked. The arithmetic average of three runs complies with regulatory requirements for determining compliance, but it does not consider the precision with which a test result is known. In CETRED⁶, EPA added twice the standard deviation to the test series average as an approximation of the value likely to contain the average with 95 percent confidence. Unfortunately, three times the standard deviation should have been added to account for the uncertainty associated with using the sample⁷.

A better approach is to rank the facilities using the 95 percent statistical upper confidence limit for the average of lognormally distributed data as suggested by Land⁸. The following equations by Rigo⁹ produce the same numeric estimates for the upper confidence limit, but have the advantage of being implementable using standard statistical tables and functions available in modern spreadsheets like Excel[®]:

$$Plus2 = \bar{X} + 2 \times S \quad (6)$$

$$Plus3 = \bar{X} + 3 \times S \quad (7)$$

$$UCL_{Land} = \mu + \frac{1}{2}\sigma^2 \left(t_{v,\alpha/2} \sigma^2 + \left[\frac{1}{2}\sigma^2 \left\{ \frac{N-1}{\chi^2_{N-1,1-\alpha}} - 1 \right\} \right]^2 \right)^{1/2} \quad (8)$$

Experience using the various formulations indicates that *Plus3* and UCL_{Land} produce generally similar rankings. *Plus2*, on the other hand, frequently differs materially from either the correct nonparametric limiting value and the upper confidence limit on the mean for lognormally distributed data.

Method Precision—The Accuracy of Reported Numbers

Test results that are below the analytical laboratory detection limit (ADL), and even those below the Reference Method Practical Quantitation Limit (RMPQL), contribute no meaningful information about the operation of a source since these results are either indistinguishable from zero or are too variable (error greater than ± 30 percent for methods evaluated in accordance with 40 CFR 63, Method 301 Method Validation). These results must be eliminated from the data in order to calculate stable between- and within-test estimates of variability. When values below the ADL are eliminated, much of the “data” currently being used to establish variability are lost.

Correct Statistical Confidence Level and Interpretation of Data-Derived Limits

In the proposed Hazardous Waste Combustor Rule, there are five data-derived emissions limitations that must be met simultaneously (mercury, lead, semivolatile metals, low-volatile metals and total chlorine). For the statistics of the proposed rule to be at the 95 percent confidence level recommended by OSW for other RCRA applications and by the Office of Air Programs for New Source Performance Standards and Guidelines for Existing Sources (see 40 CFR 60 Appendix A, Method 19, for example), individual data-derived MACT Floor limits must be set at the 99 percent statistical confidence level.

Gastwirth¹⁰ explains that “the probability that the *joint procedure* rejects” (the null hypothesis that a plant is in compliance) is:

$$P(A \cup B) = P(A) + P(B) - P(A \cap B) \quad (9)$$

The above equation can be extended to cover the situation where 5 test conditions must be simultaneous met at the 95 percent statistical confidence level.

Using the Bonferroni approximation, the significance level for k comparisons to meet the intended α level is:

$$\alpha^* = \alpha/k \quad (10)$$

The intended overall statistical significance is achieved by using a statistical significance — α^* — of 0.01, which is the 99 percent statistical confidence level.

Data-derived emissions limitations provide floors below which no one should write or accept a limit in a regulation permit¹². A data-derived emissions limitation based permit must include either additional margin or a provision that passage of a prompt retest deems the initial test a statistical aberration that is not subject to citizen suits and enforcement actions.

Pitfalls of Pollutant-by-Pollutant Calculations

A pollutant-by-pollutant (also known as HAP-by-HAP) approach to setting emissions limits precludes consideration of confounding and conflicting affects between and among the various proposed limitation. Potentially conflicting parameters must be considered when setting standards for various constituents. When pollutants are controlled by different techniques, it may be appropriate to analyze them separately. However, this decision must be re-verified for conflicts in performance of individual control technologies applied in series. For instance, the design of air pollution control devices [APCDs] to control particulates, semi-volatile metals and low volatile metals is the antithesis of designs needed to minimize the synthesis of dioxins and furans. Larger ESPs and baghouses reduce particulate and particulate related pollutant emissions. Unfortunately, these larger APCDs also increase the amount of time the flue gas is held at elevated temperature before being exhausted to the environment. More dioxins and furans are formed in ESPs and baghouses operating at the same temperature which have larger specific collector areas (SCAs) and lower air-to-cloth ratios (ACRs).

It must be recognized that several pollutants are controlled by the same device. Overlooking this point can quickly lead to the ridiculous conclusion that an individual source must be simultaneously equipped with ESPs (lower dioxins) and FFs (lower metals), but not both! This clear technical impossibility is easily avoided if a common pool of best performing facilities or at least a common set of characteristics for those plants is used.

ALTERNATIVE APPROACHES TO CALCULATING A DATA-DERIVED EMISSIONS LIMITATION

Over the past few years, a number of different methods of calculating data-derived emission limitations have been forwarded. These were originally developed to lend a scientific basis to a historically judgmental problem. Since the passage of the 1990 Clean Air Act Amendments with the requirement to establish Maximum Achievable Control Technology (MACT) floors for historically unregulated sources, the attention paid to this problem has increased. The following brings together the most recent versions of the concepts currently in use.

Combined Statistical—Technical Procedure

The combined statistical—technical procedure used by EPA in the Hazardous Waste Combustion Rule procedure is conceptually simple. All the data for a single pollutant and category are arrayed in ascending order. Additional test averages are included until 6% of the facilities for which complete data

are available are included. This means that several test conditions for some facilities will make it into the pool and some low emitting facilities will be excluded because of incomplete emissions characterization data. All other facilities having similar design and feed characteristics are identified and brought into the facility pool. These additional facilities with similar characteristics to the best performing group are called the expanded universe (EU).

The average emissions from the highest emitting test condition among this group of deemed equivalent facilities are used as a proxy for between-test variability. The data-derived MACT emissions limitations is set equal to the data-derived emissions limitations for that test condition using the pooled within-test variability for all included test conditions. Unfortunately, this specific formulation proffered by EPA did not recognize that the pooled within-test standard deviation is only an estimate of the population standard deviation and used the normal deviate ($\phi^{-1}(0.99)$) instead of the appropriate tolerance interval ($K_{0.055, 0.99, N}$).

Equation (11) was used by EPA to determine data-derived emissions limitations and design values (annual average emissions) from the data used to characterize the pool facilities¹³.

$$EL_{EPA} = \exp \left[\mu_3 + \phi^{-1}(0.99) \sigma_3 \sqrt{1 + \frac{3}{N}} \right] \quad (11)$$

where: $\mu_3 = \log(\bar{X}) - \frac{1}{2} \sigma_3^2$ (12)

$$\sigma_3^2 = \log \left[\frac{S^2}{3[\bar{X}]^2} + 1 \right] \quad (13)$$

$$\bar{X} = \exp \left(\mu_m + \frac{1}{2} \sigma_0^2 \right) \quad (14)$$

$$S^2 = (\exp(\sigma_0^2) - 1) \exp(2\mu + \sigma_0^2) \quad (15)$$

$$\bar{X} = \exp \left\{ \log(EL_{EPA}) + \frac{1}{2} \log \left(\frac{1}{3} \exp(\sigma_0^2) + \frac{2}{3} \right) - \phi^{-1}(0.99) \left[\log \left(\frac{1}{3} \exp(\sigma_0^2) + \frac{2}{3} \right) \right]^{1/2} \right\} \quad (16)$$

In the published equation for S^2 , σ_0 instead of σ_0^2 was incorrectly used in two places in the equation when compared to the published¹⁴ derivation for S^2 .

When $\bar{X}$ is calculated, the mean and standard deviation of the logarithms of the data for the highest emitting condition in the pool facilities are used. A more technically correct approach uses the highest test-condition average in the pool along with the pooled geometric standard deviation to estimate the internally consistent geometric mean for the highest emitting source. Of course, if the geometric standard deviation for the highest emitting source and the pool variance are similar, this refinement is not needed. Given the presence of outliers which can inflate variances, the refinement is prudent and turns out to be necessary in many cases.

As discussed previously, $\phi^{-1}(0.99)$ is a reasonable statistic to use when there is a very large emissions database that produces, say, more than 50 degrees of freedom. When fewer runs are available, the upper two-sided tolerance limit K -Statistic for 99 percent coverage, 95 percent statistical confidence level and

N runs should be used instead. Tabulated values can be found in previously referenced books by Natrella, and Hahn and Meeker.

An alternative to the combined statistical—technical procedure used for some pollutants was dubbed a breakpoint analysis. Here the average emitted concentrations, or preferably some related statistic that considers variability, is ranked from smallest to largest. Different equations¹⁵ are used to estimate the slope (SL) and inflection (I) points:

$$SL = X_{i+1} - X_{i-1} \quad (17)$$

$$I = X_{i+1} + X_{i-1} - 2X_i \quad (18)$$

By plotting SL and I versus rank on the same graph, the slope of various segments of the line describing the data is visualized. Slope changes are marked by jumps in the value of I which mark inflection points in the curve. The breakpoint is marked by the largest value of I and the corresponding emitted concentration is X_i . Once X_i is identified, if it does not already explicitly incorporate uncertainty, the relevant concentration is described by previous Equation (11) except that $\bar{X}$ is replaced by X_i and α_o is the appropriate pooled value. Consideration should be given to using the median of the individual series standard deviations in this context.

12% MACT Approach

The 12% MACT approach differs from the HWC Rule approach in that progressively higher emitting test conditions are collected until 12% of the facilities for which data are available, but not less than 5 under Sections 112 and 129 of the CAA, are included. An expanded pool of similar facilities is then established and the data-derived emissions limitation is then calculated using the average of the EU emissions and within-test variability. Adjustments for the effect of below detection limits data using the δ -log approach is recommended by EPA. This approach obviously does not consider between-test variability, even via a proxy. Thus, it ignores good engineering and statistical practice and procedures. It is not considered viable by these authors and is not discussed further.

CETRED Approach

When the Agency began the regulatory process for HWCs, they published CETRED¹⁶. In that report, most of the particulate and PCDD/F data found in EPA's emissions database were analyzed. The methodology employed was similar to EPA's current 12% MACT approach except that the results of all test conditions for individual facilities were treated as a single characterization. The data-derived emissions limitations were done considering both between- and within-facility variance¹⁷.

Most facilities have been tested several times and under various operating conditions. When the mean of the test series averages is calculated, it generally falls very close to the average developed by simply averaging each data point for all test conditions. This is an expected result since most test series involve the same number of runs and it doesn't matter how an overall average is calculated as long as each data point is included the same number of times.

The standard deviation, however, can and does explode (dramatically increase) when the results for individual test conditions are tightly clustered, but the various run conditions are widely separated. This is because the calculated standard deviation includes both the between- and within-test sources of variance.

In CETRED, the statistical methodology considered both the variability exhibited within each test series and between all test conditions contained in the best performing group using a tolerance limit formulation developed by Vangel. Vangel's method requires that the same number of runs have been conducted in each test. Since the majority of emissions test series use three runs, a statistically incorrect but practically inconsequential error is introduced by using the average number of runs in the formulas even though it is physically impossible to have a fractional number of runs. The emissions limitation is:

$$EL_{CETRED} = \bar{\mu} + k^* \sigma_x \quad (19)$$

$$\text{where: } \bar{X}_i = \frac{\sum X_{ij}}{iC} \quad (20)$$

$$S_1^2 = C \sum \frac{(\bar{x} - \bar{X}_i)^2}{i-1}, \text{ the variance calculated between test series averages} \quad (21)$$

$$S_2^2 = \sum \sum \frac{(X_{ij} - \bar{X}_i)^2}{i(C-1)}, \text{ the pooled within test series variance} \quad (22)$$

$$Q = \frac{S_1^2}{S_2^2} \quad (23)$$

$$W = (1 + (C-1)/Q)^{-1/2} \quad (24)$$

$$k^* = MAX \left(K_{C_{p,1-\alpha,ic}}, \left[K_{p,1-\alpha,ij} - K_{p,1-\alpha,c} / \sqrt{C} + (K_{p,1-\alpha,C} - K_{p,1-\alpha,ic}) W \right] (1 - 1/\sqrt{C}) \right) \quad (25)$$

CKRC Approach

EPA previously rejected the CETRED approach because no facility simultaneously met the data-derived emissions limitations when it was applied to hazardous waste combustors (cement kilns, incinerators, light weight aggregate kilns and boilers) in CETRED. An obvious touchstone, a valid calculated result, was failed. The approach, however, can be made workable. ERS¹⁸ proposed a modification which implements the CETRED approach that considers both between-test condition variability and the use of a single group of facilities to establish simultaneously achievable emissions limitations for co-controlled pollutants. The results allow well-operated facilities to simultaneously meet the calculated emissions limitations.

Instead of using the highest emitting source in the EU as a proxy for between-test variability, the CETRED approach can be correctly applied by accounting for both between- and within-test variability and recognizing that the data are lognormally distributed. As done by EPA in CETRED, the Cement Kiln Recycling Coalition [CKRC] centered the distribution on the grand mean (average of the averages). All test conditions for the best performing 12 percent of the units in the hazardous waste burning cement kiln universe were incorporated. Of course, if more than 12 percent display below reference method practical quantitation limits (RMPQL) emissions, then they must all be included. Because some pollutants are co-controlled, a common pool for all pollutants should be defined so that internally consistent and technically compatible emissions limitations can be developed.

In the ERS report, the upper confidence limit for the average particulate emissions from each facility was used to characterize test series emissions. Consistent with EPA's methodology, these sources are ranked from lowest to highest. EPA, however, further subdivides the test results by test condition and only includes those that meet the Agency's criteria rather than all permitted plant operating conditions.

Any permitted operating condition for a facility must remain in the MACT analysis to properly characterize source emissions and not just the part of them which happen to occur under some test condition. That is, it is reasonable to statistically analyze each operating condition separately, but once a facility meets the conditions used to establish a pool facility for one constituent it should remain in for all constituents. All the operating conditions for a pool facility should also be included, unless it can be demonstrated that a specific controllable operating condition resulted in previously unacceptable emissions. All measured emissions are inherent characteristics of the source. You cannot simply declare an emissions set unrepresentative unless there is a specific action the operator can take to preclude such emissions. Put differently, when the pool is selected, EPA should not stop when the required number of facilities are included. They should keep adding facilities until all test conditions for the required number of facilities are included.

The MACT Floor should then be calculated using either the tolerance limit or prediction limit as described by the Office of Solid Waste¹⁹. The tolerance limit as discussed under the 6% MACT floor is a limit designed to contain a specified proportion of the population (e.g., 99 percent of the future test results from all plants). Prediction limits, on the other hand, are designed to contain the next specified number of sample values from the characterized facility assuming that the statistical characteristics of the plant do not change (e.g., the next performance and trial burns between recertifications).

As a result of inherent physical characteristics of the emission process, emissions data tends to be lognormally distributed²⁰. Consequently, any procedure used to derive emission limitations must consider the lognormal characteristics of the emissions. A procedure for developing statistical limits for lognormally distributed data is outlined by Land²¹. Land's procedure was followed and the following equations estimate emissions limitations from lognormally distributed data including consideration of the uncertainty with which the standard deviation is known. Simulation studies comparing EPA's HWC rule formulation to that previously published by Rigo²², demonstrated that EPA's equations for going from individual run data to 3-run averages is superior and included in the following equations:

$$EL_{CKRC-T} = \exp\left(\mu^3 + K_{N,P,1-\alpha} \sigma_3 \left[1 + \frac{3}{N}\right]^{\frac{1}{2}}\right), \text{ and} \quad (26)$$

$$EL_{CKRC-P} = \exp\left(\mu^3 + t_{N,1-\alpha} \sigma_3 \left[1 + \frac{3}{N}\right]^{\frac{1}{2}}\right) \quad (27)$$

Both EL_{CKRC-T} and EL_{CKRC-P} are conceptually equivalent to EPA's EL_{EPA} emissions limitation. The numerical values are different and the choice depends on whether the limit is to contain a percentage of all future tests or the next specified number of tests. The real question is whether the limitations should be based on the percentage of tests that will be in compliance from well-run, EU similar facilities or should the Agency be concerned about the number of statistical failures an individual facility is likely to face between permit renewals. Hahn and Meeker use the analogy of an astronaut who is not concerned about the amount of fuel consumed in an average trip to the moon or the percentage of trips that can be successfully completed with a given amount of fuel. Instead, like plant managers, astronauts are concerned about getting home on the fuel carried on their trip (the fines they will receive or jail time they will serve as a result of the number of times their plants will be tested during that manager's watch).

The EL_{CKRC-P} is the correct limit to choose if a mechanism for dealing with statistically predictable exceedances is not included in a permit or regulation.

A Modified MWC MACT Approach

The MWC MACT floor was developed by taking the average of the lowest 12 percent of permitted emissions limitations. When establishing limits for previously unregulated pollutants, a conceptually consistent approach is to use the pooled within-test variability for all similarly equipped units in Equation (11) to estimate the 3-run average emissions limitation for each unit. The highest emitting source is selected to estimate the emissions limitation.

When examining the set of data-derived emissions limitations, it is important to understand the meaning of the adjective “average” in the phrase “average emissions limitation.” Failure to do so can result in selecting a limit that is only achievable by a single facility — this can happen if one plant has aberrantly low emissions results and the balance are characterized by almost identical emissions profiles—and the arithmetic average is calculated. The arithmetic average will only be above one plant and not inclusive of the 12 percent specified in Sections 112 and 129 of the Clean Air Act. The HAP-by-HAP problem also remains. If a common set of facilities are not used to establish emissions limitations for co-controlled pollutants, the resulting ménage may not be routinely achievable by any facility, much less by the intended number.

Instead of averaging the emissions limits that characterize the best performing 12 percent; the correct approach is to use the highest data-derived emissions limitation for the pool facilities as the relevant limitation. This approach maintains consistency with EPA’s previous practice in MWC regulations while making maximum use of the available data and avoiding the illogical result where only one of the facilities used to establish the emissions limitations is likely to meet the value.

COMPARATIVE RESULTS

Table 1 is a listing of 3-run average naphthalene data obtained from tests conducted at MWCs. The concentrations are in $\text{ng/dsm}^3 @ 7\% \text{ O}_2$, the units used to quantify dioxins. To convert these values to $\text{ppm}_{\text{dv}} @ 7\% \text{ O}_2$, simply multiply by 1.88×10^{-9} , 20,000 ng/dsm^3 . Naphthalene, for example, is 0.004 ppm_{dv} (3.8 ppb_{dv}) which can be compared to the OSHA PEL²³ of 10 ppm to provide an indication of the magnitude of these emissions.

The emissions limitations calculated by several of the approaches are:

- CKRC (next 5 tests) — 9,195 $\text{ng/dsm}^3 @ 7\% \text{ O}_2$
- CETRED — 10,250 $\text{ng/dsm}^3 @ 7\% \text{ O}_2$
- Modified MWC (average) — 12,426 $\text{ng/dsm}^3 @ 7\% \text{ O}_2$
- CKRC (99% Coverage) — 12,705 $\text{ng/dsm}^3 @ 7\% \text{ O}_2$
- Combined Statistical—Technical Procedures — 13,054 $\text{ng/dsm}^3 @ 7\% \text{ O}_2$
- Breakpoint Analysis — 15,645 $\text{ng/dsm}^3 @ 7\% \text{ O}_2$
- Combined Statistical—Technical Procedures (Unequal variances) — 18,915 $\text{ng/dsm}^3 @ 7\% \text{ O}_2$
- Modified MWC (highest limitation) — 21,824 $\text{ng/dsm}^3 @ 7\% \text{ O}_2$

There are clear differences in the numerical results, a little more than a 2:1 range from lowest to highest. These differences may not seem significant, but the low end is where precautionary principle advocates

target. The high end, plus a prudent margin is where plant managers and people faced with \$25,000 per day per violation fines and penalties focus their attention.

While professional judgment is involved, the methods finally selected must conform to the Clean Air Act definitions if a regulated HAP is involved or simply for public understandability. The CKRC and HWC rule approaches seem to be the best because they are scientifically defensible and correctly treat the law's grammatical construction. Setting an arbitrarily low limit is not useful if it doesn't affect plant design or operation. Regardless, the emissions are going to be what they are.

CONCLUSIONS

The problem of correctly using data to establish emissions limitations is not yet fully resolved. Great strides have been made over the past couple of years. Regulators have progressed from the rules of thumb that set emissions limitations 20 percent (or $\frac{1}{4}$ inch if a graph was being used) above the highest measured value. Now, data-derived limits—based on Congressional direction that existing facilities should all become as clean as the “emission control that is achieved in practice by the best controlled 12 percent of existing sources” and new facilities should be as clean as the best one already out there—are being calculated.

Unfortunately, the failure to recognize that data-derived emissions limitations are derived from data, has produced a number of strained interpretations of the Clean Air Act, Sections 112 and 129 designed to fulfill non-technical objectives. Clean proposals have been made including:

- EPA calculating statistical emissions limits for HWCs in CETRED that recognized source variability, even if the final produce was untenable because co-controlled pollutants were treated as if they were independent instead of being linked.
- EPA using the average of permit limitations in the MWC rule — while we can argue about the propriety of using the arithmetic average, the approach clearly recognizes that there is a necessary gap between the best performance ever measured and limits that can be achieved during routine testing.
- The HWC rule has taken this a step further by using data-derived emissions limitation based on the limit statistically achievable by the dirtiest plant in the clean pool. The clean pool is defined as all facilities with technology similar to the best performing group. This is essentially a proxy for considering between-test and plant variability in addition to within-test variability explicitly handled by the approach. Again, we can argue about the size of the pool (6% or 12%), but the concept of including all like facilities is sound.
- CKRC has extended EPA's original data-derived emissions limitation approach to recognize that the emissions characteristics of facilities for all co-controlled pollutants should be analyzed as a group using proper statistical techniques.
- A variant on the MWC and HWC rule and CKRC approaches that accounts for simultaneous control characteristics while preserving the basic frame-work of the MWC rule approach is suggested.

Each of these approaches produces different numerical results. Applied with intelligence, the results are generally comparable. Regardless, it must be recognized that data-derived emissions limitations have built-in probabilities of finding exceedances when a facility is operating exactly as it did when the limitation was established. Consequently, it is imperative that either margin be added or a violation declared only when a re-test is failed.

Needlessly low limits, however, do not affect a material improvement in the environment. They discourage innovation and waste resources. On the other hand, they do produce revenue from unavoidable fines and jobs from more testing. The method of calculating data-derived emissions limitations should provide an ample margin of safety against falsely finding violations. Public policy should not affect the way data-derived emission limitations are calculated, rather it should affect the margin of safety allowed and the decision to impose more stringent emissions limitations than the MACT floor.

NOMENCLATURE

σ	is the standard deviation of the natural logarithms of the data.; $\sigma^2 = \ln\left(1 + \left[s/\bar{X}\right]^2\right)$
S	is the standard deviation of the untransformed data; $S^2 = \exp^{(2\mu+\sigma^2)}(e^{\sigma^2} - 1)$
$\bar{X}$	is the arithmetic average of the concentrations; $\bar{X} = \exp^{(\mu+1/2\sigma^2)}$
σ	is the standard deviation of the log transformed data; $\sigma^2 = \ln\left(1 + \left[\frac{S}{\bar{X}}\right]^2\right)$
σ_3	is the standard deviation of the log transformed data associated with three-run averages derived from the pooled σ ; see Equation (11)
EL_{EPA}	is the data-derived emissions limitation using EPA's April 19, 1996 HWC procedure
EL_{CETRED}	is the date-derived emissions limitation used by EPA in CETRED
EL_{CKRC-T}	is the data-derived tolerance limit (% coverage)
EL_{CKRC-P}	is the data-derived prediction limit (number of future tests covered)
EL_{MWC}	is the average of the emissions limitations calculated using the pooled variance and each test series average then using the largest result
$\phi^{-1}(.99)$	is the 99 th percentile of the normal probability distribution
N	is the effective number of runs used to estimate σ
i	is the number of runs conducted for each test condition
C	is the number of test conditions in each average
k	is the number of future test series to be contained
m	is the number of runs to be averaged in a test series
P	is the percentage of future test series to be contained
$t_{N-1,\alpha/k}$	is the t-statistic with the Bonferroni multiple approximation so it approximately equals the prediction limit for k future tests
$K_{N,P,1-\alpha}$	is the tolerance limit coefficient designed to include P percent of future occurrences at the $1-\alpha$ statistical confidence level
X_i	is the concentration for the i th ranked result
X_{i-1}	is the next smaller concentration
X_{i+1}	is the next larger concentration.

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4. A more precise statement is that the assumption that the data are normally distributed can usually be rejected, but the assumption that the data were lognormally distributed cannot. It is impossible to prove what the underlying data distribution is; it is possible to demonstrate that an assumed distribution is not applicable.
5. Natrella, op cit., pp. 3-22 and 3-29.
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Table 1. Test series average naphthalene concentrations measured at MWCs.

FACILITY	TESTS	ARITHMETIC		LOGARITHMIC		Plus2	Plus3	UPPER CONFIDENCE LIMIT ON THE AVERAGE	TEST SERIES PREDICTION LIMIT FOR THE NEXT TEST	MWC APPROACH WITH CALCULATED LIMITS
		AVG.	STD.	AVG.	STD.					
151	3	340	16	5.828	0.046	372	388	369	446	2,546
24	2	1,741	6	7.462	0.003	1,752	1,758	1,765	1,872	13,047
24	2	1,746	91	7.464	0.052	1,928	2,019	2,635	6,957	13,072
24	3	2,772	47	7.927	0.017	2,865	2,912	2,852	3,048	20,773
175	3	1,016	371	6.880	0.359	1,758	2,129	3,940	16,536	7,288
24	4	1,713	598	7.388	0.416	2,909	3,508	3,979	11,127	12,112
175	3	1,487	444	7.271	0.330	2,375	2,818	4,787	18,266	10,774
175	12	2,356	2,941	7.254	1.020	8,238	11,179	5,864	19,502	10,598
168	9	3,742	3,302	7.977	0.706	10,347	13,649	8,320	19,464	21,824
136	6	2,005	1,116	7.397	0.815	4,238	5,354	8,376	29,833	12,225
175	3	2,114	790	7.611	0.369	3,694	4,483	8,787	38,064	15,133
67	3	5,888	1,224	8.667	0.203	8,336	9,560	9,878	23,442	43,514
168	7	5,511	4,338	8.436	0.584	14,186	18,523	10,207	24,785	34,540
433	3	6,688	1,291	8.796	0.189	9,271	10,562	10,633	23,834	49,516
136	4	1,602	1,020	7.213	0.677	3,642	4,662	11,379	51,657	10,166
91	3	5,974	1,386	8.675	0.250	8,747	10,133	12,368	35,440	43,886
24	3	4,141	1,318	8.303	0.324	6,777	8,095	12,934	48,378	30,234
166	4	10,468	2,402	9.233	0.257	15,272	17,674	15,645	30,023	76,662
85	3	441	324	5.874	0.655	1,090	1,414	27,070	221,319	2,665
24	2	2,807	385	7.935	0.138	3,577	3,962	33,401	289,563	20,935
168	9	7,963	12,222	8.471	1.013	32,407	44,629	36,365	101,991	35,790
24	2	2,017	320	7.603	0.160	2,658	2,978	54,777	583,494	15,019
24	2	1,756	295	7.464	0.169	2,346	2,641	69,932	802,491	13,068
91	3	8,866	4,381	8.976	0.478	17,629	22,010	85,017	499,153	59,259
24	3	30,264	11,862	10.271	0.364	53,987	65,849	121,494	518,520	216,450
4	3	29,446	12,453	10.243	0.436	54,351	66,803	207,987	1,096,749	210,558
91	3	25,636	13,920	10.056	0.531	53,476	67,396	421,886	2,793,124	174,573
83	5	629,971	257,853	13.294	0.376	1,145,676	1,403,529	1,035,528	2,165,717	4,447,403

Figure 1. Effect of location uncertainty on a normal distribution.

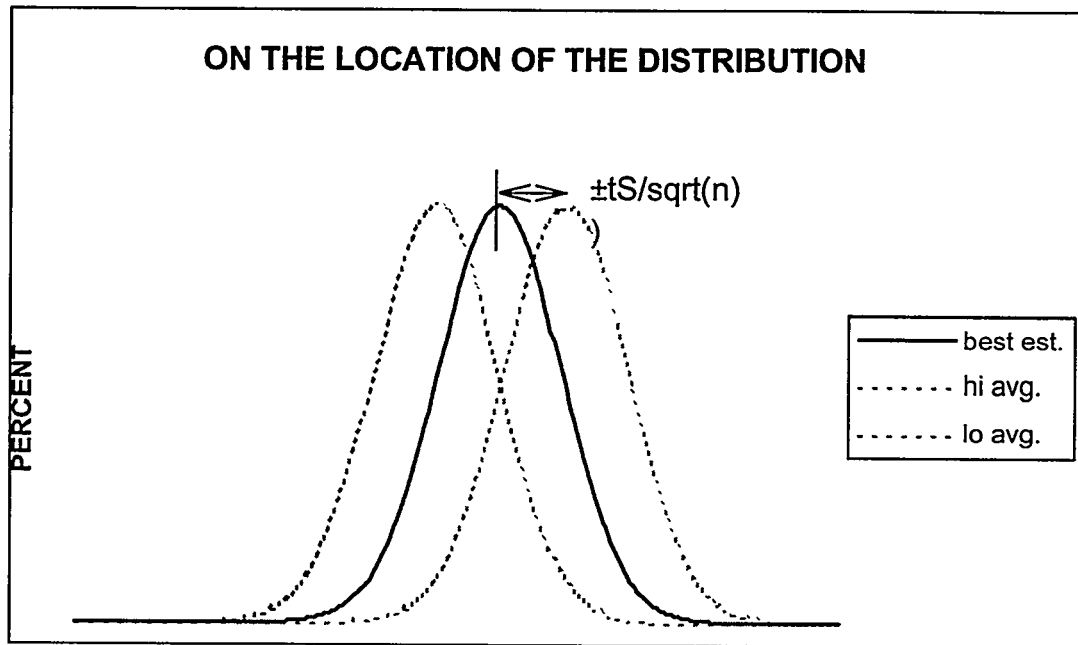


Figure 2. Effect of spread (standard deviation) uncertainty on a normal distribution.

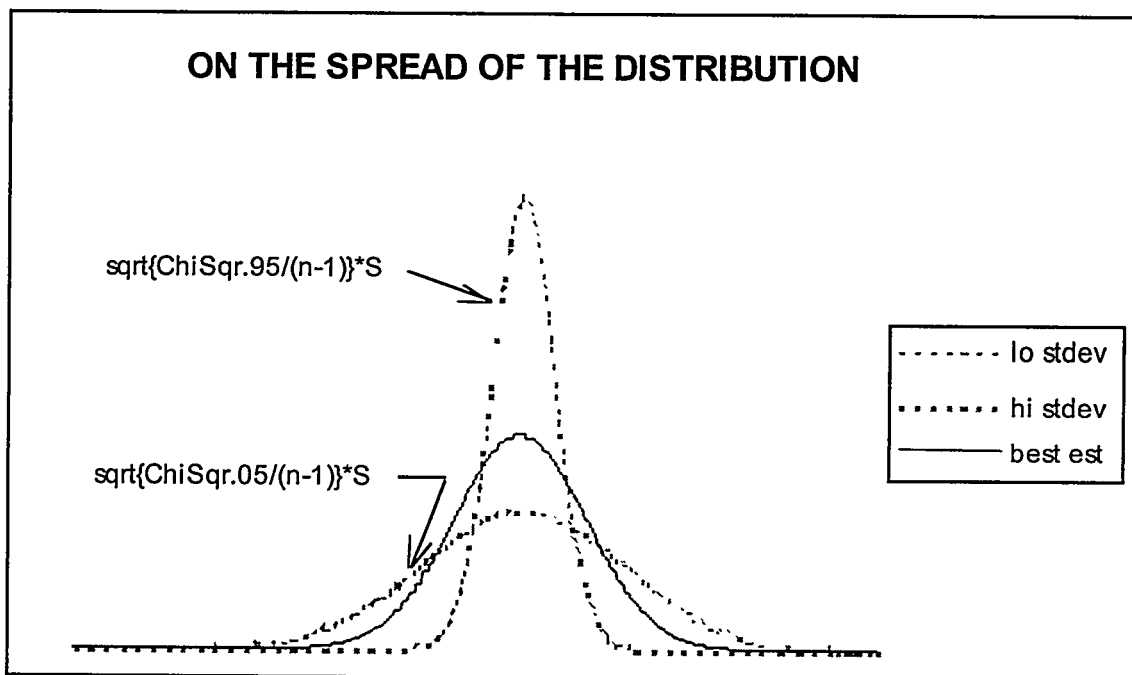


Figure 3. The difference between normal deviates and tolerance limits.

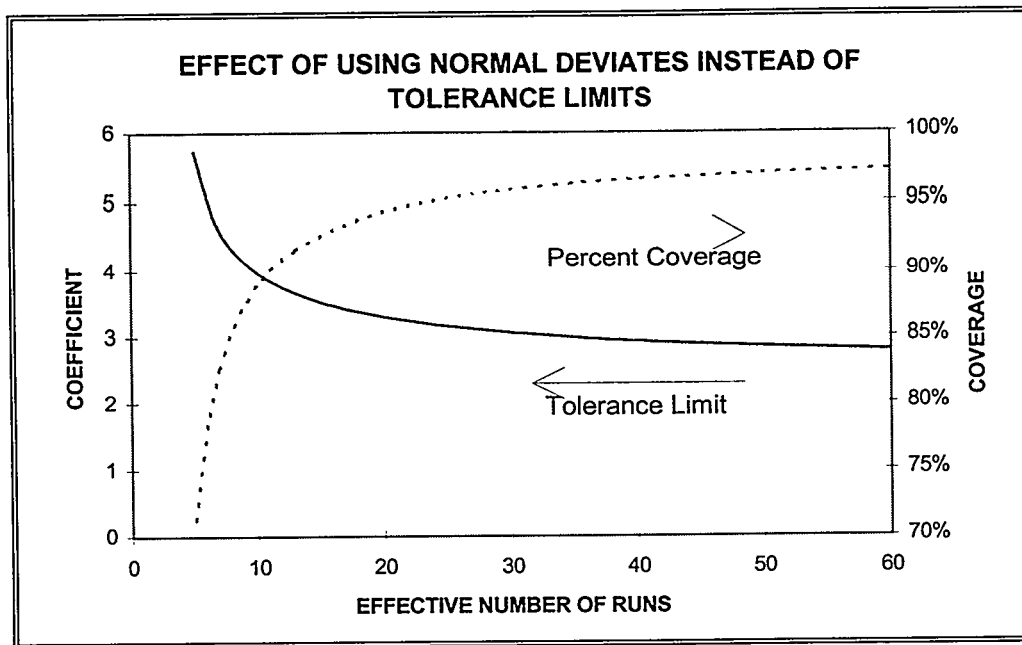
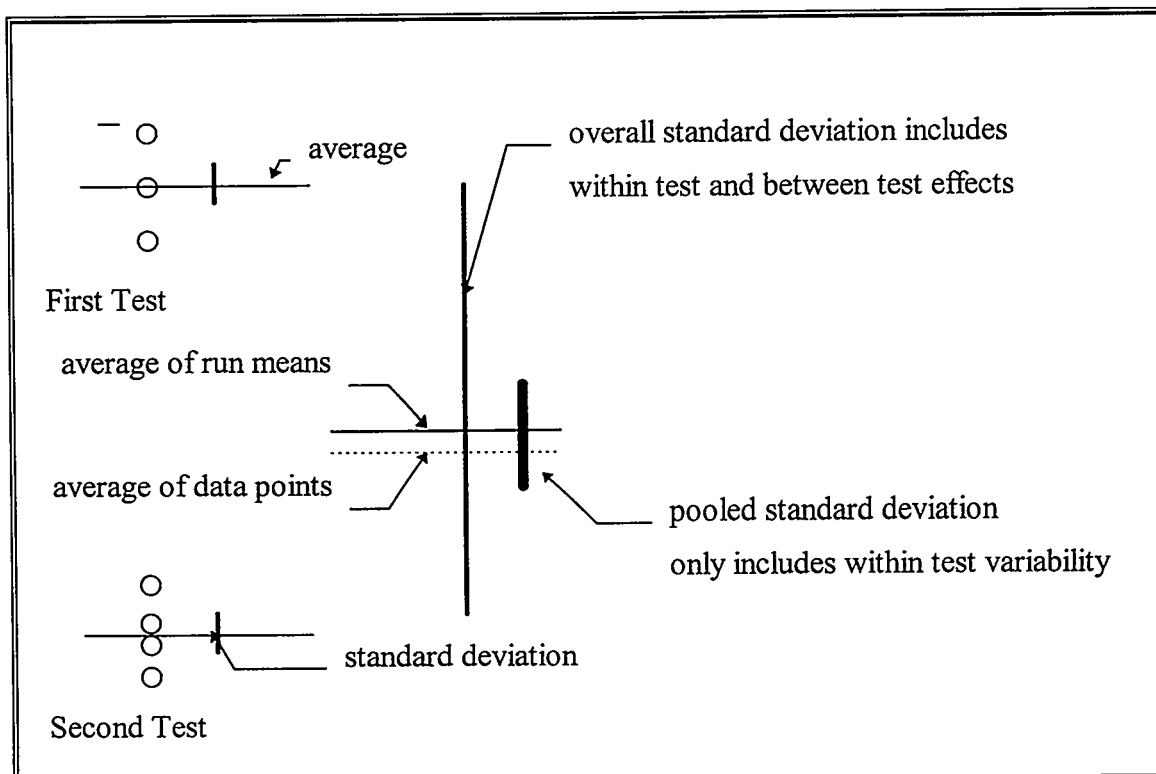


Figure 4. Conceptualization of the difference between the sources of variance.



TECHNICAL SESSION II

Ash Utilization

Gas Generation at a Municipal Waste Combustor Ash Monofill - Franklin, New Hampshire

Craig N. Musselman
CMA Engineers, Inc.
35 Bow Street
Portsmouth, New Hampshire 03801

William A. Straub
CMA Engineers, Inc.
35 Bow Street
Portsmouth, New Hampshire 03801

Jeremy N. Bidwell
Rex Technical Services
61 Hoskins Road
Bloomfield, CT 06002

Joyce E. Carpenter
Environmental Risk Limited
120 Mountain Avenue
Bloomfield, Connecticut 06002

James R. Presher
Concord Regional Solid Waste/Resource Recovery Cooperative
6B South Main Street
Penacook, New Hampshire 03303

INTRODUCTION

The characterization of landfill gas generated at municipal solid waste landfills has received significant attention in the United States in recent years. Generation of gas at municipal waste combustor (MWC) ash monofills is, however, generally assumed to be negligible and there is little, if any, published information available concerning such gases. As ash landfills move towards closure in the future, and as progress continues in utilizing certain components of MWC ash residue in construction applications, it is important to identify the mechanisms by which gases may be generated in MWC ash so that appropriate design and material management decisions can be made.

This information is based upon the analysis of gas samples from leachate collection system cleanout pipes at one lined MWC ash landfill. The data were gathered because site operating staff had posed questions as to the contents of the gaseous emissions. The gas characteristics indicated the effects of exothermic chemical reactions in the landfilled ash which affected gas composition in ways which were unexpected, and not widely known.

PROJECT BACKGROUND

The lined MWC ash landfill in Franklin, New Hampshire is owned by the 27 member municipalities of the Concord, NH Regional Solid Waste/Resource Recovery Cooperative ("the Cooperative"). The landfill was initially constructed in 1988, and has operated continuously since 1989.

The landfill accepts combined bottom ash, fly ash and dry lime scrubber product from the 500 ton per day waste to energy (or Municipal Waste Combustor) facility in Concord, New Hampshire owned and operated by a subsidiary of Wheelabrator Technologies, Inc. The MWC facility processes about 177,000 tons per year of municipal solid waste and generates about 68,000 wet tons per year of combined ash. Bottom ash is discharged from the combustion units into wet ash troughs, from which the bottom ash is removed by means of drag chain conveyors. The facility's air pollution control system consists of pneumatic injection of hydrated lime directly into the exhaust gas ductwork for control of acid gas emissions, with fabric filters for control of particulates. The fly ash and dry lime scrubber product is treated with the proprietary WES-PHix process, and combined with the bottom ash on the bottom ash drag chain conveyor. The WES-PHix process involves the addition of phosphoric acid (H_3PO_4) to the fly ash to promote the formation of lead phosphates, in order to limit the solubility of lead in the ash.

The lined MWC ash landfill in Franklin, New Hampshire consists of a double lined landfill with a primary leachate collection system consisting of HDPE piping above the primary (or uppermost) liner. The leachate collection pipes discharge to leachate tanks at the low side of the site, from which leachate is pumped to a remote sewer connection. The leachate tanks are vented to the atmosphere.

Since the primary leachate collection pipes beneath the landfilled ash flow only partially full, air/gas can flow through the pipes with intake at the leachate collection tanks at the low side of the site. Air flows through the primary leachate collection pipes and discharges through the leachate system cleanout pipes located on the high side of the site, through a "chimney" type effect.

The landfill is designed to reach a final maximum depth of about 120 feet. In 1996, residue grades were about 45 feet above the landfill liners. In order to facilitate future leachate collection needs at higher

elevations, two leachate collection pipes had been extended vertically through the fill. One of these two pipes had been perforated every several feet and wrapped with geotextile fabric. During a storm event, ash deposited in the perforated vertical pipe had clogged the bottom 1.5 feet where the pipe connected to the leachate collection pipe. This clogged pipe had a water surface within the pipe, thus closing off convective air access to the leachate collection system. A cross section of this vertical pipe is presented as Figure 1. In this condition, this one vertical pipe inadvertently functioned as a typical landfill gas well. This clogged vertical pipe is noted as the "Phase 1 Vent".

An initial evaluation of the gas was made by Cooperative staff using a handheld explosivity meter ("LEL meter"), on the various cleanouts and leachate collection pipe outlets (or "vents"). The meter's alarm was tripped at two of the outlets for elevated H_2S concentration, and the alarm for lower explosive limit ("LEL") exceedance was tripped for the Phase 1 Vent. This information led the Cooperative to decide to sample and analyze the gaseous emissions.

Ash Characteristics

There are a number of factors pertaining to the specific ash handled at the Franklin site and the operating scheme at the landfill which may affect the generation of gas. These characteristics and the potential impacts of each are listed and discussed below.

- **Ash Combustible Content** - A comprehensive ash sampling and analysis program conducted in 1990 and 1991 indicated that the bottom ash at that time had a combustible content averaging 6.4% as measured by Loss on Ignition tests (3). This combustible content may be considered moderate to high by US standards. This may have affected non-methane organic compound concentrations.
- **Lime Content** - The direct dry lime injection system requires the addition of lime at 2 to 4 times the stoichiometric requirement for acid gas control. This rate is higher than at most plants with more stoichiometrically efficient spray dryer absorption systems. The ash at Franklin may have greater alkalinity and unreacted lime than is typical of other ash monofills. The primary leachate, however, has had a pH of 7 or below for the past seven years.
- **Phosphoric Acid Addition** - Small amounts of phosphoric acid are added to the fly ash/scrubber product using the proprietary "WES-PHix" process. The addition of phosphoric acid has been considered in terms of its potential to have an effect on gas generation. Any effect is presumed minimal due to the neutralization of phosphoric acid by the lime.
- **Landfill Operating Scheme** - The Franklin ash landfill is operated aggressively as a "dry tomb" type of facility in comparison to most US landfills. The limited amount of time (2-3 years), during which the landfilled ash has been subjected to percolation of water may have an effect on chemical reactions taking place in the landfill.

Other than those factors described above, the ash generated by the Concord, New Hampshire waste to energy facility is considered to be typical of most US facilities based on the type of facility, operation and ash characterization data available.

Landfill Piping Configuration

The specific layout of the various vents is depicted schematically on Figure 2. The nomenclature for

each gas sampling point, and the specific circumstances of each location are presented in Table 1 below.

Gas Temperature and Flows

The landfill interior temperature was measured by lowering a weighted thermocouple into the Phase 1 and Phase 2 vents. Phase 2 pipes were not clogged, but were open to air/gas flow from the leachate collection system below. Ambient air temperature at the time of sampling was 39°F.

The Phase 2 vent could be measured only 9 feet down the pipe due to the presence of a bend. The temperature was 91°F. Gas in this vent was diluted by atmospheric air from the leachate collection system below.

The temperature of undiluted gas in the clogged Phase 1 vent ranged from 132°F to 156°F. The temperature profile with depth is indicated on Figure 3. These temperatures were unexpectedly high and were higher than would typically be expected in an MSW landfill. Optimum temperatures for thermophilic anaerobic digestion of MSW range from 120° to 135°F (4). It is postulated that the elevated temperatures are likely due to a variety of exothermic, primarily inorganic chemical reactions taking place in the landfilled ash.

Measured gas flows are as indicated on the piping schematic presented as Figure 2. A chimney effect is apparent as pipes open to the atmosphere at lower elevations indicated flow into the piping system and the vents connected to the piping system which outlet at higher elevations emitted gas at flows of 20 and 28 cubic feet per minute (CFM). Gas flows at the Phase I vent were estimated to be 30 to 60 CFM. This flowrate is similar in magnitude to the rate which might be experienced at steady state conditions in an active MSW landfill gas well. The zone of influence within the landfill mass of the Phase 1 vent is unknown.

MWC Landfill Gas Characteristics

The vents which had exhaust flow to the atmosphere were sampled and analyzed for atmospheric gases, non-methane organic compounds (NMOCs) and sulfur compounds. Samples were gathered using evacuated SUMMA passivated (polished) canisters with samples withdrawn over a 60 minute duration, per Method TO14. Atmospheric gases were analyzed by GC/FID/TCD using ASTM Method D-3416. NMOCs were analyzed by gas chromatograph/pyrolysis CO₂ using Method TO12 (total NMOC), and by gas chromatography/mass spectroscopy for the full Method TO14 target compound list. Sulfur containing compounds were quantified through ASTM Method 5504.

The summary of the atmospheric gas analyses is presented in Table 2. The oxygen content in the Phase 2 Vent and the Phase 1 Upper Cleanout, both of which were open to atmospheric air in the leachate collection pipes beneath the landfill, were near typical atmospheric levels. The oxygen content in the Phase I Vent, which was clogged and functioning in a way similar to a gas well, was markedly depressed, but not absent. Methane was present in the Phase I Vent at a concentration of 780 ppm. This is low compared to the levels present in gases from MSW landfills (typically 500,000 ppmv, or 50%), and at a level well below the lower explosive limit (LEL) for methane of 50,000 ppmv. If methanogenic bacterial activity was at a high level, the O₂ concentration in the Phase 1 Vent would have been expected to approach zero, and the CO₂ concentration would have been much greater.

Hydrogen was detected in the gas in the Phase 1 Vent. The hydrogen concentration in both Phase 1 Vent samples was measured to be 5.1%, which is in excess of the 4.0% LEL for hydrogen. The presence of

hydrogen at these concentrations is likely the cause of the explosiveness alarm in the initial gas screening described earlier. The hydrogen is postulated to be generated by oxidation reduction reactions of aluminum and other reactive metals, and/or other chemical reactions, taking place within the landfill mass, as discussed later herein.

Hydrogen sulfide concentrations were elevated in the Phase 2 Vent and in the Phase 1 upper cleanout, as indicated in Table 3. H_2S is typically a by-product of the anaerobic decomposition of organic matter. The H_2S concentrations are likely indicative of microbial activity within the landfill mass.

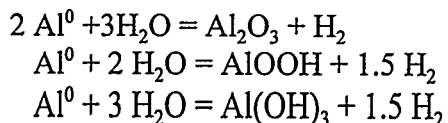
The NMOC concentrations are presented in Table 3. The NMOC concentrations were present at the low end of the range of concentrations reported in the literature (4) for NMOC concentrations in MSW landfill gas. Leachate from the landfill site rarely has detectable concentrations of volatile organic compounds with the exception of periodic low concentrations of acetone.

The concentrations of specific organic compounds were reported for two samples from the Phase 1 Vent and for one sample from the Phase 2 Vent. The results are presented in Table 4. The reported concentrations are all lower than presently applicable health and safety related standards and are generally less than those anticipated in MSW landfill gas (5).

Following the completion of the sampling and analysis described herein, the clog in the Phase 1 vent was removed hydraulically. Later LEL meter testing indicates that the Phase 1 and Phase 2 vents subsequently have similar characteristics.

Discussion of Results and Implications

Generation of Hydrogen Gas. The measured hydrogen gas may be generated by chemical reactions of elemental aluminum and other elemental metals in the presence of water. Typical oxidation reduction reactions may be as follows (6,7):



The aluminum reactions are facilitated in the presence of either strong acids or strong bases, which may etch the surface of the aluminum, exposing more elemental aluminum to the reaction. In typical uses of aluminum subject to atmospheric exposure, an adherent protective film of aluminum oxide forms on the surface of the aluminum in pH conditions in the range of 4 to 9 (8). This protective surface film precludes further corrosion of the underlying aluminum. However, in the presence of strong acids or bases, this film may be destroyed and the hydrogen gas generating corrosion reactions can continue. When the protective film is destroyed (or the aluminum is "depassivated"), the exposed elemental aluminum reacts vigorously in the presence of moisture until all exposed aluminum is reacted. The protective oxide film reforms within seconds of exposure of elemental aluminum (15), which limits the length of time that aluminum corrosion continues to occur in atmospheric exposure.

In the landfill, the conditions under which corrosion occurs are more complicated. The aluminum is present both in bulk form and in fine particles, and the chemical conditions which affect corrosion vary locally throughout the landfill mass. Aluminum corrosion can be facilitated by the presence of chloride ions (17), which are present in abundance in MWC ash. The chloride ions affect the aluminum through

pitting, exposing additional elemental aluminum to the corrosion reaction. The chemistry of aluminum is complex, and the reactions taking place in the heterogeneous landfilled residue are not well understood.

Aluminum is present in significant quantities in the ash. Bottom ash from the Concord, New Hampshire MWC facility has a range of aluminum content of 3.4 to 6.4% by weight. Aluminum is also typically present in fly ash in significant concentrations. It is anticipated that a significant percentage of the aluminum present in the ash exists in the elemental form having the potential for the hydrogen generating oxidation reduction reactions.

Hydrogen gas may also be generated by similar reactions with other elemental metals. The oxidation of elemental aluminum, zinc, chromium, iron, copper and other elemental metals can proceed in the proper environmental conditions, releasing electrons. The electrons, in the presence of water and, again, in the proper environmental conditions, can result in the generation of H_2 gas. The aluminum reaction is highlighted herein because of the redox potential of the aluminum reaction, the significant quantity of aluminum in the ash, and the likely presence of elemental aluminum in greater quantities than is likely for the other elemental metals. Oxidation reduction reactions of many elemental metals probably contribute to varying extents to the H_2 gas generation.

Hydrogen is also generated as a byproduct in certain organic decomposition reactions (i.e., in the later stages of anaerobic, non-methanogenic decomposition in an MSW landfill (4)), and can be generated as a byproduct in a variety of other chemical reactions.

It is considered unlikely that the addition of phosphoric acid plays a significant role in hydrogen gas generation at the landfill site. Although the Material Data Sheet supplied by the phosphoric acid supplier warns of the hydrogen gas generation potential when in contact with aluminum, this is due to the acidic nature of the phosphoric acid. The H_3PO_4 acid is neutralized at the MWC facility upon mixing with the highly alkaline scrubber product.

The unusually high alkalinity of the fly ash at the Franklin, New Hampshire landfill in all likelihood results in greater hydrogen gas generation than would be the case for an ash with less available lime. Hydrogen gas at other sites should still be anticipated to be present, although likely at a slower generation rate.

The hydrogen gas generating reactions of aluminum have been known for many years, and have been used in the manufacture of lightweight concrete with a cellular structure (13, 14). Aluminum powder is added to cement and sand. In the presence of lime or other alkali, hydrogen bubbles are formed throughout the concrete, creating a more porous structure. The practice is more prevalent in Europe than in North America.

Anecdotal information is available regarding experience with the generation of hydrogen gas from MWC ash. Fly ash utilized as an aggregate substitute in asphalt cement in Germany developed gas bubbles during paving (11). The gas was analyzed and found to be primarily hydrogen. The generation of hydrogen gas and methane from fly ash and scrubber residue has been documented in laboratory studies in Germany (11, 12). Explosions in a fly ash system in Denmark were attributed to hydrogen gas (15, 16). Explosive conditions were subsequently prevented through ventilation of ash conditioning equipment.

The presence of hydrogen gas at levels above the LEL is not believed to be a major risk factor with respect to landfill operations. Landfill gas from MSW landfills often exhibits methane concentrations above the LEL and below the upper explosiveness limit, at concentrations where explosions could occur in certain circumstances. This risk is managed by proper gas handling in passive or active gas collection systems at closed landfills and by appropriate monitoring of gas concentrations at the site periphery to assure that subsurface migration to nearby structures does not occur. If the generation of hydrogen gas is confirmed at other ash landfill sites, similar design and operation precautions would likely be appropriate for ash landfills as well. Appropriate precautions should be taken when excavating into ash in confined spaces, or when drilling into old landfilled ash.

The potential for generation of hydrogen gas should be considered when evaluating ash utilization alternatives. Until further information is developed, the utilization of unencapsulated ash in close proximity to confined spaces such as structures may be inadvisable. Some researchers (11) have suggested that the aging of ash prior to utilization might be effective in reducing the potential for hydrogen gas release after utilization. The length of time required and the effectiveness of any reduction in subsequent gas generation are not yet known.

- **Ash Temperature**

The elevated temperature determined within the landfill mass is most likely due to a variety of exothermic chemical reactions. Preliminary, theoretical thermodynamic calculations indicate that neither the exothermic aluminum reactions described herein nor the lime hydration reactions would be expected, alone, to generate sufficient heat to bring the landfilled mass to the 156°F maximum temperatures measured. Other exothermic chemical reactions also undoubtedly play a role.

In the peer review process, for this paper, a reviewer commented that high temperatures and carbon monoxide concentrations greater than 100 ppm are generally indicative of combustion conditions in MSW landfills. Some manner of combustion may have been occurring in the ash at the Franklin site. However, the depressed level of CO₂, which is generated in most combustion processes and is generally stable once formed, and the presence of hydrogen gas, which would likely not be present in the midst of combustion, appear to indicate that combustion is not a major factor in the formation of the gases sampled.

From a design standpoint, the elevated ash temperature is not significantly problematic. Temperatures in the ranges measured do not negatively affect most flexible membrane liners and geotextile materials typically used in landfill construction. The design of leachate collection pipes is somewhat temperature dependent in that the calculation of the pipe wall material's modulus of elasticity requires temperature input, depending upon the type of pipe used. Until valid information is developed from other sites indicating the prevalence of much lower ash temperatures, the use of 160°F as the temperature input in leachate collection pipe strength calculations, where required, may be advisable.

- **Provisions for Gas Management in Ash Landfill Closure Designs**

It is apparent from the information reported upon herein that gas management provisions need to be incorporated in the design for closure of an MWC ash landfill. Design procedures similar to those utilized for the closure of smaller MSW landfills with passive gas venting systems may be appropriate. The installation of a suitable gas migration layer beneath impervious capping materials, and passive vents through impervious capping layers, should be, and typically are, incorporated in closure designs.

Further information is needed regarding the movement of gas within landfilled ash to determine whether passive gas wells within the ash are needed or are otherwise of benefit.

- **Additional Information Needs**

Information is needed from other ash landfills to confirm the temperature of ash at depth, and to assess hydrogen gas generation rates and concentrations. Both the temperature and the hydrogen gas generation rates may be lower at other sites where less lime is available for hydration reactions. It should be noted that the hydrogen gas concentrations measured at any site are less a function of generation rate than they are a function of the site's tendency to accumulate gases. The data reported upon herein provides no information regarding the nature of gas pressure and concentration gradients within an ash monofill.

The effect of aging the ash prior to utilization with regards to the subsequent generation of hydrogen gas also deserves investigation.

CONCLUSIONS

The following conclusions can be drawn from the information reported upon herein:

1. MWC ash disposed in an ash monofill may generate gas with NMOC concentrations on the low end of the typical range for NMOCs in MSW landfill gas.
2. Gas flowrates generated in an ash monofill may be significant from a closure design perspective.
3. Hydrogen gas may be generated within the ash mass at an ash monofill from reactions of elemental aluminum and/or from other sources. Hydrogen gas concentrations may exceed the lower explosive limit.
4. Ash temperatures within an MWC ash monofill may be on the order of 156°F, due to reactions of elemental aluminum, lime hydration reactions and other exothermic chemical reactions. The potential for elevated temperatures should be considered in the design of landfill components.
5. Anaerobic non-methanogenic and methanogenic decomposition of waste does not appear to be a significant factor in the generation of gas at an ash monofill, despite the presence of an uncombusted fraction in the ash.
6. Lower ash temperatures and decreased rates of generation of hydrogen gas may be experienced at other ash landfills having less lime available for hydration reactions than was present in the ash at the Franklin, New Hampshire site. However, elevated temperatures and some hydrogen gas generation should be anticipated until experience indicates otherwise.
7. Passive gas vents, and effective gas migration layers beneath impervious caps, should be incorporated in designs for closure of ash monofills.
8. Appropriate precautions should be taken when excavating into ash in confined spaces, or when drilling into old landfilled ash.
9. The potential for generation of hydrogen gas should be considered in ash utilization programs.

Until further information is developed otherwise, the utilization of unencapsulated ash in close proximity to enclosed spaces (i.e., structures) may be inadvisable. The potential benefit of aging of ash on reducing subsequent hydrogen gas generation in utilization merits investigation.

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Table 1. Gas Sampling Locations.

Sampling Point	Type of Pipe	Depth of Ash	Age of Ash
Phase 1 Vent	Perforated, Clogged at Depth (Similar in Function to Gas Well)	42 feet	0-4 years
Phase 2 Vent	Solid Wall, Open to Leachate System Below (Diluted by air flow from below)	46 feet	1-2 years
Phase 1 Upper Cleanouts	Solid Wall, Open to Leachate System Below (Diluted by air flow from below)	54 feet	4-8 years

Table 2. Summary of Atmospheric Gas Analyses.

Location	Oxygen (%)	Nitrogen (%)	Carbon Monoxide (ppm)	Methane (ppm)	Carbon Dioxide (%)	Hydrogen (%)
Phase 1 Vent						
first (can 3)	3.5	91	110	780	.008	5.1
second (can 4)	3.6	91	110	780	.008	5.1
Phase 2 Vent						
first (can 1)	21	79	<20	<20	.038	.087
second (can 2)	21	79	<20	<20	.038	.092
Phase 1 Primary upper cleanout						
first (can 5)	21	79	<20	30	.051	<.024
second (can 6)	21	79	<20	30	.050	<.024

Table 3. Summary of NMOC and Sulfur Gas Analyses.

Location	Non-methane Organic Compounds (ppm)	Hydrogen Sulfide (ppm)	Total Reduced Sulfur (ppm)
Phase 1 Vent			
first (can/bag 3)	38	<0.004	0.290
second (can/bag 4)	40	<0.004	0.270
Phase 2 Vent			
first (can/bag 1)	3.3	11.0	11.0
second (can/bag 2)	4.4	15.0	15.0
Phase 1 Primary upper cleanout	0.45	11.0	11.0
first (can/bag 5)	0.48		
second (can/bag 6)			

Table 4. Summary of Organic Compound Analyses (All reported in ppb).

Compound	Phase 1 Vent Can 3	Phase 1 Vent Can 4	Phase 2 Vent	Typical Concentrations in MSW Landfill Gas ⁽⁴⁾	TLV ² -TWA	STEL ³
Chloromethane	75	110	29	900	50,000	100,000
Methylene Chloride	130	<40	30	19,700	50,000	
Benzene	96	97	<16	3,520	10,000	300*
Toluene	100	93	<16	51,600	50,000	
Acetone	9,900	9,500	1,400	3,360	750,000	1,000,000
Tetrachlorethane	<48	<40	<24	7,040	25,000	100,000
2-Butanone (MEK)	840	720	170	2,800	200,000	300,000
Hexane	1,300	1,200	<65	3,010	50,000	
Ethanol	6,400	5,700	4,200	3,410	1,000,000	
Heptane	690	640	<65	N/A	400,000	500,000
Total Organic Compounds	29,661	22,310	6,179	200,000	N/A	N/A

1 - ACGIH: American Conference of Governmental Industrial Hygienists

2 - TLV-TWA: "Threshold Limit Value - Time Weighted Average" (8 hour work day/40 hour work week, without adverse effect)

3 - STEL: "Threshold Limit Value - Short Term Exposure Limit" (maximum 15 minute exposure)

4 - See Reference 4, USEPA

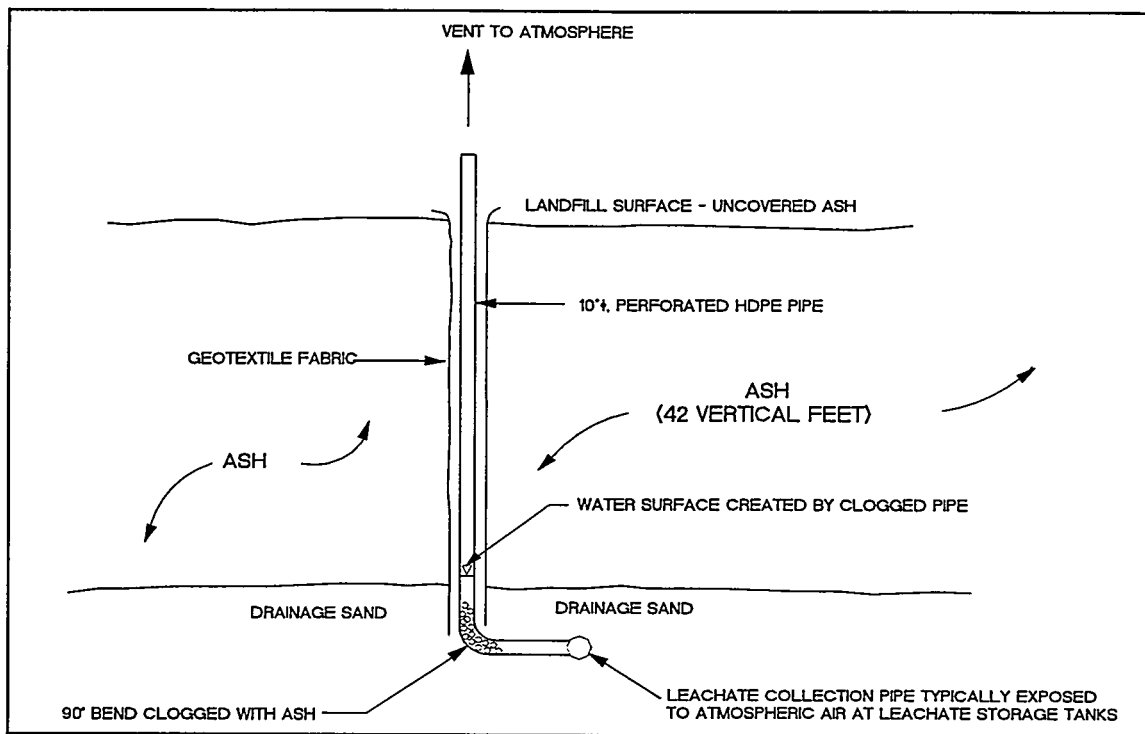


Figure 1. Phase 1 Vent - Cross Section.

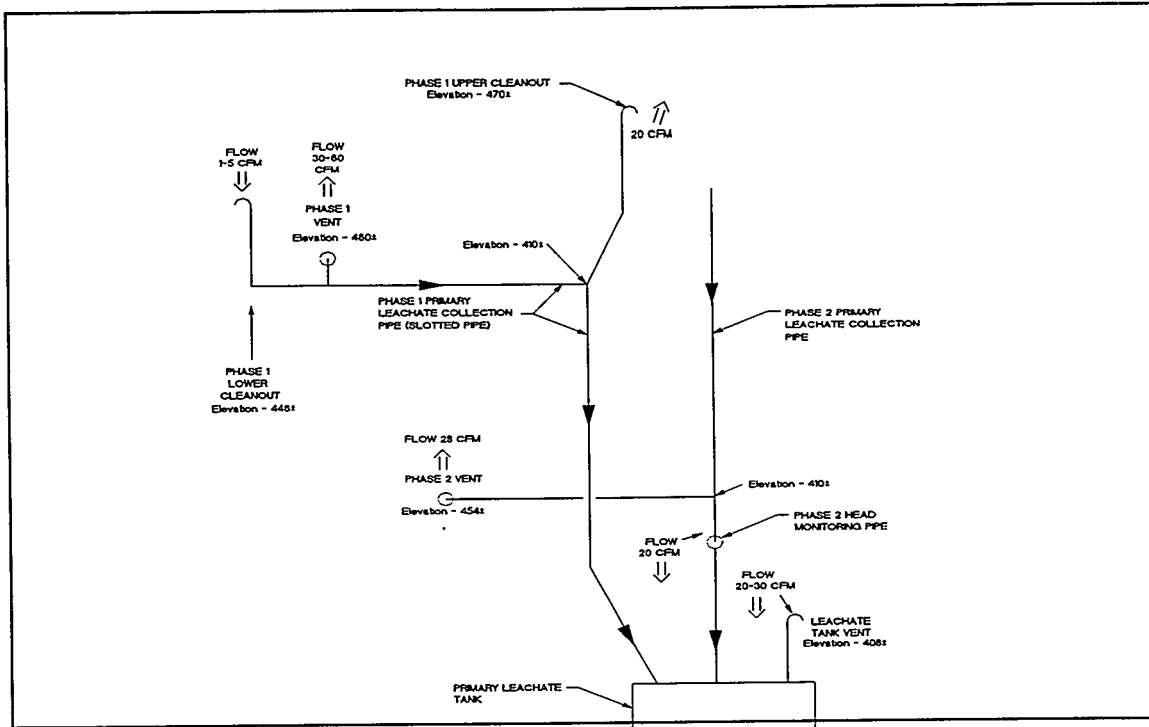


Figure 2. Leachate Collection System Schematic.

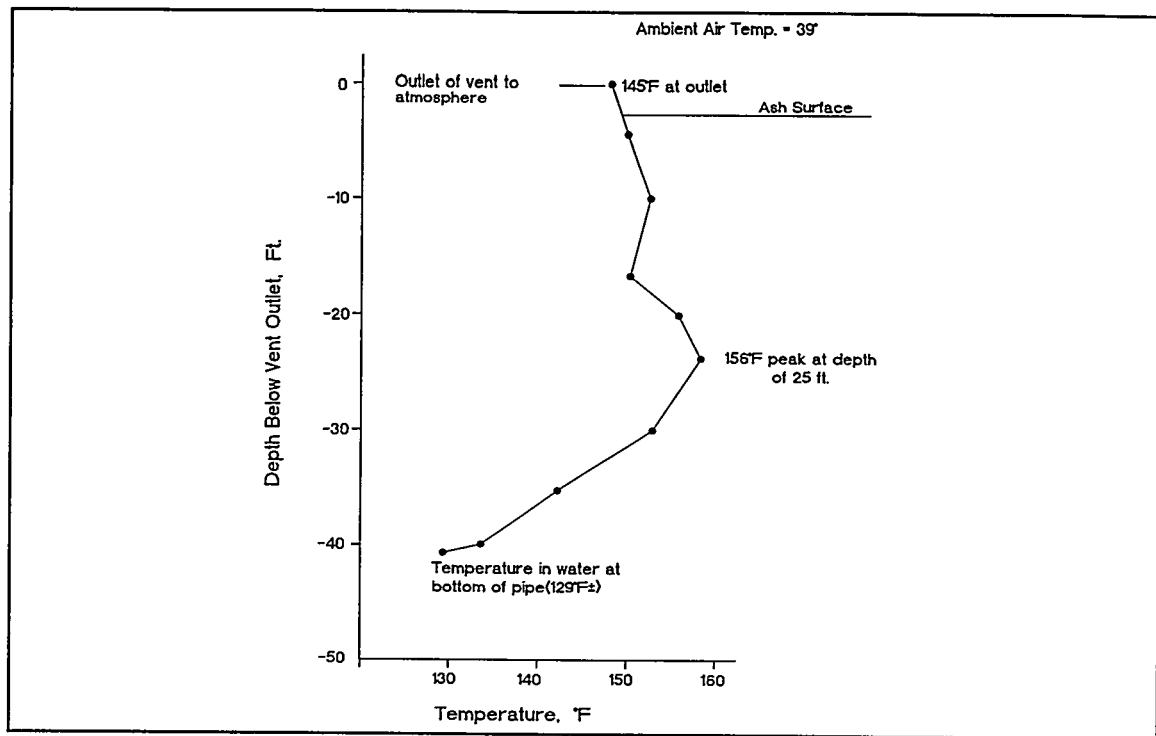


Figure 3. Gas Temperature Profile with Depth.

Ambient Air Monitoring of the Beneficial Use of Municipal Waste Combustor (MWC) Ash as Daily
Landfill Cover

Brian H. Magee
Ogden Environmental and Energy Services, Inc.
239 Littleton Rd., Suite 1B
Westford, MA 01886

Amy C. Miller
Ogden Environmental and Energy Services, Inc.
239 Littleton Rd., Suite 1B
Westford, MA 01886

Jeffrey L. Hahn
Ogden Projects, Inc.
40 Lane Road
Fairfield, NJ 07007

Colin M. Jones
City and County of Honolulu
91-174 Hanua Street
Kapolei, HI 96707

INTRODUCTION

This paper summarizes Human Health Risk Assessments of the proposed use of combined ash from the H-Power municipal waste combustor (MWC) in two beneficial uses: (1) Landfill Daily Cover for the Waimanalo Gulch Sanitary Landfill in Ewa, O'ahu, Hawai'i, which is operated by Waste Management of Hawaii, Inc. for the City and County of Honolulu and (2) Landfill Final Cover, a component in the final cover of the Waipahu landfill, in Waipahu, O'ahu, Hawai'i.

The human health risk assessment represents one phase of a larger project involving the investigation of several potential uses of H-Power MWC ash as alternatives to the current practice of disposal in a lined monofill located at the Waimanalo Gulch Sanitary Landfill. The ash consists of approximately 70% bottom ash and 30% fly ash from the MWC, hereafter referred to as H-Power combined ash.

At this time, three alternative uses of H-Power combined ash have been identified: The first option consists of using H-Power combined ash as a component in the final cover in the closure of the Waipahu Landfill; the second option consists of using H-Power combined ash as daily cover at the Waimanalo Gulch Sanitary Landfill; and, the third option consists of mixing H-Power combined ash into aggregate to be used in roadway paving material.

Investigations into these proposed ash uses are detailed in a September 1994 report which presents the rationale for and results of tests conducted to support alternative ash use as landfill cover (daily cover and final cover) and as roadway aggregate.¹ The tests conducted for this Phase I investigation included biological, chemical, and engineering tests (*e.g.*, botanical growth potential, metals content, sieve analyses, strength analyses, permeability, and others). The results of the Phase I investigation indicate that H-Power combined ash is suitable for these alternative beneficial uses.

During June 1995, subsequent to completion of the Phase I investigation, ambient total suspended particulate (dust) concentrations were measured at Waimanalo Gulch Sanitary Landfill during disposal of municipal solid waste (MSW) as well as disposal of H-Power combined ash into the lined monofill. The purpose of collecting these preliminary data was to estimate an emission factor for the combined ash. These data, together with the chemical data collected during Phase I, were used as the basis of human health risk assessments conducted for both landfill cover options (final cover and daily cover).

The human health risk assessment of the use of H-Power combined ash in the closure of the Waipahu Landfill was conducted by Ogden, and a report was submitted to the State of Hawai'i Department of Health (DOH).² Preliminary review by the DOH indicated that they approve of the methodology and procedures used therein.

Following this, Ogden prepared a preliminary human health risk assessment of the use of H-Power combined ash as alternate daily cover at the Waimanalo Gulch Sanitary Landfill. Based on chemical analytical data for ash samples collected during the Phase I investigation and other testing, noncarcinogenic and carcinogenic health effects were evaluated for ten constituents. Potential exposures to ash, ash-derived dust, and ash leachate were evaluated for key potential receptors, including landfill workers, adults and children who may visit the landfill (to dispose of household waste), and adults and children who live in nearby residential neighborhoods.

Several activities associated with the proposed use of H-Power combined ash as daily cover theoretically have the potential to create fugitive dust and, therefore, were evaluated in the risk assessment. They include:

- pushing and compacting fresh MSW on the previous day's ash cover;
- pushing and compacting fresh MSW on MSW;
- pushing and compacting fresh combined ash on MSW to create the daily cover; and,
- mining of combined ash.

The ambient air data collected in June 1995 (downwind of combined ash disposal in a lined monofill and MSW disposal in the lined landfill) were used as surrogate data for the dust concentrations associated with these specific activities. However, each of these activities has a different potential for dust generation and, at the time of the preliminary risk assessment, each was expected to produce different downwind dust concentrations. The 1995 dust data were used because activity-specific dust concentrations had not yet been measured. Analytical data generated from ash samples collected during the Phase I investigation and other testing were used to evaluate potential direct exposures to H-Power combined ash (ingestion and dermal contact), to predict leachate concentrations, and as mentioned, to estimate metals concentrations in dust. The results of this preliminary risk assessment were presented in a report to the Hawai'i and indicated that the proposed use of H-Power combined ash for daily cover would pose no significant noncarcinogenic or carcinogenic human health risk.³

The preliminary risk assessment for ash use as daily cover identified the lack of available air data associated with specific landfill activities. To address this data gap, approval was sought and obtained from the DOH to conduct a one-week demonstration program involving use of H-Power combined ash as alternate daily cover at the Waimanalo Gulch Sanitary Landfill. This demonstration program was conducted with the cooperation of the City and County of Honolulu, Waste Management of Hawaii, Inc., and the DOH.

These results were incorporated into the final human health risk assessment of the use of H-Power combined ash as alternate daily cover for the Waimanalo Gulch Sanitary Landfill. The revised risk estimates for the daily cover risk assessment are reported in this paper.

AMBIENT AIR MONITORING PROGRAM

During the one-week demonstration program, conducted during July 1996, concentrations of dust, metals, and crystalline silica were measured. Specifically, total and respirable dust, total and respirable metals (including arsenic, barium, chromium, cadmium, lead, nickel, selenium, and silver), respirable crystalline silica, hexavalent chromium, and total mercury (particulate and elemental vapor) were measured. Personal sampling was conducted in equipment cabs and on outdoor employees, and ambient sampling was conducted in numerous locations upwind and downwind of specific landfill activities. Overall, more than 100 personal and area samples were collected using personal sampling pumps, and more than 400 analyses were performed.

Ambient air samples were collected during dumping of ash into stockpiles (for use as daily cover), pushing and compacting of MSW on the previous day's ash cover, pushing and compacting of MSW on fresh MSW (current day's waste), and creating the daily cover at day's end. Data collected during the overnight period when the ash cover was exposed to the elements was evaluated separately. In addition to these daily

activities, air samples were also collected during the excavation of H-Power combined ash previously disposed in the landfill's ash monofill and subsequent loading onto dump trucks (referred to as ash mining).

At certain stations, all-day samples were collected. Locations included: OSHA U (upwind), OSHA D (downwind), CAT (in cab of caterpillar tractor), COMP (in cab of compactor), and SPOT (either on spotter or in spotter area). At other stations, designated ambient stations, samples were collected during four specific time periods defined as shifts 1-4 (S1-S4). These shifts corresponded to early morning, mid-day, late afternoon, and overnight. Ambient locations included: Ambient U (upwind), Ambient D1, Ambient D1A, Ambient D2, and Ambient D2A. In addition, a station designated ASH DUMP was established near to and directly downwind of the daily piles of H-Power combined ash that were dumped during the day for use as daily cover at day's end. Finally, on one day, a demonstration of ash mining in the ash monofill area was monitored. Station ASH MINE DUMP was established directly downwind of the operation, and station ASH MINE LOADER was on the window of the front end loader which loaded ash into dump trucks.

The analytical results from the demonstration program indicate total dust concentrations ranged from 50 to 1,400 $\mu\text{g}/\text{m}^3$, and respirable dust ranged from 30 to 840 $\mu\text{g}/\text{m}^3$ (see Tables 1 and 2). The ratio of respirable dust to total dust was calculated for each sample location where both were detected. The average ratio of respirable to total dust was 0.38 from 10 samples collected inside equipment cabs, and 0.24 from 30 outdoor ambient samples.

Arsenic, cadmium, chromium (total and hexavalent), mercury, lead, selenium, and silver were not detected in any of the total or respirable dust samples tested. Barium was detected in one total dust sample (at the detection limit of 0.0002 mg/m^3) but was not detected in any respirable dust samples. Similarly, nickel was detected in two total dust samples (at the detection limit of 0.0002 mg/m^3) but was not detected in any respirable dust samples.

Meteorological Observations

An on-site meteorological station was installed on the top of the hill at monitoring station D2A. Wind direction and wind speed data were collected for 15 minute average time periods. Windroses were developed for each monitoring period of interest so that it could be determined if a station was up-, down-, or cross-wind from a potential source during each specific time period.

The wind roses indicate that regional wind direction was generally from the north, northeast, and east directions during the monitoring period. Thus, the OSHA Upwind and Ambient Upwind stations were generally upwind of the working face at all times. The OSHA Upwind station was generally upwind of the ash piles at all times. The OSHA Compactor, Caterpillar operator, Spotter, and Downwind stations were generally downwind of the ash piles and the working face at all times. The Ambient D1/D1A stations were generally downwind of the ash piles and the working face at all times. Lastly, the Ambient D2/D2A stations were generally down- to cross-wind of the ash piles and the working face.

A simple evaluation of the OSHA eight hour samples indicates that a source other than the working face of the landfill or the ash piles is the likely source of the dust. For instance, on July 10, the total dust was highest in the upwind location and lowest directly on the working face. Respirable dust was also higher in upwind than downwind locations.

Similarly, on July 11, total dust was highest in the upwind location and lowest on the spotter. Respirable

dust was similar in upwind and downwind locations. Also, on July 12, total dust was similar in the upwind location and the spotter location. Respirable dust was greater in the upwind location than in downwind and spotter locations.

A similar evaluation of the ambient monitoring results also strongly suggests that the H-Power combined ash was not the source of the dust. Stations D1/D1A are clearly downwind of the ambient upwind location, and the latter is generally upwind of the ash piles and the working face. There is a trend of the upwind location having higher dust measurements. Out of 8 respirable dust values, 5 were higher in ambient upwind samples than in D1/D1A samples, with the average ratio being 9-fold. Out of 13 total dust measurements, 8 were higher in ambient upwind samples compared to D1/D1A samples with the average ratio being 2-fold. This again suggests that the source of the dust is not the ash piles or the working face.

Comparison of Results During Different Activities

If the ash were a source of dust, the time when most ash-derived fugitive dust would be created would have been during the S1 period when the compactor was operating atop ash and the S3 period when the compactor was creating the day's cover with ash. Measured dust during the S3 period was not elevated. In all samples from ambient downwind locations, no respirable dust or total dust was detected with detection limits of ~0.2 mg/m³. These data indicate that the spreading and compacting of H-Power combined ash to construct a daily cover does not create a significant amount of dust.

In addition, measured dust during the S1 period when the compactor was running over ash was not elevated compared to the S2 period when the compactor was generally running on fresh MSW. (On some days, the ash was not completely covered by the start of the S2 period, but it is still true that the compactor was on ash a greater fraction of the period during S1 than during S2.) Out of 28 samples (respirable dust and total dust) that had a detected value in at least one of the time periods (S1 and S2), only 7 were higher in S1 than in S2. For most of the samples (21/28), the values during S2 were higher than during S1. For this analysis, 1/2 the detection limit was used as a surrogate value for nondetects. In fact, in 17 of the 28 data pairs, dust was not even detected during the S1 period. These data indicate that the running of a heavy compactor over a landfill face covered with H-Power combined ash does not create a significant amount of dust.

The Ashdump sampling station was downwind of the OSHA Upwind station and downwind of the ash piles. The OSHA Upwind station was upwind of the ash piles. In every case (7/10, 7/12, and 7/14), the 8-hour OSHA Upwind sample was higher in respirable dust and total dust than the ashdump sample (by a factor of ~ 5 fold). This suggests that the ash pile itself was not the source of the dust monitored in the Ashdump samples.

Ashmining was also shown not to produce significant dust. No dust was detected at the ambient station placed downwind of the operation. Respirable dust was detected in the cab of the loader as would be expected. Small dust clouds were also visually observed when the loader dumped ash into the trucks.

A comparison of sampling locations where dust was detected with meteorological data concurrently collected during the demonstration program strongly suggests that the H-Power combined ash is not the source of dust concentrations observed. Lastly, it was observed during the demonstration project that running heavy equipment in and atop H-Power combined ash did not generate elevated dust levels, and therefore, typical landfill activities were grouped together and collectively evaluated as "daily activities".

HAZARD IDENTIFICATION

H-Power combined ash samples have been analyzed for several inorganic parameters as well as dioxin/furan congeners. TCLP metals data are available for combined ash samples collected between approximately 1989 and 1996. In addition, total metals analyses have included aluminum, arsenic, barium, cadmium, calcium, chromium, copper, iron, lead, mercury, nickel, potassium, selenium, silver, and zinc. From this list of constituents, aluminum, calcium, copper, iron, potassium, and zinc were eliminated from evaluation in the risk assessment because they have very low toxicity and/or are essential human nutrients. The remaining constituents were evaluated in the risk assessment.

The final list of chemicals of potential concern (CPC) includes the following metals: arsenic, barium, cadmium, chromium, lead, mercury, nickel, selenium, and silver (see Table 3). Furthermore, with the exception of nickel, these are the metals required to be tested by the Resource Conservation and Recovery Act (RCRA). Nickel was included because it is often defined as a chemical of concern for risk assessments of combustors. In addition to these metals, dioxin/furan congeners were also included in this risk assessment because they have historically been the focus of risk assessments of MWC facilities.

TOXICITY ASSESSMENT

Cancer slope factors, Reference Doses, and Reference Concentrations for all CPCs were obtained from standard EPA sources.^{4,5} However, there is currently no EPA-verified Reference Dose for lead. Risk assessments for lead commonly use models of varying complexity that predict blood lead levels, which are then compared to benchmark levels of blood lead. The benchmarks have been determined by regulatory agencies to present no significant risk of harm. Because the U.S. EPA model can only predict blood lead levels in children, the Hawai'i Department of Health requested that the California DTSC model be used for this risk assessment.

The major components of the DTSC model were used as presented in DTSC guidance.⁶ Specifically, the intake-blood lead slope factors (termed "constants" in the DTSC model) were not modified. However, several of the soil-specific default exposure parameters were modified as allowed by DTSC guidance, so that they were applicable to the assessment of human health risks posed by lead in *ash* versus residential soil. In addition, site-specific information on background lead exposures from air, water, and food was incorporated.

A review of the recent literature revealed that the lowest current regulatory blood lead limit for adults was 25 µg/dL.⁷⁻¹³ This value was used as the benchmark for risk assessment of adult worker exposures in this analysis. The benchmark for young children and adult females of childbearing age was defined as 10 µg/dL.

EXPOSURE ASSESSMENT

The exposure assessment is presented separately for the Landfill Daily Cover Project (Waimanalo Gulch Sanitary Landfill) and the Landfill Final Cover Project (Waipahu Landfill).

Landfill Daily Cover (Waimanalo Gulch Sanitary Landfill)

It is proposed that H-Power combined ash be used for daily cover of the working face at the Waimanalo Gulch Sanitary Landfill. It is assumed that the daily cover would involve the placement and compacting of H-Power combined ash to a depth of approximately 6 inches over the working face of the landfill. This is assumed to require an 18 inch thickness of uncompacted ash. The risk assessment assumes that the dimensions of working face are approximately 55.5 m by 20.7 m, or 1,149 square meters (12,350 square feet). This was based on actual measurement of the working face during the July 1996 demonstration project.

The risk assessment assumes the amount of H-Power combined ash required for daily cover at the landfill is 686 cubic yards per day. H-Power currently produces approximately 300 cubic yards of combined ash per day. Since H-Power ash has been landfilled at the Waimanalo Gulch Sanitary Landfill for many years, the remaining amount needed for daily cover during the demonstration project, 354 cubic yards, was mined from the previously landfilled H-Power ash. For conservative purposes, it is assumed that the daily cover is 100% H-Power combined ash, supplied by current H-Power operations as well as by mining of the previously landfilled ash.

Ash was mined during the demonstration project from July 9 - July 13. Mined amounts ranged from 360 tons/day to 900 tons/day, with the average amount mined per day being 504 tons. No ash was mined on July 14. Deliveries of unprocessed combined ash during the demonstration project averaged 332 tons/day, which corresponds to approximately 332 cubic yards per day.

It is proposed that the ash will be processed before using it for daily cover of the working face at the Waimanalo Gulch Sanitary Landfill. Ferrous and nonferrous metals will be removed and the water content of the ash will be adjusted to a moisture content of approximately 25%. The estimated volume of processed ash produced per day is 176 cubic yards (214 tons/day / 1.215 tons/cubic yard). Thus, the daily requirement for processed combined ash exceeds the production rate for a working face of 12,350 square feet. In the future, it is proposed that the remaining need for daily cover be mined from the previously landfilled ash. Also, the working face is often as small as 6,000 square feet. Daily production of H-Power combined ash would be sufficient to provide daily cover for this size working face, and no ash mining would be required.

The use of H-Power ash as daily cover assumes the following activities: In the morning (0700-1000 hours), workers push and compact municipal solid waste (MSW) over the previous day's ash cover. This ash has been exposed to the air for 14 hours and may have a lower moisture content than fresh H-Power ash. During the mid-day (1000-1500 hours), workers push and compact MSW over MSW deposited earlier the same day (*i.e.*, by this time, the previous day's ash cover has been covered with the current day's MSW, on top of which additional MSW is placed). During this time period, the workers are not running equipment atop of H-Power ash. During the late afternoon (1500-1700 hours), the workers are pushing and compacting ash over the fresh MSW to create the day's cover. This ash is fresh ash, which has a high moisture content. Then, this cover is exposed to the elements during the evening and night (1700-0700 hours). In addition to the daily operations described above, mining of H-Power ash previously disposed at the Waimanalo Gulch Sanitary Landfill is conservatively assumed to take place throughout every workday (0700 - 1700 hours).

Landfill Final Cover (Waipahu Landfill)

It is proposed that H-Power combined ash be used as the bottom layer of the final cover in the closure of

the Waipahu Landfill. This risk assessment assumes that the landfill area to be covered is 43 acres. It is assumed that the closure as proposed would involve the placement and compacting of 24 inches of H-Power combined ash and then 18 inches of local soil. The total amount of H-Power combined ash required to cover 43 acres to a depth of 24 inches is 138,746 cubic yards.

It is proposed that the H-Power combined ash be used as it is produced and processed. Each day's production of ash would be transported to the Waipahu Landfill, placed, compacted, and covered with local soil. The risk assessment addresses potential exposures that might occur during the period when the ash is proposed to be placed, compacted and covered at Waipahu Landfill and during the post-closure period.

The Waipahu Landfill is located adjacent to West Loch of Pearl Harbor with a small residential area to the northwest of the landfill. Accordingly, the risk assessment evaluates potential exposures that might occur in these areas. In addition, there is another residential area towards the southwest of the facility. Exposures in this area are also evaluated. In addition, risks posed by contact with surface water, sediment, and fish in West Loch are quantitated.

The risk assessment evaluated three potential scenarios regarding the manner in which the H-Power ash would be used as part of the landfill closure. In the first, it is assumed that the H-Power ash is delivered to Waipahu Landfill during the week and diverted to Waimanalo Gulch over the weekend. Deliveries only occur during the daylight hours. During the week, ash is stored at the H-Power Plant in covered trailers overnight and delivered to the landfill each morning. At the end of each day, it is assumed that the ash is spread, compacted, and covered with soil. This scenario is referred to as "Closure-No Stockpile" throughout the risk assessment.

In the second scenario, it is assumed that all of the combined ash is delivered to the Waipahu Landfill. Again, however, deliveries only occur during daylight hours (10 hours/day). Overnight during the week, it is assumed that ash is stored in covered trailers at the H-Power plant. During the weekend, the ash is continued to be delivered throughout the day on Saturday and Sunday, thus creating a temporary stockpile at the site that is spread, compacted, and covered with Mililani soil on Monday of each week. At the end of each day, it is assumed that the ash is spread, compacted, and covered with soil. This scenario is referred to as "Closure-Stockpile" throughout the risk assessment.

In the third scenario, it is assumed that the amount of ash delivered daily is spread and compacted, but it is not covered with Mililani soil at the end of the day. It is assumed that the day's ash delivery dries somewhat and can become entrained into the air as fugitive dust overnight before it is covered with soil on the next day. This scenario is referred to as "Closure-Uncovered" throughout the risk assessment.

After closure, it is possible that the Waipahu Landfill will be converted to a soccer field, a softball field, or a picnic area. There is no possibility that the ash can cause airborne dust or surface water run-off, however, because the ash will be covered with 18 inches of native soils. The landfill will also be vegetated. Accordingly, a Post-Closure scenario was defined in which the ash was disrupted so that there was a mechanism by which ash-derived dust and surface water run-off could be created.

For this scenario, it is assumed that dirt bikers have disrupted the integrity of the vegetated cover. It is assumed that this disruption has resulted in 10% of the landfill area (17,402 square meters) becoming unvegetated and thus subject to surface run off. It is also assumed that 2% of the landfill area (3,480 square

meters) has been compromised to the extent that H-Power combined ash is exposed at the surface and subject to dust generation in addition to surface run off. This scenario is referred to as "Post Closure" throughout the risk assessment.

Identification of Receptors

Potential human receptors were identified for on-site and offsite scenarios on the basis of land use information (see Table 5). For the landfill daily cover risk assessment, receptors were identified on-site and offsite at the nearest inhabited location to the south of the site. For the landfill final cover risk assessment, potential human receptors were identified for each closure and post closure scenario. Receptors were identified on-site, off-site at the nearest inhabited locations to the north and south of the site (in the direction of both Trade and Kona Winds), and at locations where relevant activities such as fishing or swimming could occur.

Exposure Point Concentrations

Total metal concentrations in H-Power combined ash are used as exposure point concentrations for the ash, itself (see Table 3). Data from TCLP analyses are used as estimates of chemical concentrations in ash leachate (see Table 3).

On-site and off site receptors may be exposed to chemicals of potential concern in ash via inhalation of fugitive dust generated by placement, grading, and compacting of ash, as well as fugitive dust generated by wind erosion of uncovered ash placed in piles or placed in a layer over a portion of the area of either landfill. The on-site concentrations of fugitive dust generated by various ash use activities were directly measured during the two monitoring events in 1995 and 1996.

To estimate the off-site concentrations of dust generated by these activities, measured on-site concentrations were used to estimate respirable dust emission rates. These emission rates and local meteorological data were used as input parameters for EPA-recommended air dispersion models to estimate off-site dust concentrations. The modeled concentrations of dust in ambient air offsite were combined with chemical concentrations detected in ash to evaluate potential human exposures via inhalation.

This approach is health-protective in that it assumes that all dust is ash-derived and that all of the chemicals detected in ash are transported to dust. As noted above, the dust measured during the daily cover demonstration project was not correlated with ash handling and use. Instead, the dust observed during the project was correlated with truck traffic on dusty roads and rock crushing activities at the adjacent quarry. However, the measured dust concentrations can be used as worst case estimates of the dust generated by ash handling and use.

On-Site Dust Concentrations. During the six day demonstration project during which air monitoring was performed, twelve day-long total suspended particulate samples were taken inside of the caterpillar tractor and the MSW compactor. The average TSP value was 0.278 mg/m^3 . The average ratio of TSP to PM_{10} for samples taken inside of equipment was 0.38. Accordingly, the PM_{10} concentration for the landfill workers working inside the cabs of heavy equipment was derived as 0.105 mg/m^3 .

One landfill worker, the spotter, worked outdoors throughout the entire work day. Five day-long samples of total suspended particulates were taken. The average TSP value was 0.558 mg/m^3 . The average ratio of TSP to PM_{10} for samples outside was 0.24. Accordingly, the PM_{10} concentration for the landfill workers

working outside was derived as 0.134 mg/m^3 .

To be health-protective, the respirable particulate (PM_{10}) concentration for the spotter was used for all on-site workers during daily operations. This concentration overestimates the exposures for workers who are working inside of earth moving equipment.

During the ash mining operation, one sample was taken for respirable dust on the window of the front end loader, but no samples were taken for total suspended particulates. Accordingly, the respirable dust value of 0.300 mg/m^3 was used for this potential receptor.

Samples collected during the 1996 demonstration project were used to derive the average outdoor TSP concentration. The average TSP concentration for all outdoor samples was higher than the average TSP concentration for all outdoor *downwind* samples. Of the total dataset of outdoor samples, those samples collected in upwind locations (e.g. at or near the adjacent quarry's rock crushing operations) were excluded. Thirty nine samples were taken outdoors in downwind areas where visitors might be exposed to on-site dust. The average TSP value was 0.268 mg/m^3 . The average ratio of TSP to PM_{10} for samples outside was 0.24. Accordingly, the PM_{10} concentration for the on-site landfill visitors (landfill daily cover) or trespassers (landfill final cover) was derived as 0.064 mg/m^3 .

Off-Site Dust Concentrations. PM_{10} emission rates were estimated from measured concentration data using a simple Box Model¹⁴ and site-specific data for source length and mean wind speed (5.14 m/sec). The PM_{10} concentration in the box was assumed to be uniformly mixed by human activities on the landfill. Mixing height was assumed to be 2 m.

The SCREEN3 model (Version 95181)¹⁵ was used to estimate offsite ambient PM_{10} concentrations for the various scenarios. SCREEN3 is a USEPA-preferred model and is recommended by USEPA for a screening-level air dispersion modeling. The SCREEN3 model determines 1-hour chemical concentrations. Eight-hour and annual average PM_{10} concentrations are calculated by multiplying factors of 0.7 and 0.08, respectively.

Wind data are site-specific with the stability of D and wind speed of 5.14 m/s . Source areas were modeled as ground-level area sources with site-specific areas. A receptor height of 1.0 m was assumed. Site locations were considered as rural areas, and they were modeled using the simple terrain approach because the terrain heights of nearby human receptors are lower than the emission sources.

RISK CHARACTERIZATION

Table 4 presents the results of the lead risk assessment for all receptors and scenarios for both the Landfill Daily Cover risk assessment (Waimanalo Gulch Sanitary Landfill) and the Landfill Final Cover risk assessment (Waipahu Landfill). In all cases, the 99th percentile blood lead concentration is less than the applicable blood lead health benchmark. In all cases, the majority of blood lead was associated with the assumed ingestion and dermal contact with ash. Only a small fraction was associated with inhalation of dust. For instance, for the Landfill Daily Cover risk assessment, inhalation of lead from ash-derived dust in air by on-site workers contributes $0.49 \text{ } \mu\text{g/dL}$, 7% of the total blood lead concentration. Inhalation of lead

from ash-derived dust in air by ash mining workers contributes 1.1 µg/dL, 15% of the total blood lead concentration. Inhalation of lead in ash-derived dust contributes less than 1% of the total blood lead concentration for the on-site adult visitor receptor. Inhalation of lead in ash-derived dust contributes less than 0.1% of the total blood lead concentration for the on-site child visitor receptor.

The same is true for the Landfill Final Cover risk assessment. Inhalation of lead from ash-derived dust in air contributes 0.20 µg/dL, 4% of the total blood lead concentration for construction workers. For the trespasser closure scenarios (assuming no stockpile, stockpile present, and uncovered ash), inhalation of lead in ash-derived dust contributes less than 1% of the total blood lead concentration for each receptor.

For other receptors and scenarios, such as the West Loch recreator (Closure-Stockpile, Closure-Uncovered, and Post-Closure scenarios), exposures to lead in background air, food, and water contribute essentially all of the 99th percentile blood lead concentrations. Surface water, sediment, and fish consumption exposures are associated with less than 1% of the total blood lead concentration for each receptor.

Table 5 presents the results of the noncarcinogenic risk assessment for all receptors and scenarios for both the Landfill Daily Cover risk assessment (Waimanalo Gulch Sanitary Landfill) and the Landfill Final Cover risk assessment (Waipahu Landfill). In all cases, the hazard indices are less than 1.0. These results indicate that proposed use of ash for daily cover at the landfill poses no unacceptable incremental increase in noncarcinogenic health risks.

Estimated Lifetime Cancer Risks (ELCRs) are also shown in Table 5. For all receptors and scenarios, the estimated cancer risk is within or below U.S. EPA's acceptable risk range of 10^{-4} to 10^{-6} and OSHA's criteria of 1×10^{-3} for setting occupational standards. Note that inhalation risks for all receptors were calculated based on the assumption that 100% of dust is ash-derived (*i.e.*, 100% of metals concentrations detected in ash were assumed to be present in dust), and that worker risks were estimated assuming that exposure occurs without regard to personal protective equipment and personal hygiene practices required under the applicable OSHA standards for arsenic, cadmium, and lead.

SUMMARY AND CONCLUSIONS

Human health risk assessments were performed for two proposed beneficial uses of H-Power combined ash: Landfill Daily Cover (Waimanalo Gulch Sanitary Landfill) and Landfill Final Cover (Waipahu Landfill).

In all cases, with all receptors and ash use scenarios, estimated blood lead concentrations were less than 25 µg/dL for adult male workers and 10 µg/dL for nonworkers assumed to be young children or female adults of child-bearing age. Estimated hazard indices were all less than 1.0, and estimated excess lifetime cancer risks were within or below U.S. EPA's acceptable risk range of 10^{-4} to 10^{-6} and OSHA's criteria of 1×10^{-3} for setting occupational standards.

Ambient and personal monitoring was performed during a demonstration project of landfill daily cover. Although no metals were detected in total or respirable dust and total dust was not found to be correlated with ash handling and use, measured dust concentrations were assumed to represent worst case estimates of ash-generated dust levels. The risk assessment assumed that dust was totally ash-derived, and ash-derived metal concentrations were derived from the total metals content of H-Power combined ash. Even with this very health-protective assumption, the risk assessment results were found to be dominated by the assumptions that potential receptors would directly ingest and dermally contact H-Power combined ash.

While such assumptions are commonly made by risk assessors, it should be noted that construction workers or landfill workers must adhere to strict requirements concerning personal hygiene practices and the use of personal protective equipment required under the applicable OSHA standards for arsenic, cadmium, and lead. Thus, assuming that workers will violate Federal law is a very health-protective approach to human health risk assessment.

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TABLE 1
TOTAL DUST CONCENTRATIONS

OSHA STATIONS	Day 1 7/10/96 (mg/m3)	Day 2 7/11/96 (mg/m3)	Day 3 7/12/96 (mg/m3)	Day 4 7/13/96 (mg/m3)	Day 5 7/14/96 (mg/m3)	Day 6 7/15/96 (mg/m3)
OSHA U	0.73	1.0	0.43	1.3	0.36	0.21
OSHA D	0.31	0.54	0.32	0.45	0.94	0.20
CAT	0.11	0.22	0.19	0.17	0.25	0.60
COMP	<0.02	0.41	0.27	0.62	0.20	0.28
SPOT	0.48	0.59*	0.07	1.4	0.63	0.21
AMBIENT STATIONS						
U S1	0.2	0.42	0.36	0.1	<0.08	<0.1
U S2	0.65	0.44	0.76	0.27	0.05	0.09
U S3		0.4	<0.2	<0.1		
U S4	<0.02	<0.02	0.06	<0.02	<0.02	<0.02
D1 S1	<0.09		0.3		<0.07	
D1 S2	0.62		0.3		0.12	
D1 S3						
D1 S4			<0.02		<0.02	
D1A S1		0.34		0.33		0.2
D1A S2		0.22		0.39		
D1A S3		<0.2		<0.2		
D1A S4		<0.02		<0.02		0.03
D2 S1	<0.09		<0.07		<0.07	
D2 S2	0.23		0.30		0.17	
D2 S3			<0.2			
D2 S4	<0.02				<0.02	
D2A S1		0.42		<0.02		<0.1
D2A S2		<0.03		0.16		<0.03
D2A S3		<0.2		<0.2		
D2A S4		<0.02		<0.02		<0.02
ASH DUMP		0.83		0.44		0.05
ASH MINING						
ASH MINE DUMP			<0.08			
ASH MINE LOADER						

NOTES:

*Cassette found on the ground and reconnected to sampling apparatus.

TABLE 2
RESPIRABLE DUST CONCENTRATIONS

OSHA STATIONS	Day 1 7/10/96 (mg/m3)	Day 2 7/11/96 (mg/m3)	Day 3 7/12/96 (mg/m3)	Day 4 7/13/96 (mg/m3)	Day 5 7/14/96 (mg/m3)	Day 6 7/15/96 (mg/m3)
OSHA U	0.19	0.23	0.09	0.25	0.03	0.08
OSHA D	0.05	0.27*	0.11	0.09	0.08	0.09
CAT	0.03	0.07	<0.02	0.09	0.05*	0.24
COMP	0.04	0.14	0.13	0.25	0.13	0.07
SPOT	0.09	0.18	0.17*	0.15	0.18	0.06
AMBIENT STATIONS						
U S1	0.4	<0.08	<0.09	<0.09		<0.2
U S2	0.03	0.03	0.05	0.1	<0.04	
U S3		<0.2	<0.3	0.3		
U S4	<0.02	<0.02	<0.02	0.6	<0.02	<0.02
D1 S1	<0.1		<0.08		<0.08	
D1 S2	0.1		0.04		0.05	
D1 S3			<0.2			
D1 S4	<0.02		<0.02		<0.02	
D1A S1		<0.08		0.84		<0.2
D1A S2		0.05		0.07		
D1A S3		<0.2		<0.2		
D1A S4		<0.02		<0.02		<0.02
D2 S1	<0.1		0.2		<0.08	
D2 S2	<0.03		<0.04		0.09	
D2 S3			<0.2			
D2 S4	<0.02		<0.02		<0.02	
D2A S1		<0.07		<0.08		
D2A S2		<0.04		0.1		
D2A S3		<0.2		<0.2		
D2A S4		<0.02		<0.02		<0.02
ASH DUMPING		0.04		0.02		<0.03
ASH MINING						
ASH MINE DUMP			<0.09			
ASH MINE LOADER			0.3			

NOTES:

*Laboratory report indicated sample was contaminated with tap water; results may be biased high.

TABLE 3
DATA SUMMARY FOR H-POWER COMBINED ASH

Chemical	Concentration in Ash (Dry Weight, mg/kg) ^{1,2}	Concentration in TCLP Leachate (mg/L) ^{2,3}
Arsenic	49	0.67
Barium	410	1.6
Cadmium	29	0.31
Chromium	69	0.064
Lead	2500	1.0
Mercury	11	0.0045
Nickel	75	not analyzed
Selenium	0.91	0.19
Silver	7.1	0.088
TCDD-Toxic Equivalents ⁴	0.00043	not analyzed

¹ Combined ash samples with metal pieces removed, samples collected during 3/20/95-12/18/95.

²Upper 95% confidence interval of the mean concentration using H statistic per U.S. EPA guidance assuming lognormal distribution.

³Combined ash samples with metal pieces removed, samples collected from 12/89-8/95.

⁴Mean of two samples in which total congener profile was measured.

TABLE 4
ESTIMATED BLOOD LEAD CONCENTRATIONS

LANDFILL DAILY COVER		
Receptor	95th %ile (ug/dl)	99th %ile (ug/dl)
On-Site Worker pushing/compacting MSW/Daily Cover	5.3	6.7
On-Site Worker - ash mining	5.8	7.3
On-Site Visitor - young child	2.7	3.4
On-Site Visitor - female of childbearing age	1.4	1.8
Off-Site Resident - young child	1.5	1.9
LANDFILL FINAL COVER		
Receptor	95th %ile (ug/dl)	99th %ile (ug/dl)
On-Site Construction Worker	4.0	5.0
On-Site Trespasser (young child)		
Closure No Stockpile	2.1	2.7
Closure with Stockpile	2.7	3.4
Closure Uncovered	2.7	3.4
Off-Site Resident (young child)		
Closure No Stockpile	1.5	1.9
Closure with Stockpile	1.5	1.9
Closure Uncovered	1.5	1.9
Post Closure	1.5	1.9
Recreator (fishing/swimming)		
Closure with Stockpile	1.5	1.9
Closure Uncovered	1.5	1.9
Post Closure	1.5	1.9
Recreator (child dirt biking)		3.4
Post Closure	2.7	

TABLE 5
ESTIMATED NONCARCINOGENIC AND
CARCINOGENIC HEALTH RISKS

LANDFILL DAILY COVER		
Receptor	Hazard Index	Cancer Risk
On-Site Worker pushing/compacting MSW/Daily Cover	0.4	3×10^{-5}
On-Site Worker - ash mining	0.6	5×10^{-5}
On-Site Visitor - young child	0.2	4×10^{-6}
On-Site Visitor - female of childbearing age	0.05	4×10^{-6}
Off-Site Resident - young child	0.001	2×10^{-8}
LANDFILL FINAL COVER		
Receptor	Hazard Index	Cancer Risk
On-Site Construction Worker		
Closure No Stockpile	0.2	2×10^{-6}
Closure with Stockpile	0.2	2×10^{-6}
Closure Uncovered	0.2	2×10^{-6}
On-Site Trespasser (young child)		
Closure No Stockpile	0.08	9×10^{-7}
Closure with Stockpile	0.3	1×10^{-6}
Closure Uncovered	0.3	2×10^{-6}
Off-Site Resident (young child)		
Closure No Stockpile	0.001	2×10^{-8}
Closure with Stockpile	0.008	2×10^{-8}
Closure Uncovered	0.001	2×10^{-8}
Post Closure	0.0008	2×10^{-8}
Recreator (fishing/swimming)		
Closure with Stockpile	0.001	7×10^{-8}
Closure Uncovered	0.004	2×10^{-7}
Post Closure	0.07	9×10^{-7}
Recreator (child dirt biking)		
Post Closure	0.2	1×10^{-6}

**Fundamental Mechanisms of Phosphate Stabilization
of Divalent Metals in MSW Combustion Scrubber Residues**

T. Taylor Eighmy
Environmental Research Group
A115 Kingsbury Hall
University of New Hampshire
Durham, NH 03824

Bradley J. Crannell
Environmental Research Group
A115 Kingsbury Hall
University of New Hampshire
Durham, NH 03824

James E. Krzanowski
Mechanical Engineering Department
134 Kingsbury Hall
University of New Hampshire
Durham, NH 03824

Leslie G. Butler
Chemistry Department
Louisiana State University
Baton Rouge, LA 70803

J. Dykstra Eusden Jr.
Geology Department
Carnegie Hall
Bates College
Lewiston, ME 04240

Frank K. Cartledge
Chemistry Department
Louisiana State University
Baton Rouge, LA 70803

Elizabeth L. Shaw
Analytical Shared Experimental Facility
Center for Material Science and Engineering
Room 13-4137
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

Earl Emery
Chemistry Department
Louisiana State University
Baton Rouge, LA 70803

Carl A. Francis
Harvard University Mineralogical Museum
24 Oxford Street
Cambridge, MA 02138

Daniel Oblas
Center for Advanced Materials
University of Massachusetts Lowell
1 University Avenue
Lowell, MA 01854

INTRODUCTION

Chemical stabilization of waste materials offers the potential to reduce the leachability of heavy metals in the waste. The principal objective during stabilization is to form new mineral phases with reduced solubilities and increased geochemical stability in a leaching environment. One stabilization agent of recent interest, particularly for Pb^{2+} , is PO_4^{3-} .^{1,2,3,4,5}

A patented soluble phosphate treatment process, marketed by Wheelabrator Environmental Systems as the WES-PHix process, is used in 23 MSW combustion or ash processing facilities in the United States. It is also used at 7 wire recycling facilities. The process is licensed to Kurita Water Industries Ltd. of Japan where it is marketed as the ASHNITE process. It is used in over 80 MSW combustion or ash processing facilities in Japan.

Phosphate combines with over 30 elements to form about 300 naturally-occurring minerals.^{6,7} Metal phosphates are ubiquitous secondary minerals in the oxidized zones of lead ore deposits and as assemblages around ore bodies.⁷ They also occur in soils, sediments, and phosphatic beds.⁷ As such, they are stable with respect to pH, Eh, and mineral diagenesis. Isomorphic substitutions are very common for both divalent cations (e.g. Pb^{2+} for Ca^{2+}) and oxyanions (e.g. AsO_4^{3-} for PO_4^{3-}) in these minerals.⁷

Past research efforts have shown that phosphate minerals are likely controlling solids for Ca^{2+} , Cd^{2+} , Cu^{2+} , Pb^{2+} and Zn^{2+} in natural soil systems.^{8,9,10,11,12,13} The use of PO_4^{3-} to immobilize metals has been advocated for industrial wastewaters^{14,15} and lead-contaminated soils.^{13,16,17,18,19,20} Both phosphate-containing minerals and soluble phosphate have been advocated as sources of PO_4^{3-} .

In the case of phosphate-containing minerals as a PO_4^{3-} source, the ongoing work by Traina's group^{4,16,17,18,19,20} has explored apatites (e.g. calcium hydroxyapatite, $\text{Ca}_5(\text{PO}_4)_3\text{OH}$) or waste phosphate rock as a source of PO_4^{3-} to precipitate Pb^{2+} from solution or in contaminated soils as lead hydroxypyromorphite ($\text{Pb}_5(\text{PO}_4)_3\text{OH}$); a more thermodynamically stable isostructural analogue to calcium hydroxyapatite.⁴

In the case of soluble phosphate as a PO_4^{3-} source, chemical stabilization mechanisms can involve a continuum from surface sorption processes to existing or newly formed particulate surfaces in a waste material, through the formation of new surface precipitates, to the formation of discrete heterogeneous or homogeneous precipitates.²¹ Spectroscopic and geochemical modeling techniques exist to help distinguish between sorption and the various forms of precipitation (e.g. surface, heterogeneous, homogeneous).^{22,23,24,25}

When soluble phosphate is used to stabilize metals in waste materials containing appreciable concentrations of Ca^{2+} , it is useful to understand Ca^{2+} and PO_4^{3-} crystallization and precipitation chemistry as this reaction sequence is likely to dominate the system. When Ca^{2+} and PO_4^{3-} are titrated in solution, a variety of phases form.^{26,27} In a simple system, the reaction sequence generally involves $\text{Ca}_9(\text{PO}_4)_6$ (non-stoichiometric amorphous calcium phosphate), $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$ (brushite); CaHPO_4 (monetite); $\text{Ca}_8\text{H}_2(\text{PO}_4)_6 \cdot 5\text{H}_2\text{O}$ (octacalcium phosphate), $\beta\text{-Ca}_3(\text{PO}_4)_2$ (whitlockite); and ultimately $\text{Ca}_5(\text{PO}_4)_3\text{OH}$ (calcium hydroxyapatite); the most geochemically stable calcium phosphate.²⁸ The sequence is influenced by ion activity products (IAPs), pH, ionic strength, reaction kinetics, the presence of precursor substrates or "seed", and the presence of inhibitors like Mg^{2+} .^{26,27,29}

This reaction sequence is useful in interpreting likely immobilization mechanisms in Ca^{2+} -containing waste materials treated with PO_4^{3-} . There is evidence for relatively fast sorption processes onto calcium hydroxyapatite at low metals concentration for Cd^{2+} , Cu^{2+} , Pb^{2+} , and Zn^{2+} .^{15,30,31,32} At higher metals concentration, evidence of surface precipitation on the calcium hydroxyapatite is observed; more so for Pb^{2+} and less so for Cd^{2+} and Zn^{2+} .^{5,33} In systems where Pb^{2+} is present in high concentrations in solution, evidence is given that less stable calcium hydroxyapatite will dissolve and preprecipitate as more stable lead hydroxypyromorphite.^{4,5,16,17,18,19,20} In systems where all components are initially soluble, it is simple to precipitate lead hydroxypyromorphite^{7,10} or ternary metal apatites where Pb^{2+} , Cd^{2+} , Cu^{2+} , and Zn^{2+} isostructurally substitute for Ca^{2+} and form solid solutions like $(\text{Ca}, \text{Pb}, \text{Zn})_5(\text{PO}_4)_3\text{OH}$.^{34,35}

Dry scrubber residue is a particulate material from the use of dry lime powder (CaO) or dried slaked lime powder ($\text{Ca}(\text{OH})_2$) in the scrubbing of flue gas from combustion of municipal solid waste. This is the second largest residual stream for modern waste to energy facilities.³⁶ The residue contains high concentrations of acid gas scrubber products (e.g. CaCl_2 , CaSO_4), unreacted scrubber material (CaO or $\text{Ca}(\text{OH})_2$), condensed semivolatile elements (e.g. Cl^- , Pb^{2+}), condensed volatile elements (e.g. Na^+ , K^+ , Hg^{2+} , Zn^{2+} and Cd^{2+}), aluminosilicate fly ash particles, and char.³⁷ The fine-grained residue is highly soluble and very alkaline, making it sometimes difficult to treat or dispose.³⁶

The approach taken by our group to understand stabilization mechanisms and identify reaction products formed during treatment of scrubber residues is shown in Figure 1. A variety of spectroscopic and geochemical modeling procedures are used as each provides specific and complementary information and because some suffer from small databases relative to the more exotic mineral phases found in granular waste materials.

This study was designed to determine the mechanisms and reaction products of chemical stabilization of dry scrubber residues treated with soluble orthophosphate. The data gleaned from various spectroscopic analyses, leaching procedures, and geochemical modeling show that precipitation/solid solution formation rather than sorption is the immobilization mechanism and that apatite minerals and solid solutions are the principal solubility-controlling reaction products. As in nature, these minerals are geochemically stable and very insoluble.

These results hold promise for the industry. Knowledge about the basic mechanisms of immobilization allows for further optimization of the process. Successful identification of reaction products using both spectroscopic and geochemical modeling techniques provides confidence for the use of geochemical models as predictive tools for refining treatment formulations, examining long term disposal behavior, and developing management strategies. Research is also ongoing by our group on soluble phosphate treatment mechanisms in MSW bottom ash, MSW ash vitrification dusts, smelter dusts, electric arc furnace dusts, and mine tailings.

METHODS

Combustor Description

A 1,500 ton per day mass burn facility was sampled. It consists of two parallel units comprised of reciprocating grates, water wall boilers, scrubber venturis, and $\text{Ca}(\text{OH})_2$ scrubbers with fabric filters. Activated carbon is used as a mercury sorbent; it is injected with the lime. It was operational during sampling.

Sampling occurred over the period from January 3rd to January 7th, 1995. Dry scrubber residue was collected by plant personnel. A grab sample (1 kg) was collected every 10 minutes to make a 4 hour daily composite from one of the scrubber transfer conveyors. The five daily composites were made into a weekly composite using a clean, lab-scale cement mixer.

Processing

For the purposes of this study, an experimental laboratory-scale treatment formulation was selected to ensure that stabilization reaction mechanisms and reaction products could be detected. A standard industrial grade H_3PO_4 acid solution was used. The treatment formulation involved using a dose of 1.2 moles H_3PO_4 per kg of residue. Process mixing water at a liquid to solid (L/S) ratio of 0.4 was used to facilitate mixing. The residues were mixed for 10 minutes in a Hobart mixer and then air dried. The mixing regime is similar to full scale treatment systems. The treated working sample was subsampled for subsequent analyses; the subsample was stored under vacuum desiccation until use.

Total Composition

The dry scrubber residues were quantified for over 47 elements using neutron activation analysis (NAA) for all elements except Pb, Cu, P, S, C and O. Procedures are provided elsewhere.^{38,39,40} X-ray fluorescence (XRF) was used for Pb, Cu, S, and P analyses. X-ray photoelectron spectroscopy (XPS) was used to quantify C and O (see below).

STEM-XRM

STEM-XRM was used to examine discrete particle morphology and determine elemental composition and possible mineral formula in discrete particles of the treated and unleached as well as the treated and leached fractions. STEM examinations were conducted on a Hitachi H-600 TEM operated at 100 kV accelerating voltage.

SIMS

SIMS was used to elucidate the stabilization mechanism. The method was used to depth profile selected atomic masses ($^{40}\text{Ca}^+$, $^{208}\text{Pb}^+$, $^{31}\text{P}^+$, $^{35}\text{Cl}^+$, $^{28}\text{Si}^+$) so as to examine concentration as a function of particle depth (particle exterior to interior). This would provide evidence of possible surface adsorption or surface precipitation or evidence of new discrete phase precipitation.²⁴

A Fisons/VG SIMSLAB I (upgraded) quadrupole filter type mass analyzer was used to conduct positive ion (+m/z) depth profiling using an O_2^+ ion beam source. Profiles were conducted at high vacuum (10^{-9} torr). Indium foil was used for sample mounting to minimize charging. Generally, the ion source was operated at 10 keV and 20 nA. Target biases were usually 5-15V. The profiles were done at 200x with the extractor operated at 1,500 V. Estimated sputtering rates were roughly 1 to 10 Å per second. Profiles for $^{208}\text{Pb}^+$, $^{31}\text{P}^+$, $^{40}\text{Ca}^+$, $^{28}\text{Si}^+$, $^{35}\text{Cl}^+$, and $^{113}\text{In}^+$ were usually conducted for 45 minutes to 1 hour.

XRPD

XRPD was used to identify crystalline mineral phases in the residues. A Rigaku-Geigerflex goniometer was used along with a copper X-ray source (45 kV, 35 mA, 1500 W). A divergence slit of 1° , a scattering slit of 1° , a receiving slit (crystal) of 0.8° , and a receiving slit (monochromator) of 0.6° were used. Details on search-match procedures are provided elsewhere³⁸.

MAS-NMR

MAS NMR was used to monitor the ^{31}P isotropic chemical shifts and chemical shift anisotropy tensors of the component species in the treated and unleached as well as the treated and leached fractions. The

spectra were taken on a 400 MHz Chemagnetics Infinity NMR spectrometer with a 9.4 Tesla magnet corresponding to a ^{31}P NMR frequency of 161.9 MHz. The samples were spun in 7.5 mm (OD) zirconia rotors in a double resonance probe at spin rates between 1 to 7 kHz at a temperature of about 23 ± 2 °C. The magic angle was set by observing the chemical shift of the aromatic resonance of hexamethylbenzene. The spin rate was measured with a fiberoptic sensor and is accurate to ± 2 Hz. All spectra were recorded with proton decoupling while using $10\ \mu\text{s}$ 90° ^{31}P pulses (except where noted); pulse lengths were calibrated by observing the ^{31}P resonance of $\text{NH}_4\text{H}_2\text{PO}_4$ (ammonium dihydrogen phosphate). The recycle delay was set to 10 s based on approximate ^{31}P T_1 measurements of some of the samples. The number of scans acquired ranged from 500 to 4,000. Chemical shifts were referenced to an external standard sample of $\text{NH}_4\text{H}_2\text{PO}_4$; (δ (^{31}P) = 0 ppm with respect to 85% H_3PO_4).⁴¹

The analysis of ^{31}P NMR spectra of inorganic phosphates is generally done by a consideration of both the isotropic chemical shift and the individual chemical shift tensor elements (principal axis system). These values are obtained from the ^{31}P NMR spectrum using the graphical method of Herzfeld and Berger⁴² or by a Simplex and gradient search method.⁴³ The latter was used here as it is optimized for multiple component systems.

XPS

A Perkin Elmer Physical Electronics Division 5100 hybrid XPS was used to identify and quantify possible chemical phases as well as to quantify elements in the samples. Detailed methods are provided elsewhere.³⁸ For energy referencing, the entire system was calibrated to the gold $84.0\ 4f_{7/2}$ binding energy. Correction for peak shift due to static charge buildup on the sample was achieved through the adventitious carbon reference method using a C 1s binding energy of 284.8 eV as a conducting reference.⁴⁴ Details on full width, half maximum values used for curve fitting^{45,46,47} as well as spectral deconvolution are provided elsewhere³⁸.

Leaching Apparatus

All leaching tests were conducted in leaching apparatus maintained in a laminar flow hood (Enviroco, Houston, Texas) with Type 2 HEPA air filters ($>0.3\ \mu\text{m}$). The apparatus is comprised of parallel units; each consisting of a 1000 ml Teflon leaching vessel with a screw cap, a stir plate, a stir bar, and constant temperature bath (25°C). Each vessel was maintained at a constant pH using a Cole-Parmer pH/ORP Controller (Model 5652-10). The controller opens and closes solenoids allowing the introduction of strong acid (3N HNO_3) or base (3N NaOH). The set points on the controller allowed for a ± 0.1 pH variation around a target value.

Total Availability Leaching Procedure

The procedure is based on the Dutch Total Availability Leaching test NEN 7341.⁴⁸ It was used to quantify the elemental mass fraction available for leaching. The method can assess what fraction of the total concentration of an element is leachable over geologic time (1,000-10,000 years). During the extraction, all readily soluble and marginally soluble minerals will solubilize. Desorption of tightly sorbed species will also occur. Details are provided elsewhere³⁸.

After filtration the leachates were combined. The sample was then split for metals analysis (graphite furnace and flame atomic absorption spectrophotometry), anions analysis (ion chromatography), and alkalinity determinations (titration).^{49,50,51} Additionally, the weight of the leached residue was determined for mass balance purposes. Residues were dried for 72 hours at 60°C to obtain a dry weight measure.

pH-Dependent Leaching

The pH-dependent leaching procedure is a means of determining the equilibrium leaching behavior over a range of pH values. Each extraction was done at a L/S ratio of 10.0 so as to ensure solid phase control. Eighty grams of sample were placed into the Teflon vessel to which 800 mls of distilled, deionized water was added. 3N HNO₃ was used to control the pH at various set points 4,6,8 for 24 hours. This pH range corresponds to values expected for both regulatory leaching tests and open CO₂(g) leaching systems (e.g. landfills). The leachates were filtered and analyzed as described above. Additionally, Pb²⁺ was determined using isotope dilution procedures and thermal ionization mass spectrometry after ion exchange concentration.⁵² PO₄³⁻ was also determined by using a Lachat low level colorimetric assay.⁵³

Leaching Modeling

The geochemical equilibrium model MINTEQA2⁵⁴ was used to determine which solid phase controlled leachate composition as a function of pH. The thermo.dbs and type6.dbs databases for MINTEQA2 were modified to include a large number of phosphate mineral phases shown in Table 1. Modeling details are provided elsewhere³⁸.

The likelihood of solid solution formation during dissolution and reprecipitation required further modification to the MINTEQA2 databases to allow for idealized solid solutions to act as possible controlling solids. A simplistic zero heat of mixing and ideal site substitution model was assumed.^{59,60} Standard free energies of formation for the solid solutions ($\Delta G^\circ_{f,ij}$) between end members i and j were used to determine theoretical K_{sp} values for the solid solutions using:

$$\Delta G^\circ_{f,ij} = x\Delta G^\circ_{f,i} + (1-x)\Delta G^\circ_{f,j} + nRT [x \ln x + (1-x) \ln (1-x)] \quad (1)$$

where x is the mole fraction of end member i, $\Delta G^\circ_{f,i}$ and $\Delta G^\circ_{f,j}$ are the free energies of formation of end members i and j, respectively, n is the number of sites in the mineral undergoing substitution (e.g. 1.0), R is the universal gas constant, and T is degrees Kelvin. K_{sp} values for hypothetical binary ideal solid solutions [e.g. for (Ca,Pb), (Ca,Cu), (Ca, Cd), and (Ca, Zn)] for the minerals Ca₃(PO₄)₂, Ca₅(PO₄)₃OH, Ca₅(PO₄)₃Cl, and Ca₄O(PO₄)₂ (Pb and Ca only) were calculated and entered into the MINTEQA2 databases. No attempts were made to evaluate the likelihood of these solid solutions with respect to theoretical (e.g. $K_{sp,i}/K_{sp,j}$) or experimental distribution coefficients.

RESULTS AND DISCUSSION

Total Composition

Table 2 provides information on the total elemental composition of the dry scrubber fabric filter residue as determined by NAA, XRF, and XPS. The major constituents (> 10,000 mg/kg) in the fabric filter residue were O, Ca, Cl, C, Si, Al, S, Na, and Zn. Minor constituents (1,000-10,000 mg/kg) included K, Ti, Fe, Mg, Pb, and Br. Trace constituents (< 1,000 mg/kg) included Cd, Cr, Hg, and many other elements. These concentrations are fairly typical for MSW dry scrubber fabric filter residues.³⁶ The presence of small quantities of activated carbon as a mercury sorbent may explain the relatively high C concentrations as well as the relatively high Hg concentrations in the residues. The concentrations of S, Pb, Cd, Cu, and Zn are in typical ranges for these wastes.³⁶ The observed phosphorus concentration, 2,100 mg/kg, is within the range of reported values (1,700 to 4,600 mg/kg) for untreated scrubber residues.

Particle Composition Based on STEM-XRM

Table 3 contains the atomic percent data generated from the analysis of discrete particle assemblages with STEM-XRM. Analyses were conducted on 10 assemblages for both the treated unleached and the treated and leached fractions. Particles were polycrystalline and small (100-5,000 nm). A wide variety of elements were observed in the residues. For the treated and unleached residues, O, Ca and Cl were very common elements. Mg, Al, Si, P, S, and K were also present. No Fe, Zn or Pb was observed. For the treated and leached residues, O, Al, P, S, Ca, Fe and Zn were very common elements. Mg, Si, Cl and K were also observed. Leaching appeared to have increased the relative concentration of many elements, particularly Al, P, Fe and Zn. This occurred because of the relative loss of Cl, K and Ca.

It is very likely that given the very small particle sizes that were interrogated (100 to 5,000 nm) as well as the complex structure of the polycrystalline particles, discrete homogeneous single crystals were not analyzed. The determination of molecular formulas from the data proved tedious and inconclusive.

It is important to note that the elements that were observed are many of the major and minor elements seen in the residues with total compositional analyses. Further, the elemental complexities of the assemblages agrees in principal with the types of phases observed with other methods like XRPD and XPS (see below). Finally, virtually all of the assemblages contained phosphorus; particularly in the leached residues. This is viewed favorably with respect to the availability of the stabilization agent to all particles at the nanometer scale under the mixing regime that was used.

Stabilization Reaction Mechanism Based on SIMS

Figure 2a shows typical depth profiles for the mineral standard $\text{Ca}_5(\text{PO}_4)_3\text{Cl}$ (calcium chloroapatite; Harvard University Mineralogical Museum 107354) which was ground to very small particle sizes ($<50\ \mu\text{m}$). This control sample represents a "homogeneous precipitate". As can be seen in the figure, $^{40}\text{Ca}^+$, $^{31}\text{P}^+$ and $^{35}\text{Cl}^+$ were relatively constant with depth (up to depth less than or equal to $0.5\ \mu\text{m}$). The background indium foil signal is also relatively constant. As expected, the homogeneous particulate gave a rather uniform depth profile for all of its constituents.

Figure 2b shows typical depth profiles for the treated and unleached fraction (other fraction mass fragment depth profiles are not shown). The profiles are similar to the calcium chloroapatite standard. Elements were uniformly distributed with depth. More $^{31}\text{P}^+$ was present in the treated residue than in the chloroapatite. The $^{113}\text{I}^+$ and $^{28}\text{Si}^+$ profiles did not change significantly with depth (up to less than or equal to $0.5\ \mu\text{m}$).

The use of ion mass fragment ratios is more illustrative of relative behaviors as a function of depth. $^{40}\text{Ca}^+$ is used to normalize the data. As shown in Figure 2c, the $^{31}\text{P}^+ / ^{40}\text{Ca}^+$ ratios in the chloroapatite, treated and unleached fraction and the untreated and unleached fraction were similar. The $^{31}\text{P}^+ / ^{40}\text{Ca}^+$ ratio was relatively constant with depth. These ratio profiles are similar to ones reported by Fulghum et al.²⁴ for the coprecipitate. They differ markedly from the adsorbed scenario. This suggests that the stabilization process produced a homogeneous precipitate. Stabilization via surface sorption was not likely. The leached residues showed clear enrichment of P relative to Ca in the particle surface. This is ascribed to preferential loss of Ca and salts during leaching at pH 4.0 in the Total Availability Leaching test. Though resorption of PO_4^{3-} cannot be ruled out at pH 4.0, the other spectroscopic techniques (particularly XPS) also showed clear loss of calcium in the outer particle surfaces during leaching.

The $^{208}\text{Pb}^+ / ^{40}\text{Ca}^+$ ratios showed similar, though less dramatic behavior, to the $^{31}\text{P}^+ / ^{40}\text{Ca}^+$ ratios as a function of depth. As shown in Figure 2d, the leached samples were surface enriched in $^{208}\text{Pb}^+$ while the

unleached samples showed uniform distribution as a function of depth. Contrary to PO_4^{3-} resorption, Pb^{2+} will not readily sorb at pH 4 so the data support the theory that the surface enrichment is an artifact of Ca salt loss during leaching. Similar behaviors were seen with the untreated and leached residues, though heterogeneity at the nm level was less than heterogeneity with depth.

These results strongly suggest that stabilization of Ca^{2+} and Pb^{2+} is largely via PO_4^{3-} -based precipitation and not by surface sorption processes. The former reaction mechanism is more geochemically stable and resistant to leaching than the latter mechanism. However, it is also likely that at a smaller spatial scale level, some sorption processes are occurring. There are other techniques that can be employed to verify the presence or absence of sorption processes.^{22,25} However, sorption isotherms, desorption assays, and isotopic exchange experiments are problematic with respect to the highly soluble nature of these residues. The use of SIMS is just one spectroscopic technique that was used in elucidating reaction mechanisms.

Phosphate Crystalline Phase Identification Based on XRPD

Table 4 contains possible phosphate crystalline phases that were identified in each of the four fractions using the computerized search-match routine. As stated above, the list is extensive and it is unlikely that all the listed phases are present. In the untreated and unleached residues, a few apatite family minerals (e.g. $\text{Ca}_5(\text{P},\text{Si},\text{S})\text{O}_{12}(\text{Cl},\text{OH},\text{F})$, chlorellestadite and $\text{Ca}_{10}(\text{PO}_4)_3(\text{CO}_3)_3(\text{OH})_2$, carbonate apatite) and CaHPO_4 (monetite) are observed. This is likely given the presence of phosphorus in the untreated residue. These phases are generally absent after leaching. After treatment with the soluble phosphate, a large number of potential phosphate mineral phases are observed, including apatite family minerals (e.g. $\text{Ca}_5(\text{P},\text{Si},\text{S})\text{O}_{12}(\text{Cl},\text{OH},\text{F})$, $\text{Ca}_{10}(\text{PO}_4)_3(\text{CO}_3)_3(\text{OH})_2$), tertiary metal phosphates (e.g. $\alpha\text{-CaZn}_2(\text{PO}_4)_2$, $\text{Zn}_3(\text{PO}_4)_2$), and more complex phosphate minerals. Ca, Al, Zn, Fe, K, Pb, and Cd phosphate minerals are seen. Particularly noteworthy minerals for Pb are $\text{Pb}_4\text{O}(\text{PO}_4)_2$, and two apatite-family minerals: $\text{Pb}_5(\text{PO}_4)_3\text{OH}$ (lead hydroxypyromorphite), and $\text{KPb}_4(\text{PO}_4)_3$. After leaching, many of the same phosphate minerals remain; indicating their relative stability to aggressive leaching environments.

^{31}P Chemical Environment Based on MAS-NMR

The treated and unleached and treated and leached spectra are found in Figure 3a and 3b, respectively. Table 5 summarizes the data from the Herzfeld-Berger (deGroot program⁴³) analysis of the spectra.

The ^{31}P MAS NMR spectrum of the treated and unleached fraction was acquired at 2, 4 and 6 kHz spin rates. The faster spin rates enable better detection of small differences in the isotropic chemical shift, while the slower spin rates yield more sidebands and should, in principal, be easier to fit. One problem that can be encountered is an isotropic chemical shift that occurs at the same frequency as the sideband from another resonance. This did not occur (see Table 5), but a fit of the 6 kHz data with a two component model showed a convergence to an isotropic chemical shift at the spinning sideband of a neighboring resonance leading us to discount the two component model for the 6 kHz data. The spectra for the 2 and 4 kHz data were both fitted to two component models (see Figure 3a for the 4 kHz data); the quality of the fit was better for the 4 kHz data based on the smaller residual.

The closest match between the 4 kHz major component in the treated and unleached spectrum and likely calcium phosphate minerals⁶¹ appears to be with a mixture of minerals with isotropic chemical shifts near 0 ppm. A mixture containing $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$ (brushite), CaHPO_4 (monetite), $\text{Ca}_5(\text{PO}_4)_3\text{OH}$ (calcium hydroxyapatite), and $\alpha\text{-CaZn}_2(\text{PO}_4)_2$ would lead to a good match with the major component with central transitions near 0 ppm and $|\Delta\delta|$ from 27 to 103 ppm. These minerals were detected by both

XRPD and XPS (see below). The three calcium phosphates also belong to the generalized Ca-phosphate precipitation reaction sequence.²⁸

The closest match between the 4 kHz minor component in the treated and unleached spectra and likely calcium phosphate minerals⁶¹ is $\text{Ca}_2\text{P}_2\text{O}_7$ or another pyrophosphate (e.g. $\text{Na}_4\text{P}_2\text{O}_7$). The minor component has a very large $|\Delta\delta|$ of 181 ppm. To our knowledge, this is one of the largest ^{31}P chemical shift anisotropies seen, and it indicates a distorted coordination geometry at phosphorus with non-ideal O-P-O bond angles. This conclusion is based on the correlation of $|\Delta\delta|$ with O-P-O bond angle as reported by Oldfield and coworkers.⁶²

The ^{31}P MAS NMR spectrum of the treated and leached fraction (Figure 3b) was acquired at 6 kHz. A two component fit was used with some residuals present. Based on the intensity of the ^{31}P signal and the spectral side band intensity; it is obvious that the four likely major components were susceptible to aggressive leaching during the Total Availability Leaching test at pH 4.

The closest match between the 6 kHz major component in the treated and leached spectrum and likely calcium phosphate minerals⁶¹ is $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$ (brushite), a mineral also seen by MAS-NMR in the treated and unleached fraction (see Table 5). The closest match between the 6 kHz minor component in the treated and leached spectrum and likely calcium phosphate minerals⁶¹ is $\text{Ca}_2\text{P}_2\text{O}_7$; a mineral also seen by XPS.

Crystalline and Amorphous Surface Phosphate Phases Based on XPS

As shown in Table 6, there are a number of crystalline phosphate phases found in the surface layers of the residues. In the untreated and unleached fraction, only a few phases were identified. After leaching, and with subsequent improvement in detection limit, some small quantities of apatite family (e.g. $\text{Ca}_5(\text{PO}_4)_3\text{OH}$, $\text{Ca}_5(\text{PO}_4)_3\text{Cl}$) and tertiary metal phosphate ($\text{Ca}_3(\text{PO}_4)_2$, $\text{Pb}_3(\text{PO}_4)_2$) minerals were seen. However, after treatment with the PO_4^{3-} , significant quantities of numerous Ca and Na phases were seen; including $\text{Ca}_5(\text{PO}_4)_3\text{OH}$, $\text{Ca}_5(\text{PO}_4)_3\text{Cl}$, $\text{Ca}_2\text{P}_2\text{O}_7$, $\text{Ca}_8\text{H}_2(\text{PO}_4)_6 \cdot 5\text{H}_2\text{O}$, CaHPO_4 , Na_3PO_4 , and $\text{Na}_4\text{P}_2\text{O}_7$. A number of the Ca-phosphates from the generalized Ca-phosphate precipitation reaction sequence²⁸ were seen (e.g. $\text{Ca}_8\text{H}_2(\text{PO}_4)_6 \cdot 5\text{H}_2\text{O}$, CaHPO_4 , and $\text{Ca}_5(\text{PO}_4)_3\text{OH}$). After leaching of the treated residues, these same Ca-phosphate phases were still seen at high levels; suggesting resistance to solubilization at pH of 4. The principal Pb phase that was observed in the treated and leached fraction was chloropyromorphite ($\text{Pb}_5(\text{PO}_4)_3\text{Cl}$).

Total Availability Leaching Behavior

The total availability leaching data for the untreated and treated residues are shown in Table 7. The table contains data on the concentration of the analytes in the leachate (not corrected for added weight of treatment additives) and a calculated stabilization fraction (corrected for added weight of treatment additives). The calculated stabilization fraction examines the percentage of the total available fraction in the untreated residue that was immobilized by the treatment process.

The dose of 1.2 moles of H_3PO_4 per kg of residue reduced the leachability of Al (75.5%), Ba (27.7%), Ca (6.8%), Cd (37.5%), Cl (7.7%), Cu (57.9%), Pb (99.5%) and Zn (28.2%). The larger reduction in Pb leaching agrees with the insoluble phases seen with XRPD and XPS.

The treatment increased the leachability of As (-3.8%), Hg (-3,979%), Mg (-19.9%), Si (-97.5%), and PO_4^{3-} (-2,385%). The Hg data reflect large changes in a very small leachate concentration number. The Mg and As data reflect likely substitution reactions (Ca for Mg, PO_4^{3-} for AsO_4^{3-}). The increased Si

concentrations reflect the dissolution of aluminosilicates by acid attack (H_3PO_4 addition). It is also clear that either not all of the PO_4^{3-} was reacted or that some of the phases that formed were not the most thermodynamically stable ones at the pH of the Total Availability Leaching Test.

The stabilization agent has a clear positive impact on the reduction of leaching of many divalent cations (Pb^{2+} , Cd^{2+} , Cu^{2+} , Zn^{2+}) in general agreement with the formation of insoluble phases which were seen with the various spectroscopic methods. These phases are insoluble and geochemically stable even under aggressive leaching conditions.

pH Dependent Leaching and Geochemical Modeling

Particular attention is given here to the components Ca^{2+} and Pb^{2+} , although similar behaviors were seen for Cd^{2+} , Cu^{2+} and Zn^{2+} . The leaching of Ca^{2+} and Pb^{2+} is shown in Figures 4 and 5, respectively. Each of the figures depicts pH-dependent leaching of the untreated and treated residues as well as the leachate concentrations in the modeled leachates when potential controlling solids were individually introduced as infinite solids in the model at each pH. As infinite solids, the candidate mineral dictates the activity of its components in the leachate in response to system pH and to all attendant aqueous phase complexation reactions. Table 8 identifies the top few controlling solids (based on their saturation indices) that were initially identified as well as other solids of interest; some of which were used as candidate infinite solids.

Ca^{2+} shows a clear reduction in leaching over the entire pH range after treatment (Figure 4a). As shown in Table 8, there are a number of phases that were excellent candidates as controlling solids; particularly CaHPO_4 (monetite) and $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$ (brushite). These were seen with XRPD, MAS-NMR and XPS in the treated residues whereas anhydrite and gypsum were less prevalent. As infinite solids, monetite and brushite each are able to depict Ca^{2+} leaching in the treated residues (Figure 4b). Despite their high saturation indices, $\text{Ca}_5(\text{PO}_4)_3\text{Cl}$ (calcium chloroapatite) and $\text{Ca}_5(\text{PO}_4)_3\text{OH}$ (calcium hydroxyapatite) (Figure 4c) both describe the general shape and pH-trend for Ca^{2+} leaching from the treated residues. While these phases were seen with XRPD, XPS, and MAS-NMR in the treated residues; they may be less suitable, but still plausible candidates for controlling solids.

The pH-dependent leaching of Pb^{2+} shows 1 to 2 log reduction in leaching after treatment (Figure 5a). As with Cu^{2+} and Cd^{2+} , a few candidate phases may control at each of the pH values (Figure 5b). These phases include apatite and tertiary metal phosphates ideal solid solutions (e.g. $(\text{Pb}_2,\text{Ca})(\text{PO}_4)_2$, $(\text{Pb},\text{Ca}_4)(\text{PO}_4)_3\text{Cl}$). The end member $\text{Pb}_5(\text{PO}_4)_3\text{Cl}$ (chloropyromorphite) is a controlling solid (Figure 5c) and is present in the treated and leached fraction. PbHPO_4 is also not a likely candidate.

Stabilization Reaction Pathway Kinetics and Products

The typical “ideal” solution phase reaction sequence when PO_4^{3-} is titrated into a Ca-salt solution involves the sequential formation of $\text{Ca}_9(\text{PO}_4)_6$ (non-stoichiometric amorphous calcium phosphate), $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$ (brushite), CaHPO_4 (monetite), $\text{Ca}_8\text{H}_2(\text{PO}_4)_6 \cdot 5\text{H}_2\text{O}$ (octacalcium phosphate), and then $\text{Ca}_5(\text{PO}_4)_3\text{OH}$ (hydroxyapatite); the thermodynamically most stable reaction product.²⁸ This sequence of nucleation and crystallite growth from supersaturated solutions is dependent upon system pH, temperature, the presence of “seed” crystals or catalytic surfaces, and reaction kinetics.²⁶ Intermediates are typically “active”, geochemically labile, and dependent upon reaction kinetics. Under ideal conditions, hydroxyapatite is the most thermodynamically stable end product over a fairly wide pH range (e.g. 4 to above 8).²⁶

The more complex stabilization system studied here is similar in principal to the one just described. PO_4^{3-} is titrated into a Ca-salt dominated waste. While the L/S ratio is much less than the “ideal” system, there is evidence that the same reaction sequence is observed here. The minerals brushite, monetite and calcium hydroxyapatite were seen in the treated residues with XRPD, MAS-NMR or XPS. Data also suggest that the initial 10 minute mixing scenario at pH values above 12 was not sufficient time to allow for complete conversion of all Ca-phosphates to apatites. Not only were intermediaries seen, but subsequent paragenetic transformations occurred during the seven hours of the Total Availability Leaching test at pH 7 and then 4. To optimize the stabilization process, more process water and longer reaction times might be preferred. Nevertheless, despite the short reaction times, significant reductions in metals leachability and formations of more stable reaction products were seen. For instance, the dissolution of calcium hydroxyapatite in the presence of Pb^{2+} and the subsequent formation of “mature” lead chloropyromorphite can take place on the order of minutes to hours provided liquid-to-solid ratios are high and pH is in the neutral region.^{17,18,19,20}

The pH-dependent leaching modeling shows that for Cd^{2+} , Cu^{2+} , Pb^{2+} and Zn^{2+} ; ideal solid solutions of Ca-apatites (both hydroxyapatite and chloroapatite) and whitlockite were found to adequately describe pH-dependent leaching. Neither Ca-apatites nor whitlockite controlled Ca^{2+} leaching; yet these phases were detected with XRPD, XPS, and MAS-NMR; particularly the highly substituted apatite mineral chlorellestadite. It may be reasonable to assume that the solid solutions that were found to control leaching (e.g. $(\text{Cd}, \text{Ca}_4)(\text{PO}_4)_3\text{OH}$; $(\text{Cu}, \text{Ca}_4)(\text{PO}_4)_3\text{OH}$, $(\text{Pb}, \text{Ca}_4)(\text{PO}_4)_3\text{OH}$) were in fact present and controlling leaching but that the degree of isostructural substitution was small enough as to not interfere with their detection using crystallographic or nearest-neighbor spectroscopic signatures.

This is consistent with the premise that major-minor cation solid solutions limit the concentration of the minor component to levels below saturation of the minor cation end member.⁶³ Formation of these types of solid solutions allows for the “burial” of the minor cation in the Ca-apatites or whitlockite. These solid solutions can be easily formed from saturated solutions^{34,35} and it is reasonable to infer that this process occurred here.

The very small particle sizes of the reaction products as seen with STEM (100-5,000 nm) suggests that Ostwald ripening processes must also be considered. Nanometer-sized crystallites are many orders of magnitude more soluble than larger, ripened crystals.²⁸ Such phenomenon have been theorized⁶⁴ and modelled^{65,66} for Ca-phosphates. At crystallite sizes less than 500 nm, particle interfacial tensions increase solubilities exponentially.^{28,68} It is therefore also possible that some of the positive saturation indices seen for some of the major cation end members could be explained by incomplete ripening and overly “active” small crystal solubilities. If this is the case, then, the allowance for longer reaction times and more process water would ensure crystallite growth, aggregation, and maturation. This would help further decrease equilibrium leachate concentrations of Cd^{2+} , Cu^{2+} , Pb^{2+} , and Zn^{2+} and further increase the fraction stabilized during treatment.

Implications for the Waste-to-Energy Industry

Chemical stabilization of dry scrubber residue using soluble phosphate is an effective means of immobilizing divalent metals in the waste. The treatment process holds promise for the industry. Knowledge about the fundamental immobilization mechanism allows for further optimization of the process. Successful identification of geochemically stable and insoluble reaction products using numerous spectroscopic methods confirms the role of the apatite mineral family as the dominant reaction product. Geochemical modeling also showed the importance of these minerals in controlling leaching of divalent metals. Such modeling techniques can be used as predictive tools for refining treatment

formulations, examining long term disposal behavior of treated residues, and developing management strategies for the treated residues.

CONCLUSIONS

The use of soluble orthophosphate as a heavy metal chemical stabilization agent was evaluated for a calcium-based scrubber residue from the combustion of municipal solid waste. At an experimental dose of 1.2 moles of H_3PO_4 per kg of residue, the reduction in the fraction available for leaching (using the Total Availability Leaching test) is 38% for Cd, 58% for Cu, 99% for Pb and 28% for Zn. pH-dependent leaching (pH 4,6,8) showed that the treatment was able to reduce equilibrium concentrations by 0.5 to 3 log units for many of these metals; particularly Pb. Numerous spectroscopic techniques were used to identify stabilization reaction mechanisms and reaction products both prior to and after Total Availability Leaching. Depth profiling of particles with secondary ion mass spectroscopy (SIMS) suggests that stabilization is by discrete heterogeneous phases precipitation rather than by adsorption. Scanning transmission electron microscopy/x-ray microanalysis (STEM/XRM), x-ray powder diffraction (XRPD), magic angle spinning-nuclear magnetic resonance (MAS-NMR), and x-ray photoelectron spectroscopy (XPS) suggest that the insoluble metal phosphate reaction products are small (nm-sized) crystalline and amorphous precipitates and that calcium phosphates, tertiary metal phosphates, and apatite family minerals are dominant reaction products. Observed phases include $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$ (brushite), CaHPO_4 (monetite), $\beta\text{-Ca}_3(\text{PO}_4)_2$ (whitlockite), $\text{Ca}_5(\text{PO}_4)_3\text{OH}$ (hydroxyapatite); $\text{CaZn}_2(\text{PO}_4)_2$; and $\text{Pb}_5(\text{PO}_4)_3\text{Cl}$ (lead chloropyromorphite); many of which are geochemically stable. The geochemical thermodynamic equilibrium model MINTEQA2 was modified to include both extensive phosphate minerals and ideal divalent cation binary solid solutions for modeling solid phase control of leaching. Both end members (e.g. CaHPO_4 , $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$) and ideal solid solutions (e.g. $(\text{Pb,Ca})_3(\text{PO}_4)_3\text{Cl}$, $\text{CaZn}_2(\text{PO}_4)_2 \cdot 2\text{H}_2\text{O}$) were seen to act as controlling solids for Ca^{2+} , Zn^{2+} , Pb^{2+} , Cu^{2+} , and Cd^{2+} . The formation of solid solutions is both plausible and highly likely in this system and describes a mechanism whereby minor cation components (e.g. Cd^{2+} , Cu^{2+} , Pb^{2+} , Zn^{2+}) are "buried" in the precipitating calcium phosphate reaction product. However, issues related to Ostwald ripening and small reaction product particle size may also explain some of the observed leaching behavior. Soluble phosphate is an effective stabilization agent for divalent metal cations in waste materials such as scrubber residues.

ACKNOWLEDGEMENTS

This work was supported by a research contract from Wheelabrator Environmental Systems Inc. and Kurita Water Industries Ltd. We thank Nan Collins, Dr. Henri Gaudette and Dr. Ted Loder of UNH; Dr. Milenko Markovic of NIST; George Bruno of AMRAY Inc.; Dr. Sheldon Landsberger and Dr. Wesley Wu of the University of Illinois at Champaign-Urbana; Brian Hart of the University of Western Ontario; Rusty Foster and Bud Berry of Resource Laboratories Inc.; and Tim Wilson of Eastern Analytical Inc. for their assistance in this effort. The financial support for the Analytical Shared Experimental Facility at the Center for Materials Science and Engineering at MIT comes from NSF grant DMR90-22933.

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Table 1. Some Divalent Metal Phosphate Minerals and Their Solubility Products

Mineral Name	Dissolution Reaction		-Log K _{sp}	ΔG _f ^o	Reference
<u>Apatites</u>					
Hydroxyapatite	$\text{Ca}_5(\text{PO}_4)_3\text{OH} + \text{H}^+$	$\rightleftharpoons 5\text{Ca}^{2+} + 3\text{PO}_4^{3-} + \text{H}_2\text{O}$	38.15	-6,279.0	(a)
Chloroapatite	$\text{Ca}_5(\text{PO}_4)_3\text{Cl}$	$\rightleftharpoons 5\text{Ca}^{2+} + 3\text{PO}_4^{3-} + \text{Cl}^-$	46.89	-6,223.0	(b)
Hydroxypyromorphite	$\text{Pb}_5(\text{PO}_4)_3\text{OH} + \text{H}^+$	$\rightleftharpoons 5\text{Pb}^{2+} + 3\text{PO}_4^{3-} + \text{H}_2\text{O}$	62.80	-3,774.0	(b)
Chloropyromorphite	$\text{Pb}_5(\text{PO}_4)_3\text{Cl}$	$\rightleftharpoons 5\text{Pb}^{2+} + 3\text{PO}_4^{3-} + \text{Cl}^-$	84.43	-3,791.5	(b)
$\text{Cd}_5(\text{PO}_4)_3\text{OH}$	$\text{Cd}_5(\text{PO}_4)_3\text{OH} + \text{H}^+$	$\rightleftharpoons 5\text{Cd}^{2+} + 3\text{PO}_4^{3-} + \text{H}_2\text{O}$	42.49	-3,924.0	(a)
$\text{Cd}_5(\text{PO}_4)_3\text{Cl}$	$\text{Cd}_5(\text{PO}_4)_3\text{Cl}$	$\rightleftharpoons 5\text{Cd}^{2+} + 3\text{PO}_4^{3-} + \text{Cl}^-$	49.66	-3,859.0	(b)
$\text{Zn}_5(\text{PO}_4)_3\text{OH}$	$\text{Zn}_5(\text{PO}_4)_3\text{OH} + \text{H}^+$	$\rightleftharpoons 5\text{Zn}^{2+} + 3\text{PO}_4^{3-} + \text{H}_2\text{O}$	49.10	-4,309.0	(c)
$\text{Zn}_5(\text{PO}_4)_3\text{Cl}$	$\text{Zn}_5(\text{PO}_4)_3\text{Cl}$	$\rightleftharpoons 5\text{Zn}^{2+} + 3\text{PO}_4^{3-} + \text{Cl}^-$	37.53	-4,137.0	(a)
$\text{Cu}_5(\text{PO}_4)_3\text{OH}$	$\text{Cu}_5(\text{PO}_4)_3\text{OH} + \text{H}^+$	$\rightleftharpoons 5\text{Cu}^{2+} + 3\text{PO}_4^{3-} + \text{H}_2\text{O}$	51.62	-6,279.0	(c)
$\text{Cu}_5(\text{PO}_4)_3\text{Cl}$	$\text{Cu}_5(\text{PO}_4)_3\text{Cl}$	$\rightleftharpoons 5\text{Cu}^{2+} + 3\text{PO}_4^{3-} + \text{Cl}^-$	53.96	-3,168.0	(a)
<u>Tertiary Metal Phosphates</u>					
Low Whitlockite	$\beta\text{-Ca}_3(\text{PO}_4)_2$	$\rightleftharpoons 3\text{Ca}^{2+} + 2\text{PO}_4^{3-}$	32.69	-3,884.8	(b)
$\text{Pb}_3(\text{PO}_4)_2$	$\text{Pb}_3(\text{PO}_4)_2$	$\rightleftharpoons 3\text{Pb}^{2+} + 2\text{PO}_4^{3-}$	44.36	-2,364.0	(d)
$\text{Zn}_3(\text{PO}_4)_2$	$\text{Zn}_3(\text{PO}_4)_2$	$\rightleftharpoons 3\text{Zn}^{2+} + 2\text{PO}_4^{3-}$	27.11	-2,633.4	(b)
$\text{Cu}_3(\text{PO}_4)_2$	$\text{Cu}_3(\text{PO}_4)_2$	$\rightleftharpoons 3\text{Cu}^{2+} + 2\text{PO}_4^{3-}$	36.85	-2,051.6	(b)
$\text{Cd}_3(\text{PO}_4)_2$	$\text{Cd}_3(\text{PO}_4)_2$	$\rightleftharpoons 3\text{Cd}^{2+} + 2\text{PO}_4^{3-}$	32.60	-2,456.3	(b)
$\text{Mg}_3(\text{PO}_4)_2$	$\text{Mg}_3(\text{PO}_4)_2$	$\rightleftharpoons 3\text{Mg}^{2+} + 2\text{PO}_4^{3-}$	24.38	-3,538.8	(b)
<u>Tetra Metal Phosphates</u>					
Hilgenstockite	$\text{Ca}_4\text{O}(\text{PO}_4)_2 + 2\text{H}^+$	$\rightleftharpoons 4\text{Ca}^{2+} + 2\text{PO}_4^{3-} + \text{H}_2\text{O}$	17.36	-4,588.0	(b)
$\text{Pb}_4\text{O}(\text{PO}_4)_2$	$\text{Pb}_4\text{O}(\text{PO}_4)_2 + 2\text{H}^+$	$\rightleftharpoons 4\text{Pb}^{2+} + 2\text{PO}_4^{3-} + \text{H}_2\text{O}$	36.86	-2,582.8	(b)
<u>Other Phosphate Minerals</u>					
AlPO_4	AlPO_4	$\rightleftharpoons \text{Al}^{3+} + \text{PO}_4^{3-}$	17.00	-1,601.2	(b)
Monetite	CaHPO_4	$\rightleftharpoons \text{Ca}^{2+} + \text{PO}_4^{3-} + \text{H}^+$	19.09	-1,681.2	(e)
Brushite	$\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$	$\rightleftharpoons \text{Ca}^{2+} + \text{PO}_4^{3-} + 2\text{H}_2\text{O} + \text{H}^+$	18.93	-2,154.8	(b)
Cornetite	$\text{Cu}_3\text{PO}_4(\text{OH})_3 + 3\text{H}^+$	$\rightleftharpoons 3\text{Cu}^{2+} + \text{PO}_4^{3-} + 3\text{H}_2\text{O}$	5.94	-1,567.7	(c)
Libethenite	$\text{Cu}_2\text{PO}_4\text{OH} + \text{H}^+$	$\rightleftharpoons 2\text{Cu}^{2+} + \text{PO}_4^{3-} + \text{H}_2\text{O}$	14.00	-1,204.9	(c)
Pseudomalachite	$\text{Cu}_5(\text{PO}_4)_2(\text{OH})_4 + 4\text{H}^+$	$\rightleftharpoons 5\text{Cu}^{2+} + 2\text{PO}_4^{3-} + 4\text{H}_2\text{O}$	19.83	-2,771.9	(c)
Corkite	$\text{PbFe}_3(\text{PO}_4)(\text{OH})_6\text{SO}_4 + 6\text{H}^+$	$\rightleftharpoons \text{Pb}^{2+} + 3\text{Fe}^{3+} + \text{PO}_4^{3-} + \text{SO}_4^{2-} + 6\text{H}_2\text{O}$	28.66	-3,388.2	(c)
Spencerite	$\text{Zn}_4(\text{PO}_4)_2(\text{OH})_2\text{AlPO}_4 \cdot 3\text{H}_2\text{O} + 2\text{H}^+$	$\rightleftharpoons 4\text{Zn}^{2+} + 2\text{PO}_4^{3-} + 5\text{H}_2\text{O}$	24.77	-3,953.0	(c)
Zn Rockbridgite	$\text{ZnFe}_4(\text{PO}_4)_3(\text{OH})_5 + 5\text{H}^+$	$\rightleftharpoons \text{Zn}^{2+} + 4\text{Fe}^{3+} + 3\text{PO}_4^{3-} + 5\text{H}_2\text{O}$	68.55	-4,799.0	(c)
Scholzite	$\text{CaZn}_2(\text{PO}_4)_2 \cdot 2\text{H}_2\text{O}$	$\rightleftharpoons \text{Ca}^{2+} + 2\text{Zn}^{2+} + 2\text{PO}_4^{3-} + 2\text{H}_2\text{O}$	34.10	-3,553.5	(c)
Tarbuttite	$\text{Zn}_2(\text{PO}_4)\text{OH} + \text{H}^+$	$\rightleftharpoons 2\text{Zn}^{2+} + \text{PO}_4^{3-} + \text{H}_2\text{O}$	12.55	-1,621.7	(c)
Faustite	$\text{ZnAl}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4\text{H}_2\text{O} + 8\text{H}^+$	$\rightleftharpoons \text{Zn}^{2+} + 6\text{Al}^{3+} + 4\text{PO}_4^{3-} + 12\text{H}_2\text{O}$	65.70	10,355.4	(c)
Plumbogummite	$\text{PbAl}_3(\text{PO}_4)_2(\text{OH})_5 \cdot \text{H}_2\text{O} + 5\text{H}^+$	$\rightleftharpoons \text{Pb}^{2+} + 3\text{Al}^{3+} + 2\text{PO}_4^{3-} + 6\text{H}_2\text{O}$	29.36	-5,108.7	(c)
Hinsdalite	$\text{PbAl}_3(\text{PO}_4)(\text{SO}_4)(\text{OH})_6 + 6\text{H}^+$	$\rightleftharpoons \text{Pb}^{2+} + 3\text{Al}^{3+} + \text{PO}_4^{3-} + \text{SO}_4^{2-} + 6\text{H}_2\text{O}$	15.10	-4,753.0	(d)
Tsumebite	$\text{CuPb}_2(\text{PO}_4)(\text{OH})_3 \cdot 3\text{H}_2\text{O} + 3\text{H}^+$	$\rightleftharpoons \text{Cu}^{2+} + 3\text{Pb}^{2+} + \text{PO}_4^{3-} + 6\text{H}_2\text{O}$	9.36	-2,478.6	(d)

^a Estimated by method of Nriagu⁵⁵^d Rickard and Nriagu⁵⁷^b Veillard and Tardy⁵⁶^c Wagman et al.⁵⁸^e Nriagu⁷

Table 2. Total Elemental Composition for Dry Scrubber Residue

Element	Concentration mg/kg	error	Element	Concentration mg/kg	error
Ag	19.6	± 0.3	Mn	385.9	± 19.0
Al	29,600	$\pm 2,100$	Mo	29.2	± 3.5
As	46.0	± 4.8	Na	14,500	± 900
Au	0.25	± 0.01	Nd	5.55	± 0.79
Ba	449.3	± 95	Ni	49.5	± 8.4
Br	1,550	± 130	O	~300,000	
C	~70,000		P	2,100	± 200
Ca	354,400	$\pm 11,400$	Pb	1,990	± 6
Cd	99.3	± 6.8	Rb	26.9	± 1.8
Ce	12.8	± 0.4	S	19,800	$\pm 1,000$
Cl	118,400	$\pm 6,000$	Sb	473.5	± 28.1
Co	9.43	± 0.13	Sc	1.88	± 0.02
Cr	131.8	± 1.3	Se	3.07	± 0.52
Cs	1.42	± 0.08	Si	42,100	$\pm 4,900$
Cu	362.1	± 2.5	Sm	0.91	± 0.09
Dy	1.53	± 0.52	Sr	< 538	
Eu	0.25	± 0.04	Ta	0.36	± 0.05
Fe	6,570	± 107	Tb	< 0.13	
Hf	2.26	± 0.07	Th	1.93	± 0.06
Hg	31.4	± 0.3	Ti	6,090	± 400
In	0.79	± 0.07	U	< 1.80	
I	25.6	± 13.1	V	< 12.3	
K	< 7,500		W	5.78	± 0.72
La	6.83	± 0.77	Yb	< 0.41	
Mg	5,200	$\pm 1,700$	Zn	11,770	± 70
			Zr	125.5	± 28.1

Table 3. Particle Atomic Concentrations (%) Based on STEM-XRM Analyses

Fraction	Particle Number	O	Mg	Al	Si	P	S	Cl	K	Ca	Fe	Zn	Pb
Treated and Unleached	1	39.1	-	13.1	-	-	-	30.2	-	17.6	-	-	-
	2	59.7	-	5.1	-	-	-	10.8	-	24.0	-	-	-
	3	78.3	-	-	-	-	9.9	0.3	-	11.5	-	-	-
	4	31.9	-	-	0.8	7.2	5.8	12.2	-	42.8	-	-	-
	5	42.0	2.4	3.3	6.3	4.2	2.3	13.5	1.1	19.2	-	-	-
	6	45.7	0.8	0.9	1.3	2.1	15.5	4.8	0.8	27.3	-	-	-
	7	32.0	0.6	5.6	0.5	0.8	1.9	-	-	58.0	-	-	-
	8	54.6	-	-	-	-	-	22.6	0.6	22.0	-	-	-
	9	55.9	-	-	-	-	-	21.6	-	22.6	-	-	-
	10	14.6	5.3	2.9	4.4	7.0	6.1	16.5	0.8	42.4	-	-	-
Treated and Leached	1	71.2	0.9	9.8	1.9	4.9	2.8	-	-	6.1	0.7	0.7	-
	2	40.1	0.8	-	-	19.9	3.6	-	-	31.3	1.5	2.2	-
	3	17.7	-	5.2	-	28.1	1.8	1.6	-	41.1	1.3	2.4	-
	4	40.2	-	14.8	16.9	13.8	-	-	-	7.9	1.4	3.0	-
	5	73.4	-	3.0	-	10.1	1.0	-	-	10.7	-	0.7	-
	6	62.3	-	9.5	0.5	13.9	1.0	-	-	7.1	1.3	1.6	-
	7	64.3	0.8	7.4	2.6	10.0	0.6	-	-	5.7	2.2	1.9	-
	8	51.8	-	12.5	-	19.5	0.9	-	-	5.6	7.2	1.4	-
	9	67.5	0.6	3.9	-	12.4	0.9	-	-	12.2	-	0.7	-
	10	54.1	-	19.0	18.3	-	-	-	1.5	-	-	-	-

Table 4. Possible Phosphate Crystalline Phases [and Range in FOM] in the Scrubber Residue Fractions Based on XRPD^a

Element	Fraction			
	Untreated and Unleached	Untreated and Leached	Treated and Unleached	Treated and Leached
Ca	$\text{Ca}_3(\text{P,Si,S})_3\text{O}_{12}(\text{Cl,OH,F})$ [11.4-19.3]	—	$\text{Ca}_3(\text{P,Si,S})_3\text{O}_{12}(\text{Cl,OH,F})$ [17.6]	$\text{Ca}_3\text{Mg}_2(\text{PO}_4)_4$ [19.2-19.6]
	$\text{Ca}_3(\text{PO}_4)_3\text{OH}$ [16.6-17.6]	—	$\alpha\text{-CaZn}_2(\text{PO}_4)_2$ [13.6-14.0]	$\text{Ca}_3(\text{PO}_4)_2 \cdot x\text{H}_2\text{O}$ [14.4-16.6]
	$\text{Ca}_{10}(\text{PO}_4)_3(\text{CO}_3)(\text{OH})_2$ [17.6-18.3]	—	$\text{Ca}_{10}(\text{PO}_4)_3(\text{CO}_3)_3(\text{OH})_2$ [14.1]	$\alpha\text{-CaZn}_2(\text{PO}_4)_2$ [12.7]
	CaHPO_4 [17.5-22.9]	—	$\text{CaFe}_{12}(\text{PO}_4)_8(\text{OH})_{12} \cdot 4\text{H}_2\text{O}$ [13.3-13.4]	$\text{Ca}_2(\text{P,Si,S})_3\text{O}_{12}(\text{Cl,OH,F})$ [15.5]
Al	—	$\text{Al}_2(\text{PO}_4)(\text{OH})_3$ [16.3-17.2]	AlPO_4 [20.7-21.3]	AlPO_4 [15.0-21.1]
	—	—	—	$\text{AlPO}_4 \cdot x\text{H}_2\text{O}$ [11.0]
Na	$\text{NaAl}_3(\text{PO}_4)_2(\text{OH})_4 \cdot 2\text{H}_2\text{O}$ [11.8-17.4]	—	—	$\text{Al}_2(\text{PO}_4)(\text{OH})_3 \cdot \text{H}_2\text{O}$ [15.0]
	—	—	—	$\text{NaAl}_3(\text{PO}_4)_2(\text{OH})_4 \cdot 2\text{H}_2\text{O}$ [11.3-16.9]
Zn	—	—	$\text{Zn}_3(\text{PO}_4)_2 \cdot 2\text{H}_2\text{O}$ [17.5]	$\chi\text{-Na}_3\text{PO}_4$ [16.8-21.0]
	—	—	$\text{ZnHPO}_4 \cdot \text{H}_2\text{O}$ [14.5-16.1]	NaCaPO_4 [15.6-19.7]
Fe	—	—	$\text{Fe}_3(\text{PO}_4)_3(\text{OH})_5 \cdot \text{H}_2\text{O}$ [21.1]	$\alpha\text{-NaMgPO}_4$ [16.8-23.1]
	—	—	$\text{FePO}_4 \cdot \text{H}_2\text{O}$ [15.5-17.4]	$\text{Zn}_3(\text{PO}_4)_2$ [22.6]
K	—	—	FePO_4 [18.2-19.3]	$\text{Fe}_3(\text{PO}_4)_4(\text{OH})_2 \cdot 2\text{H}_2\text{O}$ [21.3]
	—	—	$(\text{Fe,Mn})\text{PO}_4$ [17.1-18.9]	$\text{Fe}_3(\text{PO}_4)_2(\text{OH})_2$ [18.2]
Mg	—	—	$\text{KPb}_4(\text{PO}_4)_3$ [16.0-18.4]	—
	—	—	$\text{KPb}_3(\text{PO}_4)_2(\text{OH})_5 \cdot \text{H}_2\text{O}$ [13.2-16.4]	$\text{KPb}_4(\text{PO}_4)_3$ [11.7]
Cu	—	—	—	$\text{KPb}_3\text{PO}_4(\text{SO}_4)_2$ [17.1]
	—	—	—	—
Cd	$\text{Cd}_3(\text{PO}_4)_3\text{Cl}$ [11.0]	—	$\text{Cd}_3(\text{PO}_4)_2$ [17.9]	$\text{CuFe}_2(\text{PO}_4)_2(\text{OH})_2$ [14.9-17.5]
	—	—	—	$\text{Cu}_3(\text{PO}_4)(\text{OH})_3$ [14.6-24.4]
	—	—	—	$\text{Cd}_3(\text{PO}_4)_3\text{Cl}$ [15.5]
	—	—	—	$\text{Cd}_3(\text{PO}_4)_2$ [22.1]

^aWithin any one element and fraction category, the possible mineral phases are listed vertically by decreasing likelihood of presence (based on average FOM).

Table 5. ³¹P MAS NMR Data and Analysis

Fraction	Component	δ_{iso}	δ_{11}	δ_{22}	δ_{33}	$ \Delta\delta $	% Comp	Probable Phases	Notes
Treated, Unleached	1	-0.30	-27.3	-1.5	27.9	42	45.8	-	2kHz ^a
	2	-1.43	-57.1	-9.8	62.6	96	54.2	-	
	1	-0.67	-36.5	-6.8	41.2	63	60.1	CaHPO ₄ •2H ₂ O, CaHPO ₄ , Ca ₅ (PO ₄) ₃ OH, α -CaZn ₂ (PO ₄) ₂	4kHz ^a
	2	-0.98	-104.4	-18.4	119.9	181	39.9	Ca ₂ P ₂ O ₇	
Treated, Leached	1	-0.8	-49.5	-10.8	57.9	88	100	-	6kHz ^a
	1	-0.95	-62.1	-2.3	61.6	94	72.9	CaHPO ₄ •2H ₂ O	6kHz ^b
	2	-9.16	-55.5	-55.4	83.5	139	27.1	Ca ₂ P ₂ O ₇	

^aSpectra acquired with 10 μ s, 90° ³¹P pulse^bSpectra acquired with 4 μ s, 90° ³¹P pulse

Table 6. Possible Phosphate Mineral Phases in the Scrubber Residue Fractions Based on XPS

Element	Fraction		
	Untreated and Unleached	Untreated and Leached	Treated and Unleached
Al ^b	(89,800 mg/Kg) NA ^c	(178,700 mg/Kg) AlPO ₄	(67,600 mg/Kg) AlPO ₄
Ca	(250,200 mg/Kg) NA	(42,700 mg/Kg) Ca ₅ (PO ₄) ₃ OH Ca ₅ (PO ₄) ₃ Cl β-Ca ₃ (PO ₄) ₂	(270,900 mg/Kg) Ca ₅ (PO ₄) ₃ OH Ca ₅ (PO ₄) ₃ Cl Ca ₂ P ₂ O ₇ Ca ₈ H ₂ (PO ₄) ₆ •5H ₂ O CaHPO ₄
Na	(57,700 mg/Kg) Na ₄ P ₂ O ₇	(ND) ^d	(54,400 mg/Kg) Na ₃ PO ₄ Na ₄ P ₂ O ₇
O	(239,300 mg/Kg) Na ₄ P ₂ O ₇	(502,100 mg/Kg) NA	(309,600 mg/Kg) Ca ₅ (PO ₄) ₃ OH Ca ₂ P ₂ O ₇ Na ₄ P ₂ O ₇
P	(ND) NA	(29,600 mg/Kg) AlPO ₄ Ca ₅ (PO ₄) ₃ OH Ca ₅ (PO ₄) ₃ Cl β-Ca ₃ (PO ₄) ₂ Pb ₃ (PO ₄) ₂	(34,900 mg/Kg) AlPO ₄ Ca ₅ (PO ₄) ₃ OH Ca ₅ (PO ₄) ₃ Cl Ca ₂ P ₂ O ₇ Ca ₈ H ₂ (PO ₄) ₆ •5H ₂ O CaHPO ₄ Na ₃ PO ₄ Na ₄ P ₂ O ₇
Pb	(16,000 mg/Kg) NA	(66,600 mg/Kg) Pb ₃ (PO ₄) ₂	(17,500 mg/Kg) Pb ₅ (PO ₄) ₃ Cl

^a Phases are listed alphabetically by first element.^b Surficial concentrations of the element in the indicated fraction are shown; concentrations based on XPS analysis and standard sensitivity factors.^c NA; no phosphate species assigned.^d ND; element not detected.

Table 7. Total Availability Leaching Data

Constituent	Leachate Concentration, mg/L		% of Available Fraction Stabilized Because of Treatment ^a
	Untreated	Treated	
Al	5.0	1.1	75.5
As	0.030	0.028	-3.8
Ba	2.0	1.3	27.7
Ca	1,540	1,290	6.8
Cd	0.600	0.337	37.5
Cl	522	433	7.7
Cr	<0.04	<0.04	0.0
Cu	0.66	0.25	57.9
Fe	<0.04	0.26	-
Hg	0.0012	0.044	-3,979
K	42	39	-
Mg	21.9	23.6	-19.9
Na	51.5	46	0.6
Pb	2.3	0.01	99.5
PO ₄ ³⁻	0.05	20.9	-2,385
Si	40	71	-97.5
SO ₄ ³⁻	113	100	1.8
Zn	41.5	26.8	28.2
Mass	-	-	2.9

^aCorrected for weight of H₃PO₄ added.

Table 8. Possible Controlling Solids and Their Saturation Indices

Component			pH		
			4	6	8
Ca ²⁺	Ranked	CaSO ₄	0.11	-0.07	-0.04
		CaHPO ₄	-0.03	-0.04	-0.49
		CaSO ₄ • 2H ₂ O	0.30	0.13	0.17
		CaHPO ₄ • 2H ₂ O	-0.21	-0.21	-0.66
	Other	Ca ₈ H ₂ (PO ₄) ₆ • 5H ₂ O	-28.07	-10.38	-4.60
		β-Ca ₃ (PO ₄) ₂	-5.37	1.77	4.98
		Ca ₅ (PO ₄) ₃ OH	-15.09	-2.48	4.26
		Ca ₅ (PO ₄) ₃ Cl	-10.81	-0.31	4.41
	Ranked	(Pb,Ca ₄)(PO ₄) ₃ Cl	0.28	5.09	9.20
		(Pb,Ca ₄)(PO ₄) ₃ OH	-6.40	0.46	6.52
		(Pb ₂ ,Ca)(PO ₄) ₂	-3.74	-0.84	0.95
		(Pb,Ca ₂)(PO ₄) ₂	-0.90	2.35	4.82
		(Pb ₃ ,Ca ₂)(PO ₄) ₃ OH	-8.12	-1.62	3.77
	Other	Pb ₅ (PO ₄) ₃ OH	-13.80	-8.37	-5.00
		Pb ₅ (PO ₄) ₃ Cl	3.15	6.53	7.95
		Pb ₃ (PO ₄) ₂	-6.72	-4.19	-3.06
		PbHPO ₄	-1.95	-2.31	-3.43

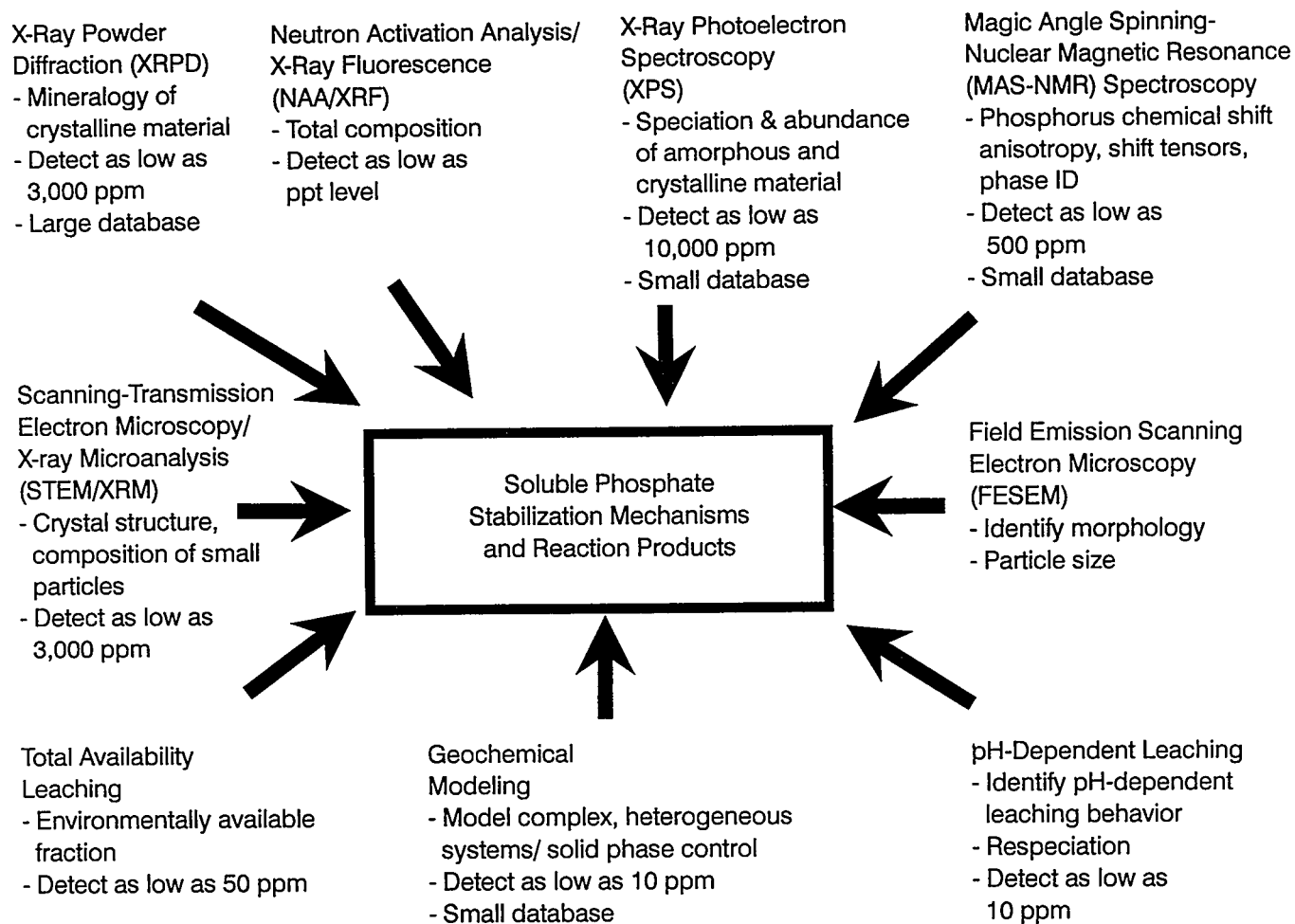


Figure 1. Schematic depicting approach used to identify stabilization reaction mechanisms and reaction products.

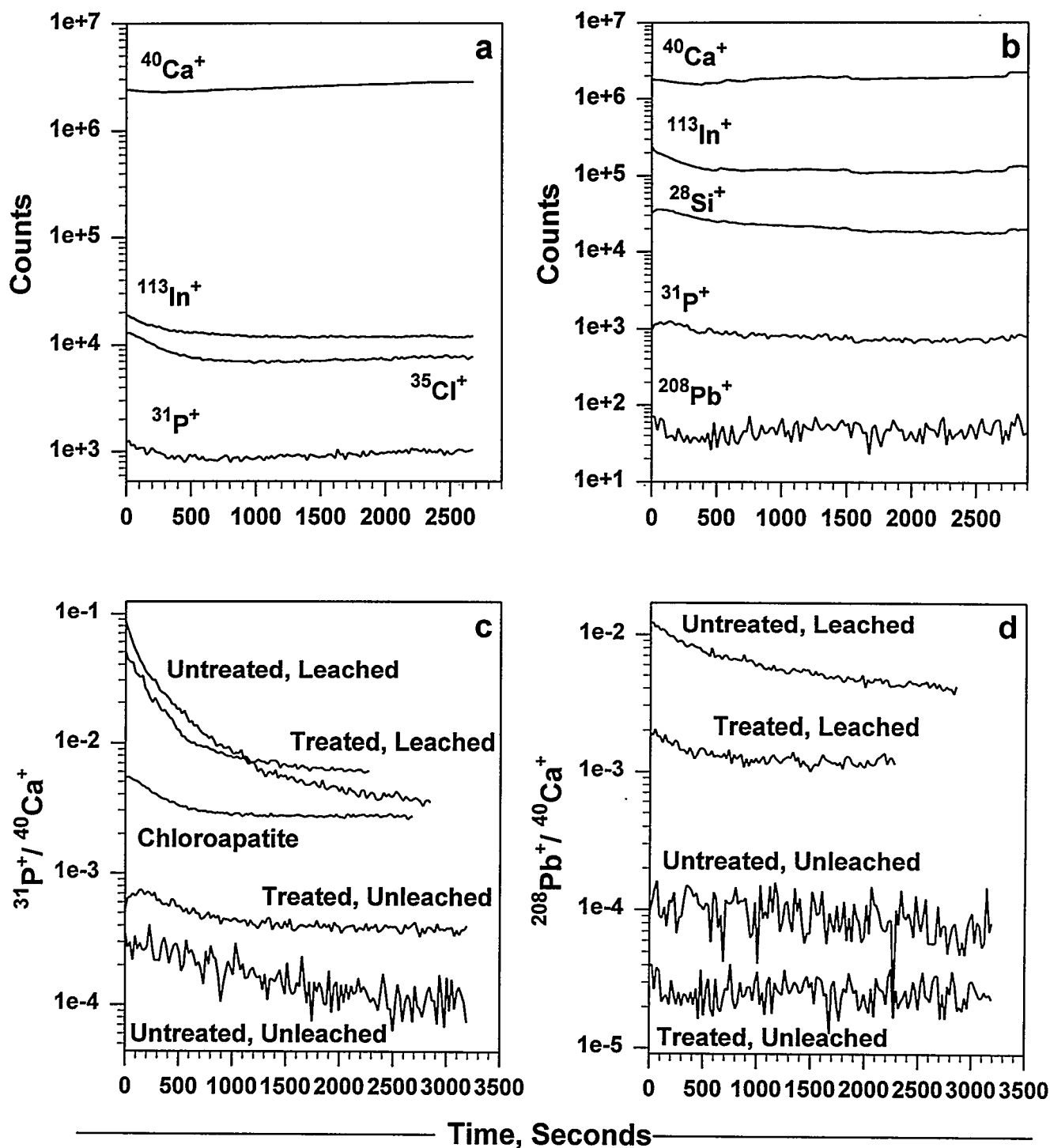


Figure 2. SIMS ion fragment depth profiles and ion fragment ratio depth profiles. (a) depth profiles for chloroapatite powder standard, (b) depth profiles for treated and leached fraction, (c) $^{31}\text{P}^+ / ^{40}\text{Ca}^+$ depth profiles, and (d) $^{208}\text{Pb}^+ / ^{40}\text{Ca}^+$ depth profiles.

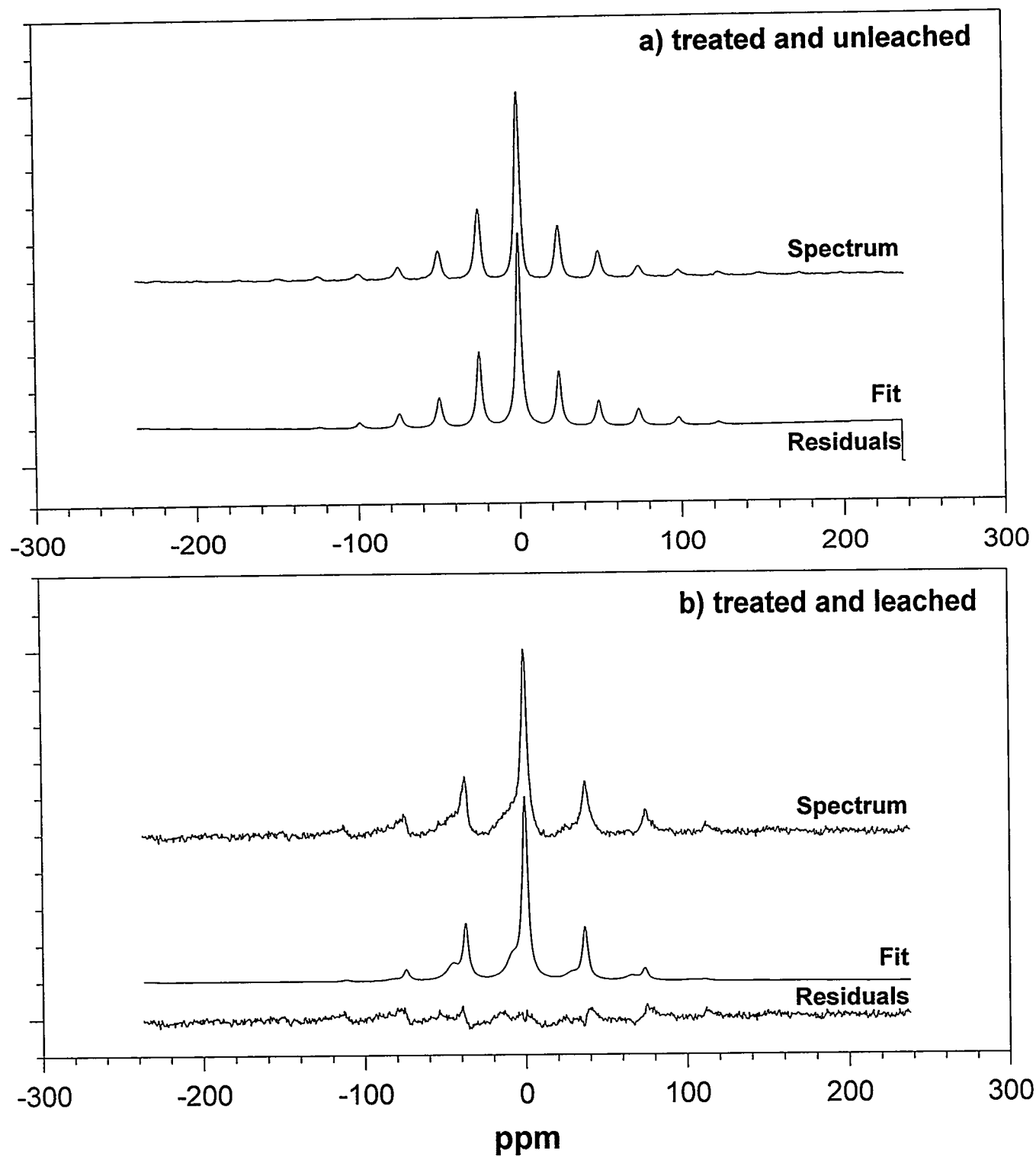


Figure 3. MAS-NMR spectra for (a) treated and unleached fraction and (b) treated and leached fraction.

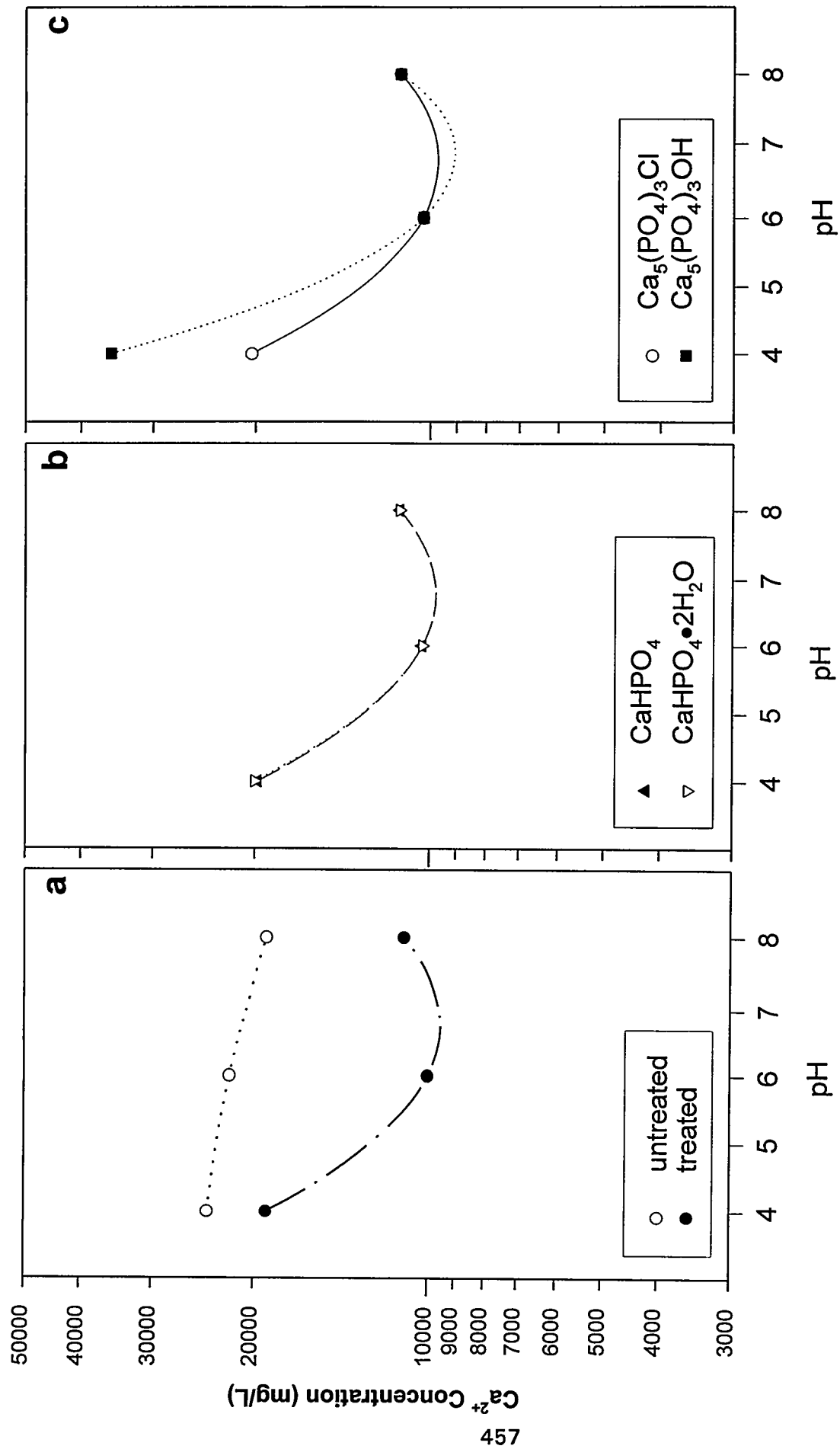


Figure 4. pH-dependent leaching plots for Ca²⁺, (a) untreated and treated plots, (b),(c) selected infinite solids plots.

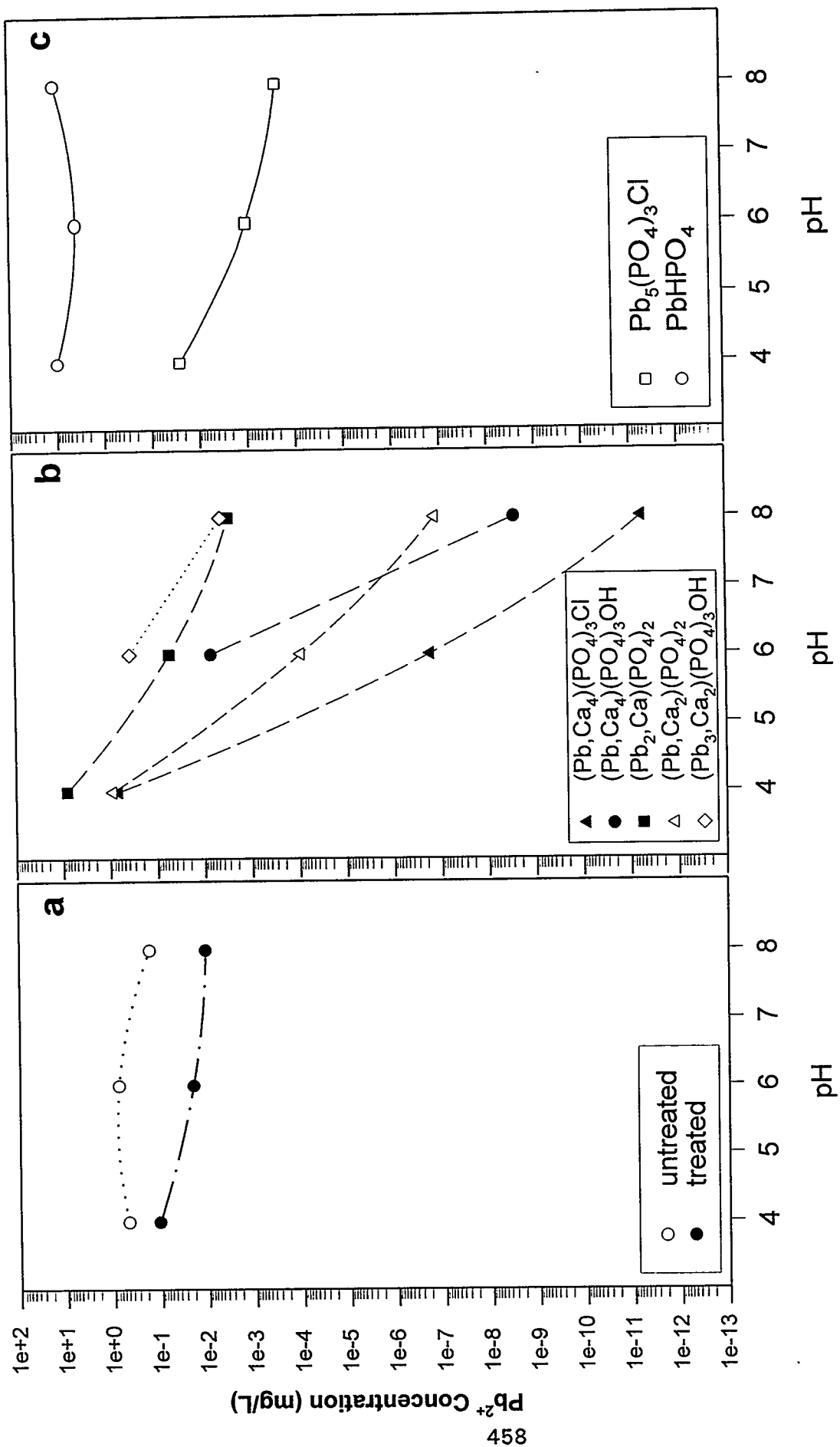


Figure 5. pH-dependent leaching plots for Pb^{2+} , (a) untreated and treated plots, (b),(c) selected infinite solids plot.

**A process for treatment of APC residues
from municipal solid waste incinerators: Preliminary results**

**Ole Hjelmar and Henrik Birch
VKI
Agern Allé 11
DK-2970 Hørsholm
Denmark**

INTRODUCTION

The problem of environmentally safe management of the residues from air pollution control (APC) systems at municipal solid waste (MSW) incinerators, particularly the residues from the semidry/dry acid gas cleaning processes (dry scrubber residues), has not yet been solved in a satisfactory and sustainable manner. These residues are in many cases simply stored indefinitely in big bags or they are landfilled under conditions that in the long term may not be able to prevent potentially harmful constituents from leaching and leaking into the environment. The APC residues, including fly ash, are in many countries classified as hazardous or special waste due to their high contents of soluble salts (particularly calcium chloride) and trace elements/heavy metals. The semidry/dry APC residues are strongly alkaline due to a content of excess lime, and the high pH favours the leaching of several contaminants, particularly lead.

This paper presents preliminary results of a study of a process for treatment of semidry/dry APC residues and fly ash from MSW incinerators. In the process the contaminants are partly removed, partly immobilized thus improving the above mentioned situation and allowing for subsequent safe management (i.e. utilization or landfilling) of the treated residues.

DESCRIPTION OF THE PROCESS

The primary objective of the study was to establish a treatment process which would render dry scrubber residue and fly ash from MSW incinerators acceptable for landfilling under sustainable conditions, i.e. without requiring total encapsulation or extended operation, management and aftercare. Another requirement was that any wastewater produced by the process should be treated in such a manner that it can be accepted for discharge into the sewer system or directly into a surface water body.

Numerous studies^{1,2,3,4} have demonstrated that it is virtually impossible to achieve the above mentioned objectives at a reasonable cost through direct solidification/stabilization or thermal treatment of raw scrubber residue. One of the major reasons for this is that the dry scrubber residues typically contain 25 to 50 percent of readily soluble salts (mainly calcium chloride) which will leach relatively fast from the solid matrix resulting from many solidification/stabilization processes. Cement-based solidification/stabilization techniques generally create highly alkaline porewater which tends to mobilize amphoteric components such as lead and zinc that are present in significant amounts in raw scrubber residues. In many thermal treatment processes partial (re)evaporation of both the chlorides and some of the trace elements will cause problems. It has also been demonstrated that chemical stabilization of raw dry scrubber residue alone or as a component of combined ash may immobilize lead, cadmium and certain other constituents of the scrubber residues rather effectively^{5,6,7}. One such example is the phosphate based WES-PHix ash stabilization process developed by Wheelabrator Environmental Systems Inc.⁸ Since these processes focus only on immobilization of the trace elements/heavy metals, the salts are relatively unaffected by the treatment and will leach unhindered from the stabilized products after landfilling. The process described in this paper is also, in part, based on phosphate fixation of some of the trace elements, but it differs significantly from those mentioned above because the additives are applied to an aqueous suspension of a washed product from which most of the soluble salts have been removed.

From an environmental perspective, a well buffered residue with a neutral to slightly alkaline pH in contact with water and a low content of soluble salts and leachable trace elements will often be preferable. The study described in this paper has been aimed at establishing a treatment process which is able to produce treated APC residues with such properties.

Since the presence of large amounts of readily soluble material in the dry scrubber residue is a major obstacle to the achievement of an acceptable result, the basic principle of the process developed in this study is removal of most of the soluble salts in an initial aqueous extraction of the residue followed by chemical stabilization of the extracted residue. The extraction and stabilization may be carried out simultaneously or in two (or more) separate stages. The latter is preferable since it ensures the most effective removal of salts from the product. Various extraction and treatment schemes have been investigated in laboratory and pilot scale. A pilot scale extraction unit was installed at an incinerator plant (KARA in Roskilde, Denmark) and used to test and partially optimize extraction and dewatering conditions (e.g. L/S, contact time, number of extraction steps, pH control vs. no control, addition of carbon dioxide). Trace elements were successfully removed from the extract by conventional methods (pH adjustment and TMT polishing). The salt containing treated extract may be discharged into a marine recipient or the salts (mainly calcium chloride) may be recovered. The solid remnant from the extraction was treated with various additives designed to immobilize specific trace elements, especially under conditions similar to those the treated residues may be expected to be subjected to in the future. The stabilization efficiency was tested and optimized using pH-static leaching procedures supported by hydrogeochemical modelling. The best performing stabilized residues were subjected to a more comprehensive test programme.

One of the most promising process configurations was a two-stage process in which the residue from a semidry APC process without precollection of fly ash was first extracted with water at a liquid to solid ratio (L/S) of approximately 3 l/kg in a continuously stirred tank. The slurry was then

passed through a filter press and the remnant collected on the filter was subsequently washed with an amount of water corresponding to $L/S = 4.6$ l/kg. The remnant was resuspended in an amount of water corresponding to $L/S = 3.1$ l/kg in a stirred tank, and an amount of phosphoric acid corresponding to approximately 35 kg H_3PO_4 /ton of raw scrubber residue (dry weight basis) was added. Carbon dioxide was then added to the stirred suspension by means of a diffuser placed at the bottom of the tank and used to maintain a pH of 9.0 in the suspension for 2 hours. The suspension was then transferred to the filter press, washed with an amount of water corresponding to $L/S = 3.2$ l/kg and subsequently dewatered by compression in the filterpress. On a dry weight basis, the amount of washed residue from the first stage of the process corresponds to approximately 720 kg/ton of raw scrubber residue and the amount of final product corresponds to 746 kg/ton of raw scrubber residue. The initial raw scrubber residue, the washed filter cake from the first extraction and the final product were subjected to leaching tests in order to assess and compare their quality.

The primary purpose of adding carbon dioxide to the suspension is to lower the pH of the suspension and the final product without losing alkalinity. The carbon dioxide reacts with the excess lime in the residue (relatively high in this particular scrubber residue = 15 percent, calculated as hydrated lime) to form calcium carbonate. The lower pH will lower the solubility of the amphoteric trace elements. Some of the trace elements may also form carbonates with low solubility. The addition of carbon dioxide alone (without phosphoric acid) produces a remnant with low leachability of many trace elements. If a full scale scrubber residue treatment facility is located at an incinerator plant, the carbon dioxide could be supplied by dispersing a sidestream of the flue gas through the suspended residue.

Although some test runs with recycling of washwater were performed, the water consumption has not been optimized. The total water consumption which corresponds to approximately 13.9 l/kg is too high and could probably be reduced to less than half that amount without significant changing the product quality. This is particularly important if there is a desire to recover the calcium chloride from the wastewater. The wastewater treatment process is comparable to the treatment processes normally used at wet scrubber systems. The sludge produced by the treatment of the wastewater from the process has relatively favourable landfilling properties.

PRELIMINARY RESULTS

The quality of the untreated scrubber residue, the washed residue and the treated scrubber residues was evaluated and compared in terms of leachability by subjecting each of the products to pH-static leaching tests at $L/S =$ approximately 5 l/kg and 100 l/kg, respectively. Some of the residues were also subjected to a two-step serial batch leaching test at $L/S = 0-2$ l/kg and 2-10 l/kg, respectively.

The pH-static leaching tests were carried out by contacting the residues with the appropriate amounts of demineralized water in covered (but not sealed) vessels for 24 hours. A constant pH of 5, 6, 7, 8, 9, 10 and 11, respectively, was maintained automatically in 7 parallel tests at each L/S value by feedback control and addition of the necessary amounts of HNO_3 and $NaOH$. The material was kept in suspension by continuous stirring with a paddle. At the end of the contact period the suspensions were filtered through 0.45 μm filters and subjected to chemical analysis (most elements

were determined by ICP-MS or ICP-AES). The tests carried out at L/S = 5 l/kg provide information about the leaching as a function of pH under conditions where several saturation phenomena are likely to occur, whereas the tests carried out at L/S = 100 l/kg represent the behaviour of the system when the conditions approach an availability controlled situation for many components.

The serial batch leaching test was carried out in accordance with the proposed European Standard compliance batch leaching test for leaching of granular waste materials and sludges, Procedure C (Draft European Standard prEN 12457⁹). The materials were leached with demineralized water in a closed bottle for 6 hours by end over end rotation at 10 rpm at L/S = 2 l/kg, the eluate was separated off by filtration through a 0.45 µm filter, new water was added to L/S = 8 l/kg and the leaching procedure was repeated for a period of 18 hours after which the second eluate was filtered. Both eluates were subsequently analyzed for the same parameters as the extracts from the pH-static tests. It is a requirement that the granular material to be tested must be < 10 mm and 90 % (w/w) must be < 4 mm. This requirement is of no concern in this case since all the residues consist of very fine particles (65 to 85 percent < 0.125 mm). This test in which the pH is controlled by the solid phase represents a more "natural" situation than the pH-static leaching tests. The results may with some caution be interpreted as two points on a curve describing the leaching from a landfill containing the tested material in terms of leachate composition or accumulated leached amounts of various components as a function of L/S (or, for a specific physical scenario, as a function of time).

Four residues were subjected to the pH-static leaching tests: The untreated scrubber residue (marked 57a), the washed residue (marked 51), a residue from a two-stage process in which the washed residue has been stabilized with carbon dioxide, but not with phosphoric acid (marked 69), and a residue from the previously described two-stage process in which the washed residue has been treated both with carbon dioxide and phosphoric acid (marked 70).

The results of the pH-static leaching at L/S = 5 l/kg are shown in figures 1a, 1b and 1c. The results of the pH-static leaching at L/S = 100 (data for the washed residue missing) are shown in tables 2a, 2b and 2c. The results of the serial batch leaching test are shown in table 3a and 3b for the untreated residue, the washed residue and the stabilized washed residue ($\text{CO}_2 + \text{H}_3\text{PO}_4$).

The results demonstrate the effect of the treatment on most contaminants, most notably lead, cadmium, chloride, sodium and potassium. Good results were obtained both with carbon dioxide alone and carbon dioxide and phosphoric acid. The phosphate is needed to minimize the leaching of lead at lower pH values. Only a few contaminants, particularly chromium, are mobilized by the treatment with phosphoric acid.

CONCLUSION

A process for treatment of dry scrubber residues from MSW incinerators have been developed and tested in pilot scale. The process involves an initial aqueous extraction followed by a resuspension and treatment of the filtercake with phosphoric acid and carbon dioxide to reach a stabilized product with highly improved leaching properties. The wastewater from the process may be discharged after treatment (pH adjustment and TMT polishing). Preliminary results of leaching tests performed on

untreated and treated residues are presented to demonstrate the effectiveness of the treatment process. Good results were obtained both with carbon dioxide alone and carbon dioxide and phosphoric acid. The phosphate is needed to minimize the leaching of lead at lower pH values.

ACKNOWLEDGEMENT

The work described in this paper was funded by the Danish Ministry of Energy, the Danish Ministry of Industry, KARA Roskilde, FLS Miljø A/S and VKI. The project was carried out by VKI, FLS Miljø A/S and KARA.

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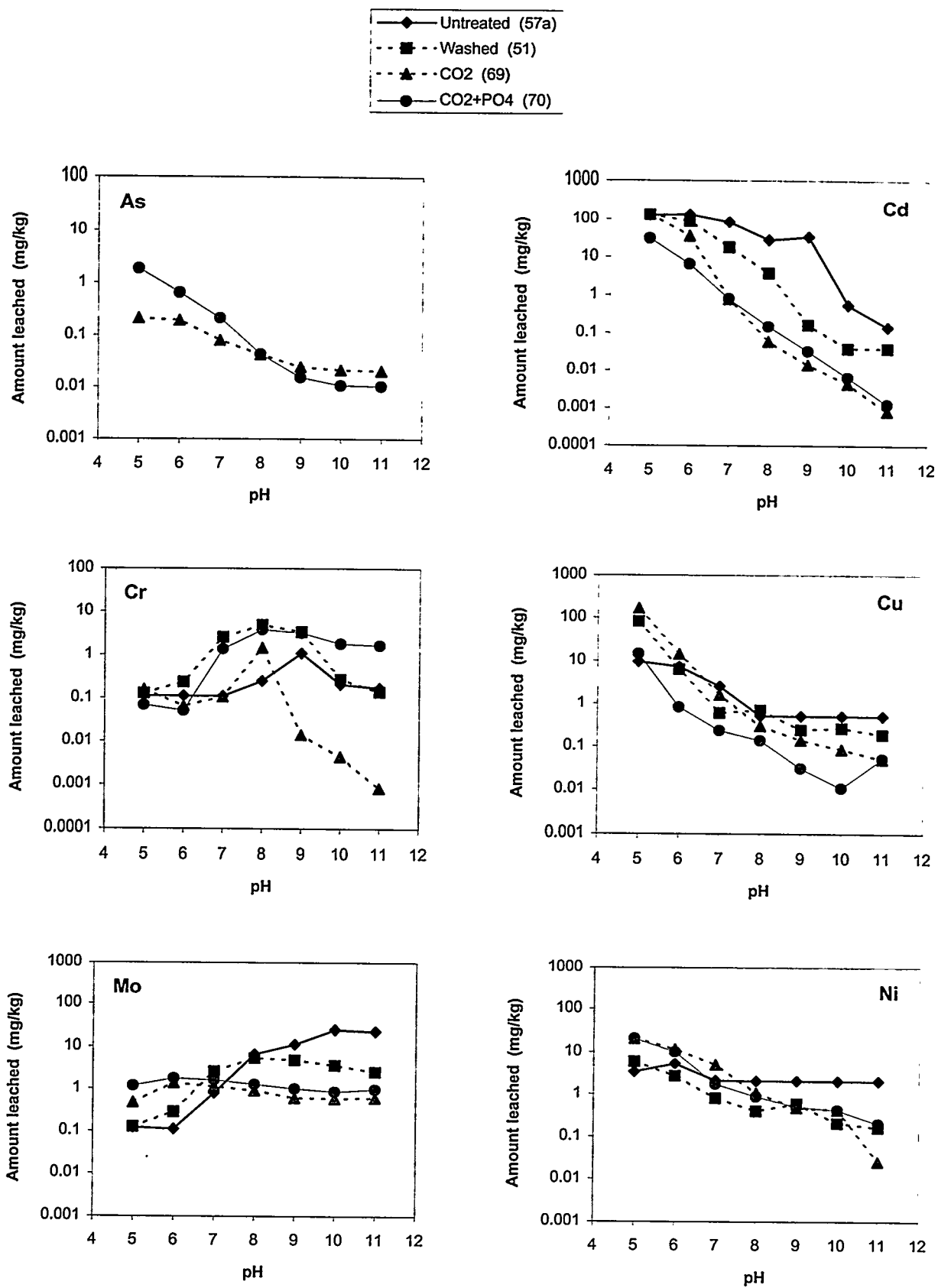


Figure 1a: Results of pH-static leaching tests at L/S = 5 l/kg

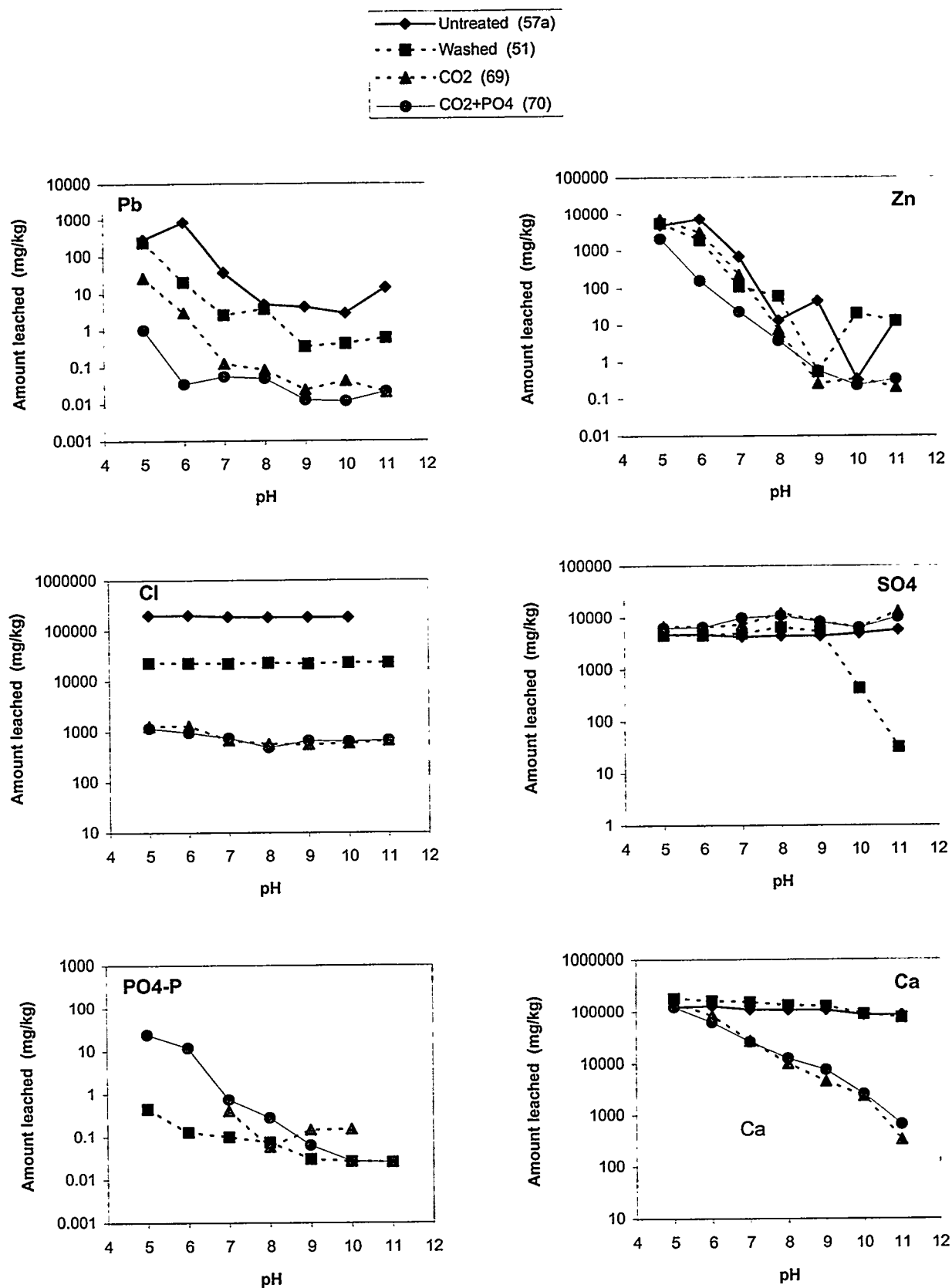


Figure 1b: Results of pH-static leaching tests at L/S = 5 l/kg.

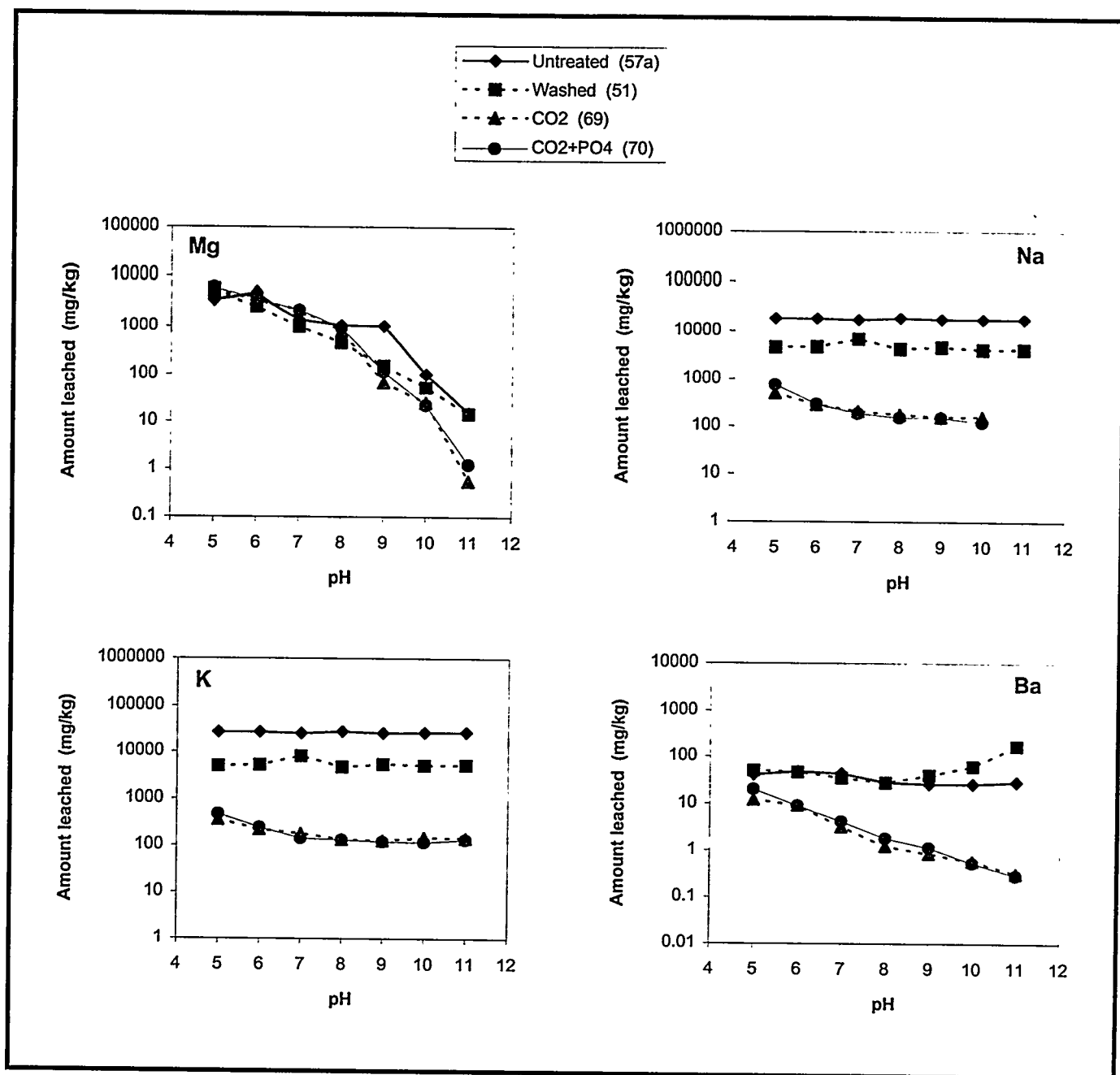


Figure 1c: Results of pH-static leaching tests at L/S = 5 l/kg.

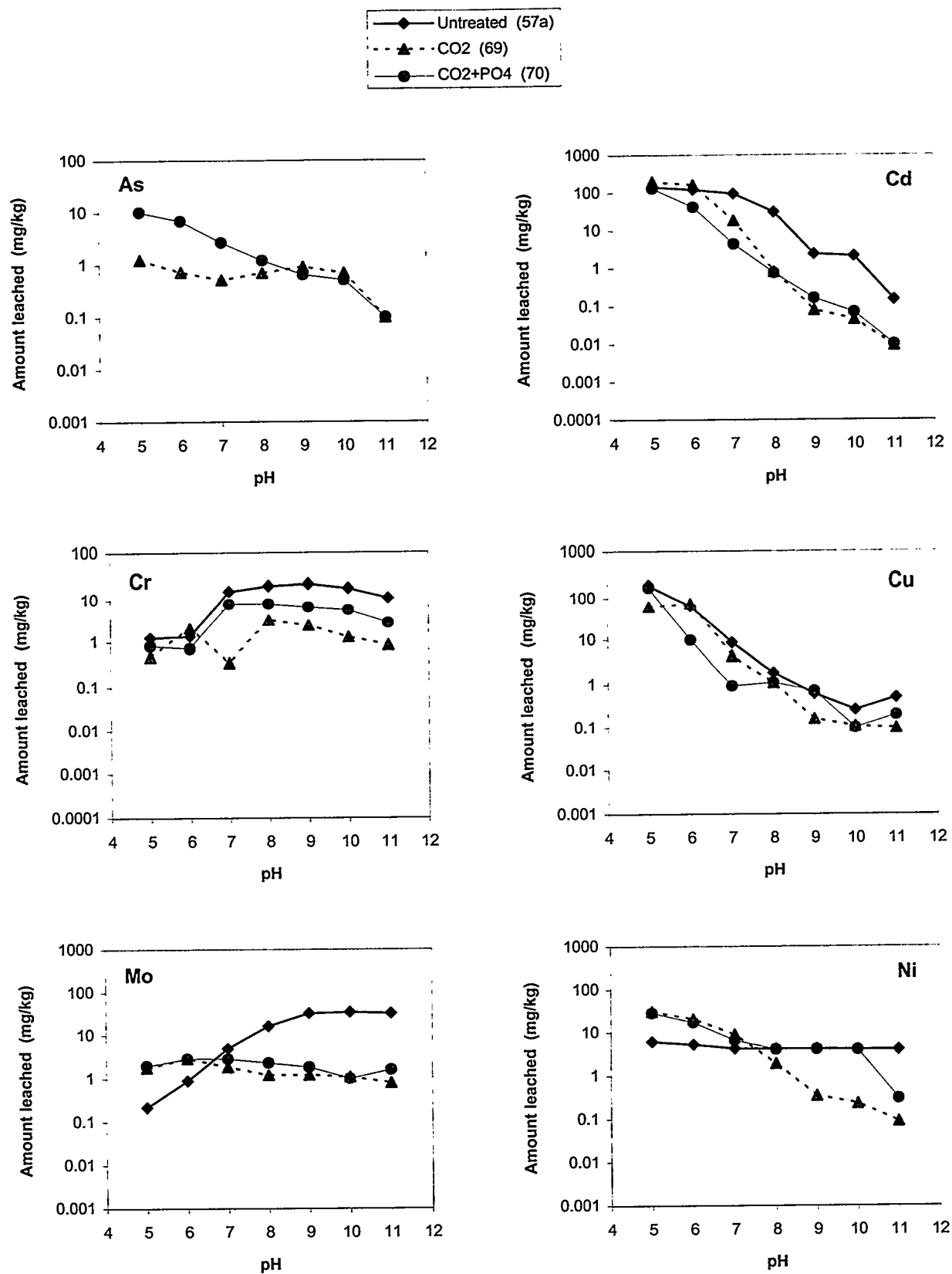


Figure 2a: Results of pH-static leaching tests at L/S = 100 l/kg.

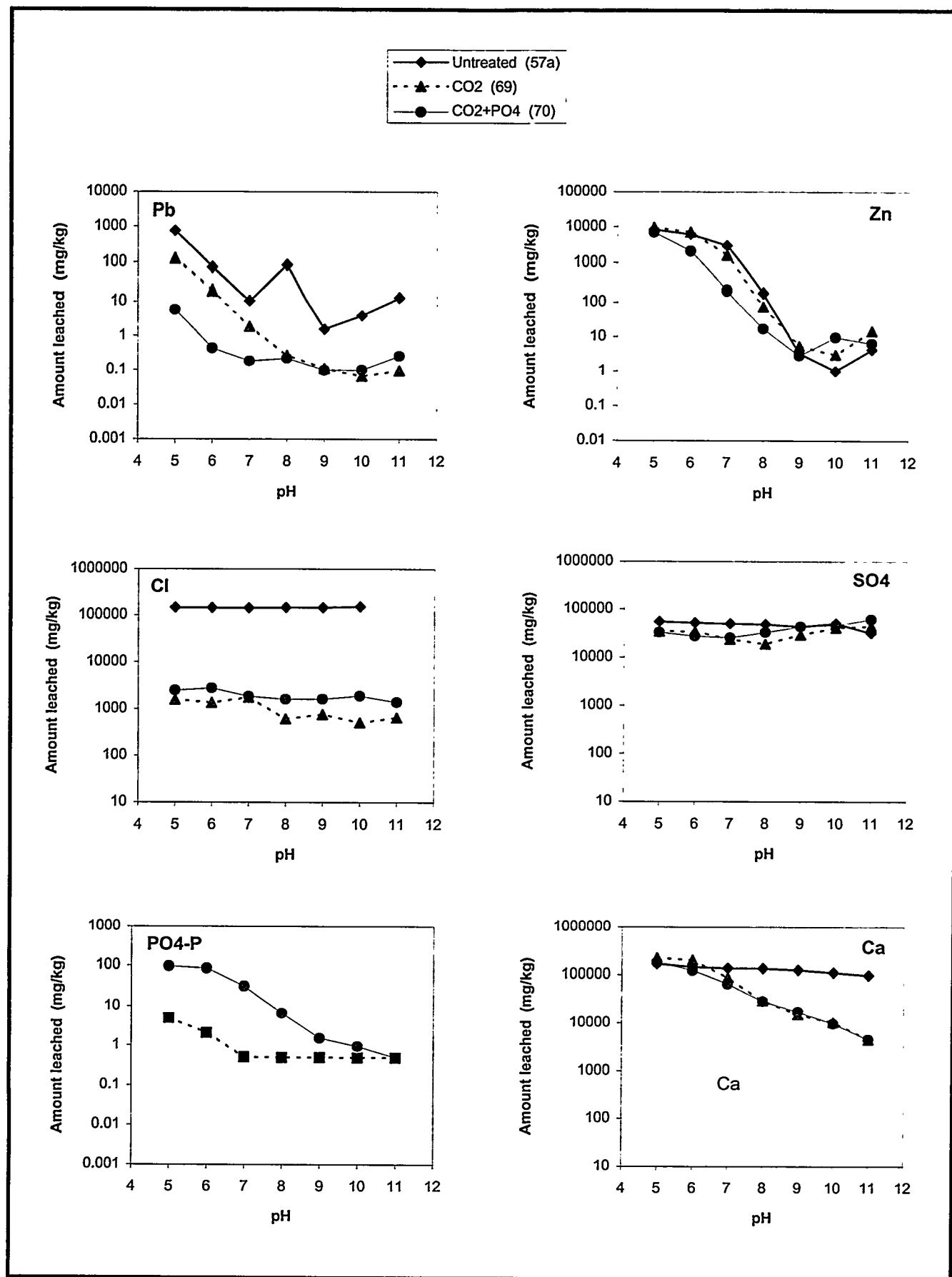


Figure 2b: Results of pH-static leaching tests at L/S = 100 l/kg.

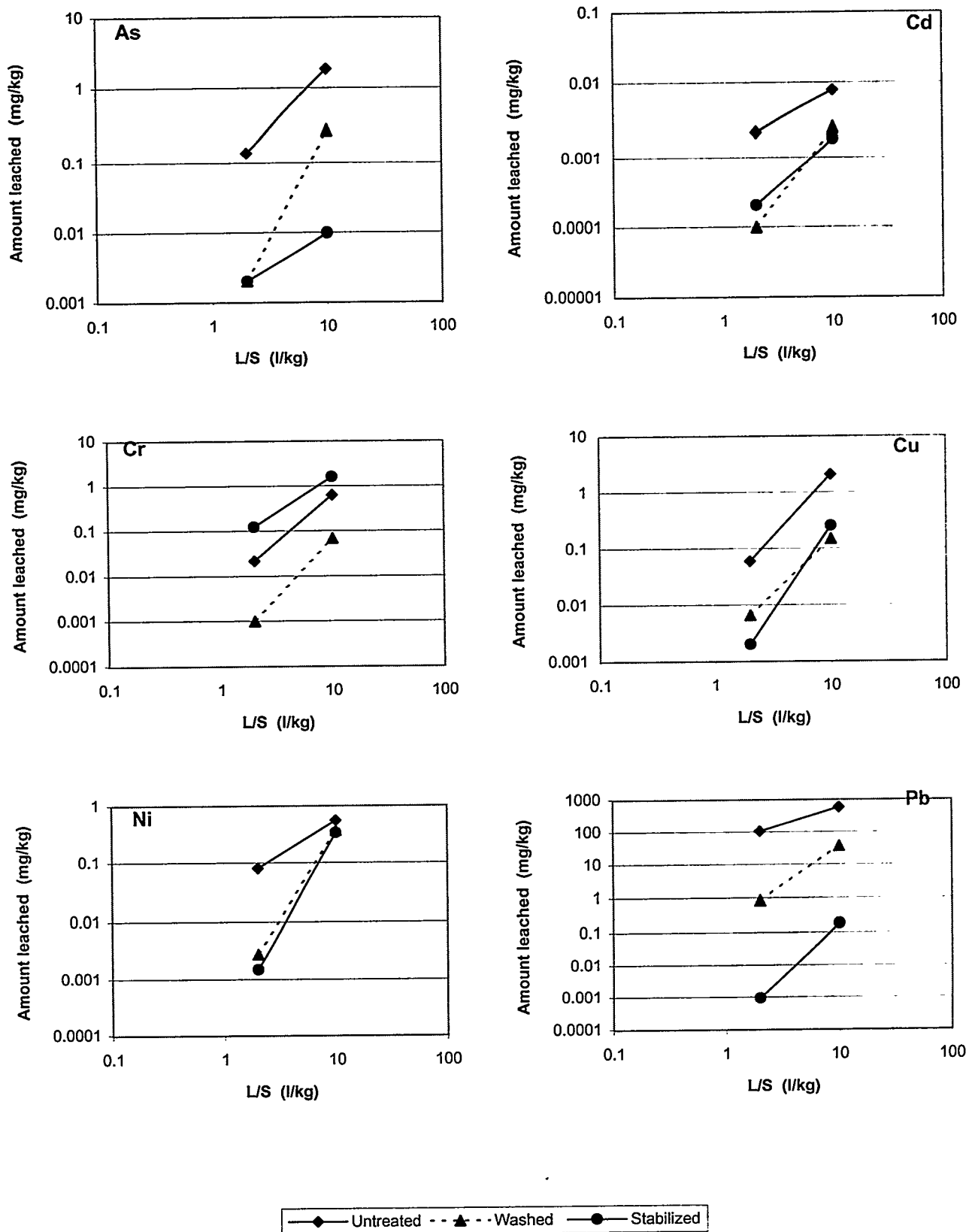


Figure 3a: Results of serial batch leaching test (two steps).

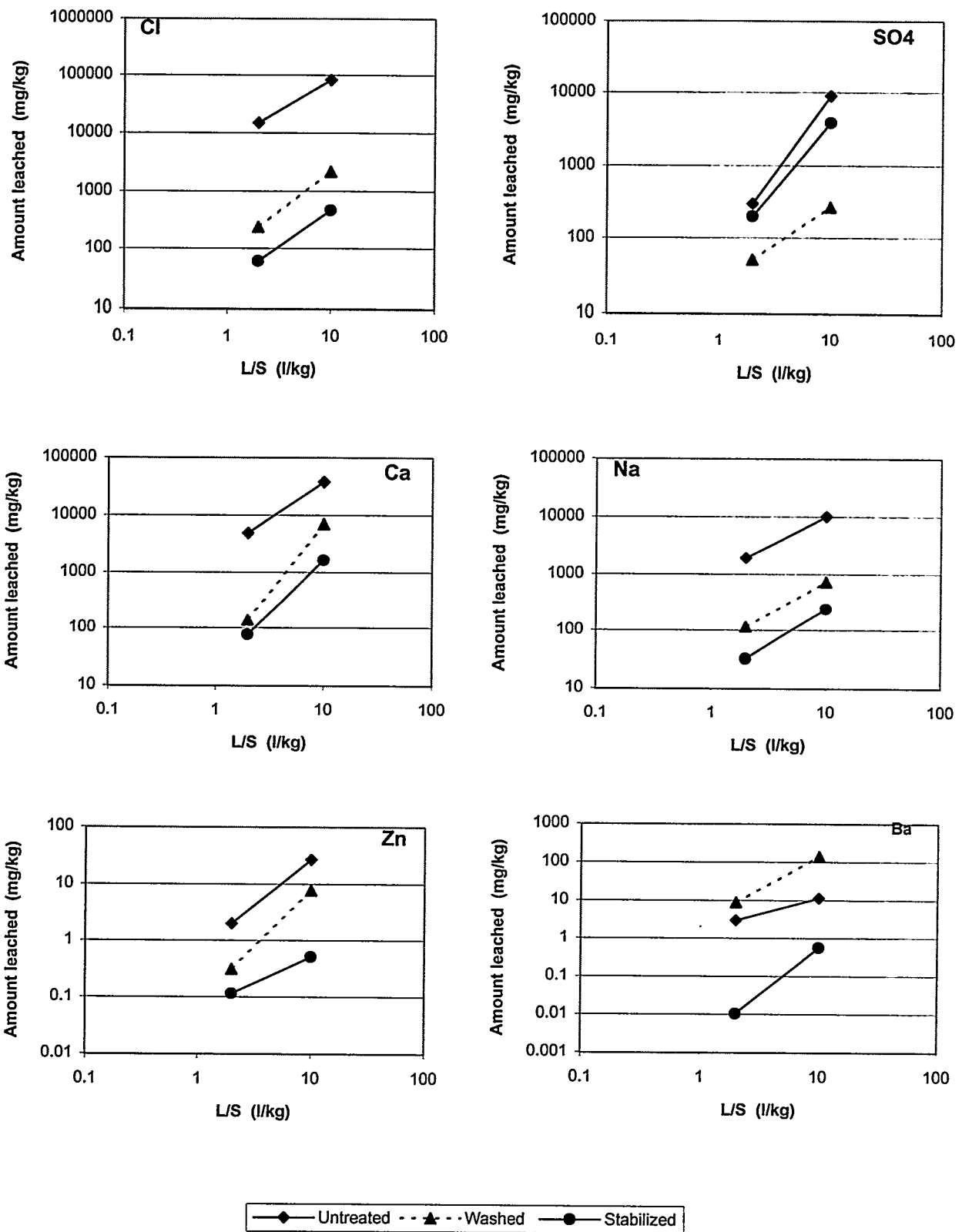


Figure 3b: Results of serial batch leaching test (two steps).

TECHNICAL SESSION III

Implementation Issues

Processed Engineered Fuels Derived From Paper and Plastics -- Techno-Economic Factors and
Regulatory Issues in a Competitive Market

Michael M. Fisher, Ph.D.
Director of Technology
American Plastics Council, Inc.
1801 K Street, NW, Suite 701-L
Washington, DC 20006

Oscar O. Ohlsson
1014 Thunderbird Lane
Naperville, IL 60563

Arun Singhania
Amoco Chemical Company
4500 McGinnis Ferry Road
Alpharetta, GA 30202

José Sosa, Ph.D.
FINA Oil and Chemical Company
Box 1200
Deer Park, TX 77536

INTRODUCTION

Plastics have gained a prominent position in modern society because their unique properties, cost-performance and versatility. They contribute to almost every aspect of modern life including transportation, recreation, medicine, packaging, appliances, furniture, textiles and building and construction. The diverse properties of plastics allow them to play a major role in providing solutions for technical progress as well as solutions for everyday life.

Plastics also make a significant contribution to effective resource management and conservation, reducing our use of natural resources and helping to minimize waste. By choosing plastics, manufacturers, designers, distributors and retailers in every sector have been able to respond to the challenge of preventing excess use of resources and, at the same time, bring increasingly sophisticated products to the market. Resource conservation seeks to maximize efficiency and minimize waste from a product's manufacture, use and disposal. It involves more than managing and minimizing waste, however; it also includes taking advantage of effective life-cycle resource management at local and global levels. There are many ways that plastics contribute to effective resource management. From manufacture to use, to recovery, to waste management, plastics help conserve resources. Not only are plastics energy efficient, but they often create less waste than other materials. They can be recovered, recycled and safely landfilled.

Plastics play an important role as a potential source of energy. Since they are manufactured from oil and natural gas, plastics can be viewed as "diverted" energy that is reclaimed in an energy recovery process. Recovering energy from post-consumer plastics is important for two reasons. First, plastics contain the highest energy value of any component of the municipal solid waste stream. Second, practical, technical and economic barriers limit the sensible reuse and recycling options of any material. By committing high-energy materials like plastics to land disposal, a significant energy resource is lost.

One objective of the American Plastics Council (APC) is to explore and extend the benefits of plastics that are not currently being realized and utilized. An important goal is to help ensure that all economic and environmentally responsible recovery options are available for plastics. By providing information about the environmental and economic impacts, positive and negative, of each municipal solid waste management and resource recovery option, we can make more informed decisions and achieve the goal of effective resource conservation.

This paper reviews the energy recovery option for post-use plastics. It discusses plastics' role in modern waste-to-energy (WTE) systems and then reviews some recent work exploring the use of plastics as alternative fuels. The emphasis is on solid fuels, often referred to as process engineered fuel or PEF. The liquefaction and gasification of plastics offers additional opportunities for resource recovery, but this subject is only briefly discussed in this paper.

OVERVIEW

Figure 1 summarizes three basic options for the recovery of energy from post-use plastics. They are municipal solid waste combustion or waste-to-energy; process engineered fuel (PEF) derived from plastics or combinations of plastics and paper; and liquid or gaseous fuels derived from the liquefaction or gasification of post-use plastics. The end product from all three processes is useful energy. The first option can be categorized as commercial and mature, the second as commercial and embryonic, especially with regard to the use of plastics; and the third as developmental. On the basis of these three options and the expanding need for energy worldwide, energy recovery from post-use plastics is expected to grow as a significant component of integrated resource management.

WASTE-TO-ENERGY (MUNICIPAL WASTE COMBUSTION)

According to the most recent U.S. EPA report on municipal solid waste titled *Characterization of Municipal Solid Waste in The United States: 1995 Update*,¹ plastics make up 9.5 percent by weight (19.8 million tons) of municipal solid waste. On this basis, plastics contribute almost 30% to the fuel

value of MSW. In combination with the non-recycled paper content of MSW, the combined contribution is more than 50% of the fuel value (Figure 2).

The same EPA study found that in the United States, 20% of MSW, after recycling and composting, is combusted--essentially all with energy recovery. The 20% figure is not often cited. The more common convention in the United States is to report the percentage for a given disposal or recovery technology applied to the total of all MSW generated. On this basis, the percent of MSW combusted is about 15.5% according to both EPA and Integrated Waste Services Association (IWSA) data.² It is often unclear on which basis European and Japanese data are being presented. Nevertheless, many countries such as Denmark, Switzerland, and Japan, and some regions of the United States, presently recover the energy from over 50% of generated MSW. Table 1 summarizes information from the Integrated Waste Services Association (Washington, DC) on municipal waste combustion, which confirms that more than 97% of MSW combustion in the United States involves energy recovery.

A recent modeling study suggests that there is significant potential for further growth of the waste-to-energy industry in metropolitan areas across the United States under the assumption that the minimum viable resource recovery plant throughput is 400 tons per day of MSW.³ This was essentially a hypothetical landfill diversion study. The study indicated that up to 76% of the U.S. population could effectively be served by modern mass burn technology compared to about 16% today. With 76% of the population served, approximately 58% of generated MSW would be managed in waste-to-energy facilities. In practice, of course, marketplace economics are often the controlling factor as to which waste management option is used.

The same study examined certain economic assumptions which could impact the viability of WTE in the future. Figure 3 shows a theoretical relationship between the calculated tipping fee which would need to be charged by a newly constructed WTE plant to break-even as a function of electricity sales price (effectively revenue). For comparison, Figure 3 also shows the range of average regional landfill tipping fees across the U.S. According to the assumptions of this model, relatively high electricity sales revenues are needed for WTE costs to be competitive with average landfill tipping fees. It is important to note, however, that this model is for new plants and assumes that all of the ash would be landfilled as an expense, rather than beneficially used.

As noted above, plastics provide an important fuel source for the waste-to-energy process. Indeed, in the U.S. today, roughly one out of every five pounds of post-use plastics are used for energy recovery in modern waste-to-energy plants. A recent study in Würzburg, Germany involving a mass burn municipal waste combustor equipped with baghouse and carbon injection demonstrated that mixed plastics in the MSW stream improve burn-out of gases and solid residue without adversely affecting ash or emissions.⁴ As plastic loadings were increased during the tests, CO and SO₂ emissions were reduced. In addition, higher polymer content, including specific addition of polyvinyl chloride, did not result in an increase in dioxins and furans. This finding supports the general conclusion of a recent ASME study that dioxin emissions from modern waste-to-energy plants do not correlate statistically with the quantity of chlorine in the feed.⁵ In fact, both the findings of the Würzburg study and the International Ash Working Group Report⁶ indicate that modern waste-to-energy plants are a net destroyer of dioxins.

Today, waste-to-energy technology is playing an important role in utilizing the energy content of plastics and other polymeric materials, and there are additional opportunities for the future. Recently, APC completed a study to assess the energy recovery option for automotive shredder residue, the byproduct of the automobile shredding operation.⁷ The energy content of ASR ranges from about 4000 to 11,000 Btu/lb depending on the degree of processing. The study looked at mass burn technology, RDF, industrial boilers, cement kilns, and emerging gasification technologies, and concluded that co-firing ASR with MSW in a modern mass burn waste-to-energy plant offered the most practical means to capture the inherent energy of this material.

PROCESS ENGINEERED FUEL

Basic Definition

Process engineered fuel (PEF) can be defined as a processed solid fuel, made from segregated plastic and paper, derived from industrial, commercial, and residential sources, for use by utilities and industry.⁸ The term paper is used broadly to refer to a wide variety of non-recyclable paper, boxboard, corrugated, and other cellulosic-based feedstocks. Plastic feedstocks can be in rigid, foam, or film form. Figure 4 shows the sourcing options, fuel processing step, and markets for PEF. PEF can be produced and marketed in both densified and fluff forms.

The term Process Engineered Fuel has not yet gained wide acceptance in Europe. The terms Packaging Derived Fuel (PDF) and Plastics Packaging Derived Fuel (PPDF) have been proposed⁹ but not broadly accepted. "Alternative fuel" is considered an appropriate generic term. In practice, PEF feedstocks often go beyond packaging-derived materials. When derived from post-use materials or from industrial, agricultural, or forest based products, or related industrial process streams, e.g., certain biofuels, these fuels all fall under the broad category of renewable fuels. The production and use of PEF is often referred to as fuel recovery rather than energy recovery.

Process engineered fuel should not be confused with Refuse Derived Fuel (RDF). A recent paper proposed a classification system to differentiate PEF, RDF, and MSW based on certain fuel properties.¹⁰ A basic distinction can be made on the basis of higher heating value with a lower limit of 6500 Btu/lb suggested for PEF (Table 2). This comparison is useful, but the definition of PEF provided above suggests that only in certain cases would PEF feedstocks be related to MSW or RDF. PEF should be viewed as a manufactured fuel not a waste. Definitions and terminology related to PEF are further discussed in the section on Regulatory Issues.

Production of PEF

Very little has been published concerning the manufacture of process engineered fuels. Beyond a few captive operations within the paper and forest products industry, there are probably fewer than twenty commercial PEF producers manufacturing a true PEF product operating in the U.S. today. World-wide, the total production of PEF is believed to be less than 2 million tons. APC believes that advances in technology could expand the use of PEF significantly.

The production of PEF requires specialized equipment and reliable quality control procedures. A representative PEF plant might include the following processing steps:

Specified Feedstock Acquisition→Feedstock QC→First Stage Size Reduction→
Separation/Blending→Second Stage Size Reduction→Separation/Blending→
Densification (optional)→Product QC

Densified forms of PEF are produced by either a cubing or a pelletizing operation using size reduced feedstocks. Moisture content is an important variable. Table 3 compares representative properties of pellets, cubes, and non-densified PEF. The authors believe that proper size reduction is one of the most critical factors when incorporating higher loadings of plastics. Much more work needs to be done to optimize fuel pellets and cubes containing high levels, i.e., greater than 10% by volume of plastics. Heated dies are being explored to facilitate the incorporation of higher loadings of plastics while maintaining good structural integrity of the densified fuel and associated handling properties.

PEF Economics

The overall economics of PEF are highly case-specific and very dependent of feedstock acquisition costs, disposal avoidance costs, and markets. Reference 10 provides a good introduction to PEF economics. An often overlooked factor is the ability of PEF to compete with other alternative fuels, not

just coal, on a dollars per million Btu delivered basis. All other things being equal, PEF becomes more competitive as its Btu value increases, i.e., plastics content, increases. For a densified PEF of 7500 Btu per pound, a value of approximately \$0.80 per million Btu is representative. At this price, PEF can be competitive with many other alternative fuels including agricultural waste and hog fuel. Any complete financial study must also include the cost to retrofit an industrial or utility boiler to handle PEF in either densified or non-densified form.

One PEF scenario that has been studied at some length is the addition of a PEF production capability to a mixed waste processing facility.¹¹ A key variable is avoided disposal cost. Capital costs start at about 0.75 million dollars to add densified PEF production capacity to typical mixed waste processing facilities depending on the amount of infrastructure already available such as a building to house the system and the throughput of the facility. Figure 5 shows the relationship between net PEF revenues (fob PEF market) and net savings to the mixed waste processing facility for recovering targeted materials as PEF as compared to landfill disposing of the same materials. The analysis shows that the production of PEF can be cost-effective in some regions of the U.S. In the final analysis, the PEF industry will need to grow and broaden its base of operation before real world economics can be identified and reliably analyzed.

Characterization of PEF

Beginning in late 1995, APC began to characterize samples of commercial and developmental PEFs and to compare their fuel properties with fossil fuels and other alternative fuels. The database presently consists of seventeen samples and continues to grow. Residential, commercial, and industrial feedstocks are included among the samples tested. Representative higher heating value (HHV), chlorine, nitrogen, and sulfur data for a number of samples in the database are shown in Figures 6-9. HHVs ranged from about 5000 Btu/lb to over 15000 Btu/lb. In general, most of the samples easily meet the criteria for PEF presented in Table 2. Sulfur content was consistently low, and over 90 percent of the samples had a chlorine content below 0.5%. The complete database includes ultimate, proximate, ash fusion temperature, ash mineral content, trace metals (17) and TCLP analyses. A detailed report on these findings is being prepared.

PEF Test Burns

Published information on the performance of PEF in industrial and utility boilers is limited. Test burns of densified PEF co-fired with coal in a spreader stoker traveling grate system at Argonne National Laboratories has been reported by Ohlsson.¹² Blends of densified PEF with coal up to 50 percent based on Btu content were investigated. In these experiments the PEF was sourced from a residential and commercial mixed waste processing facility and involved special processing including the addition of lime as a binding agent. The PEF averaged about 7500 Btu/lb. The results showed a reduction in flue gas SO₂, NO_x and CO₂ when PEF was substituted for high sulfur coal. The same paper reported favorable results co-firing a similar paper derived fuel with coal at the Otter Tail pulverized coal boiler. However, the Btu value of the fuel used at Otter Tail was reported to be only 6400 Btu per pound and therefore does not meet the definition for PEF used in this paper. PEF and RDF did not negatively affect ash quality in any of these tests.

Recently, Doraiswamy, et al.,¹³ reported results from the co-firing of a secondary fiber/plastics recycled paper mill reject stream with coal. This process stream had a heating value above 10,000 Btu/lb and on this basis would be considered PEF. The reject stream contained about 40% plastic on a dry basis. The tests showed no adverse affects on emissions or ash quality co-firing 10% rejects with coal. Economics looked favorable and the co-firing of this type of PEF at other mills and industrial sites can be expected to grow.

Except for some recent Finnish studies reported by Martin Frankenhaeuser,¹⁴ very little has been published on the co-firing of process engineered fuels in fluidized bed systems. Last year, a two day trial burn of densified PEF derived from commercial paper and plastic feedstocks was completed using the fluidized bed boiler at the Idaho National Engineering Laboratory. The boiler has a maximum rated capacity of 67,500 lb steam/hr.

Fuel characterization data for the coal and PEF is shown in Table 4. This was a true PEF with a HHV of 7,449 Btu/lb. The test program measured emissions of trace metals, particulate matter, hydrochloric acid (HCl) and gaseous species (for NO_x, SO₂, CO₂, O₂) while firing three different PEF pellet to coal ratios (10%:90%, 20%:80%, 25%:75%) in the boiler. Baseline emissions of the species listed above were also measured while firing only coal in the boiler. The coal was relatively low in sulfur (0.37%) and had a higher heating value of 12,600 Btu/lb. Boiler performance was uncompromised at all pellet feed ratios and emissions profiles held essentially constant even at the highest PEF to coal ratio. Preliminary emissions data for CO₂, NO_x, and SO₂ are shown in Table 5. A complete report of this test burn will be available later this summer. The role of PEF containing sufficient quantities of plastics and the effect of such plastics in achieving HHVs in excess of 10,000 Btu/lb needs to be more thoroughly documented.

In the Fall of 1995, APC completed a bibliography of published information on refuse derived fuels and process engineered fuels including test-burn reports.¹⁵ The bibliography is available from APC in hard copy and disk format.

Regulatory Issues

Regulatory Issues were prominent on the agenda during the recent Pellet Fuel Conference held in Washington, DC.¹⁶ Regulations, laws, and policies can act as drivers or barriers to the use of PEF as a supplemental fuel. Regulatory issues affecting the use of PEF are briefly discussed below and fall into four categories.

- Definitions and terminology
- Fuel standards and quality assurance
- Air emissions standards
- Ash management

PEF Definitions and Terminology. The concept of PEF is relatively new, so federal and state regulations generally do not contain a definition for PEF. Regulators may be inclined to interchangeably use the terms "PEF" and "RDF", but the general consensus of the industry is that PEF is higher quality and more homogeneous fuel than RDF, as noted earlier. In order to minimize barriers to the growth of PEF use, it is important that PEF be considered a resource by regulators rather than a waste, in order to avoid the generally more stringent regulations associated with waste management as compared to resource management. Earlier, this issue also had to be addressed by the traditional recycling industry in order for it to grow to its current level.

PEF can also be considered an indigenous and renewable fuel because it is generally composed of post-use paper and plastics. Clearly defining PEF as a renewable fuel would further the industry by allowing PEF to qualify for incentives or mandates established to encourage the use of renewable fuels in the United States, as well as further its perception as a valuable energy resource. This issue is developing as an important consideration during the electricity deregulation discussions underway at both the state and federal levels.

Some states offer recycling (or waste diversion) credit for materials that are diverted from disposal through PEF systems, thus acknowledging their role in resource conservation. For example, Florida and Maine provide recycling credit to local governments for combustion of PEF in existing boilers. It is interesting to note that recycling credit in Florida cannot be obtained for combustion of the same materials in traditional WTE facilities.

PEF Standards and Quality Assurance. Also because the concept of PEF is still relatively new in the United States, standards and quality assurance measures for PEF have not yet been developed, although some efforts to start this process are underway. An effort to develop similar standards is currently active in Europe for recovered fuel. Ideally, the development of such specifications in the United States would potentially:

- Minimize the stringency of regulations imposed on PEF production and use (such as reducing expensive air emissions and ash testing requirements often imposed by regulators on boiler operators wanting to co-fire alternative fuels with other conventional fuels) or possibly exempt PEF from some regulations;
- Simplify permitting procedures and requirements associated with the production and use of PEF and make them comparable to those for conventional fuels; and
- Facilitate the perception and definition of PEF as a resource and renewable fuel.

The development of standards and quality assurance for PEF must address both producer and user responsibilities and specific sampling and testing protocols. A classification system based on key properties is a possibility.

Air Standards. Under the Clean Air Act, up to 30 percent by weight of MSW can be co-combusted with other fuels without triggering municipal waste combustor (MWC) regulations. It is probable that PEF, with one or more source separated types of post-consumer materials such as paper, would fall under the 30 percent restriction. However, PEF made from industrial scrap that has not been commingled with MSW may not fall under the same percentage restriction. At the state level, additional restrictions are sometimes placed on the amount of PEF that can be co-fired before triggering MWC regulations. For example, Washington state has a limit on the use of PEF that supersedes and is more stringent than the 30 percent exemption in the Clean Air Act.

Regulations that govern WTE facilities, or MWC regulations, are generally more stringent for certain pollutants (such as organics and trace metals) than regulations for boilers fired with conventional fuels. Therefore, it is possible that co-firing PEF in existing boilers will be less stringently regulated than combusting MSW in WTE facilities. However, regulatory consequences could result from co-firing PEF depending on the emissions consequences. Testing will most likely be required to determine the impact of co-firing PEF on emissions unless strict PEF standards and quality assurance measures are developed.

Co-firing of PEF with conventional fuels, particularly coal, can have positive affects on air emissions. Most notably, co-firing of PEF with coal offers a potentially more cost-effective means to achieve compliance with the federal Acid Rain Program of the 1990 Clean Air Act Amendments than through installation of scrubbers or other capital-intensive alternative compliance strategies.

Anticipated regulatory changes could affect the way and the amount of PEF used by industrial combustion facilities. It is anticipated that relevant definitions and regulations will be thoroughly revisited as part of the Industrial Combustor Coordinated Rulemaking Process underway at the U.S. Environmental Protection Agency. The uncertainty regarding environmental regulation of PEF use can be a barrier to the development of the PEF industry. Some state-level restrictions on the amount that can be co-fired before triggering MWC regulation can also be barriers, as well as costs for ongoing required testing can be prohibitive to the use of PEF. However, potential positive effects on air emissions are helping to drive the industry.

Ash Management. The regulation of ash resulting from the co-firing of PEF with conventional fuels is not clear. Currently, ash from combustion of coal is treated as a "Bevill waste" and need not be tested for hazardous characteristics. Bevill waste can be fired with up to 50 percent of other types of fuels and not be subject to Subtitle C regulation. However, the Clean Air Act exemption of 30 percent does not clearly exempt the resulting ash from MWC ash regulations which includes testing requirements for hazardous characteristics. Also, it is not clear if ash from boilers co-firing PEF from residential sources is exempt from Subtitle D regulations and there is no clear guidance on the federal level regarding how ash from a facility co-firing PEF derived from industrial feedstocks should be regulated. Federal legislation or regulatory clarification of these issues could improve the use of PEF.

States generally have the primary responsibility for regulating the management of ash from facilities co-firing PEF although general guidance is typically provided from the federal government such as that

discussed above. Typically states require ash from facilities co-firing MSW with any type of conventional fuels in amounts greater than 30 percent of the total fuel to be regulated the same as ash from MWC's. Ash from co-firing PEF derived from industrial feedstocks with coal at levels greater than 50 percent must generally be tested for hazardous characteristics. Regulations for management of ash from co-firing wood waste with PEF derived from industrial sources at any percentage must be completely determined at the state level since no specific federal regulations address this issue.

In general, competition in the fuel and energy industries is increasing as a result of in place and planned deregulation of the electric utility industry. Increased competition is resulting in a reassessment of alternative fuels. PEF, on the basis of overall environmental performance and economics, has the potential to be the alternative fuel of choice in many situations.

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Table 1. Municipal Waste Combustion Industry Profile (1995)

	Number	Annual Operating Capacity (MM tons)
Mass Burn Facilities	70	22.6
RDF Combustion Facilities	23	7.9
Modular Facilities	21	0.8
Incinerators (without energy recovery)	21	0.9
States with Facilities	34	
Communities Served	1688	
Population Served (million)	41.2	
Total Capacity		32.2
Percentage of MSW Processed	15.4	

Source: Adapted from The 1996 IWSA Municipal Waste Combustion Directory

Table 2. Comparative Properties of Characteristics of PEF, RDF, and MSW

Type of Fuel	Moisture (% by wt)	HHV (Btu/lb)	Ash Content (% by wt)	Dry Basis	
				Sulfur Content (% by wt)	Chlorine Content (% by wt)
MSW, unprocessed	15-50	4,500-5,500	18-30	0.10-0.50	0.10-1.00
RDF	3-35	5,500-6,500	8-25	0.10-0.50	0.10-1.00
PEF	3-20	6,500-16,000	2-15	0.02-0.20	0.03-0.50
Bituminous Coal	2-20	11,000-14,500	3-16	0.50-4.7	0.01-0.90

Table 3. Comparison of Pelletizing and Cubing Technologies

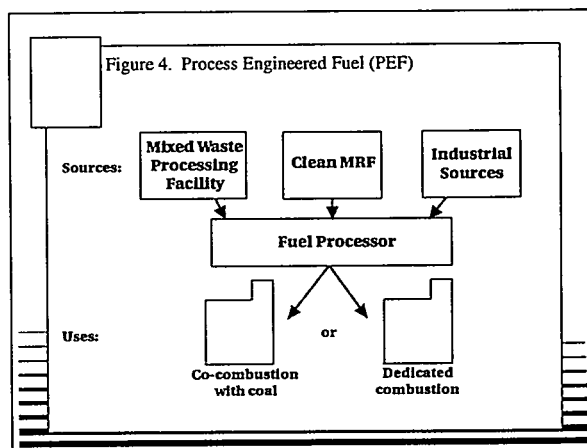
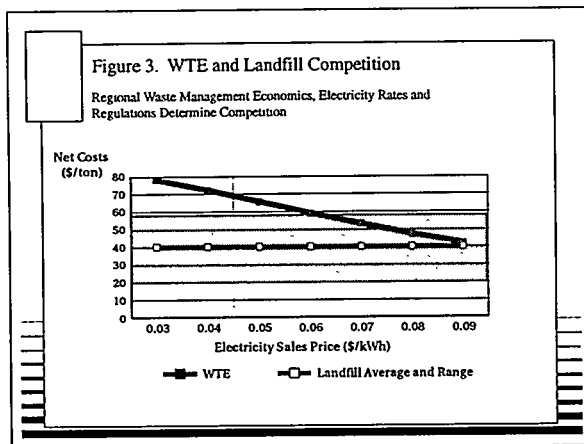
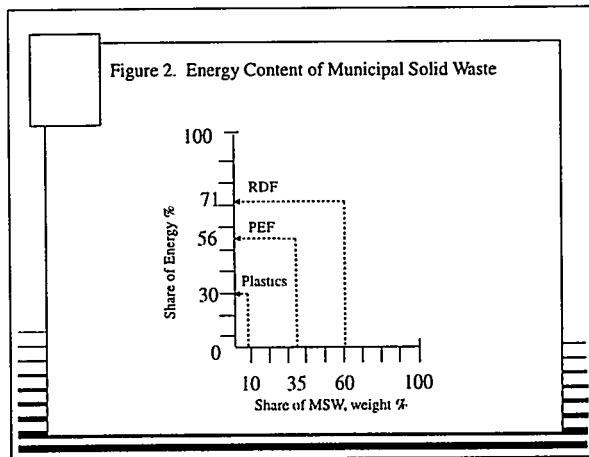
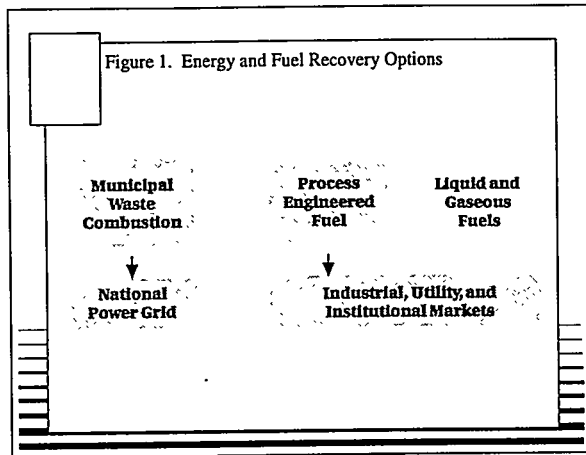
Criteria	Pellets	Cubes	Non-densified
Size Reduction Required	1/4" to 3/4" max size	3/4" to 3-1/2 (1-1/2" nominal)	1/4" - 2"
Final Bulk Density	35-45 lbs/cu ft	20-33 lbs/cu ft	2-12 lbs/cu ft
Final Product Diameter	1/4" to 3/4"	1" to 1-1/4"	N/A
Cooling Required After Densification	Yes	No	N/A
Throughput	2-4 tons per hour	6-8 tons per hour	> 5 tons per hour

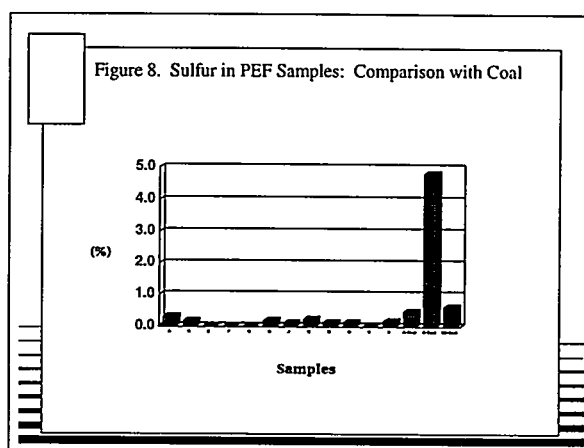
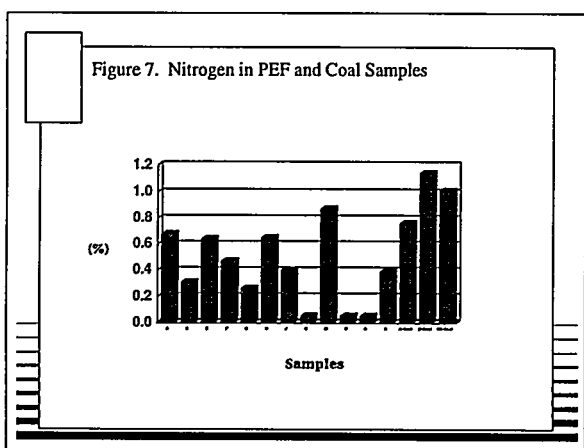
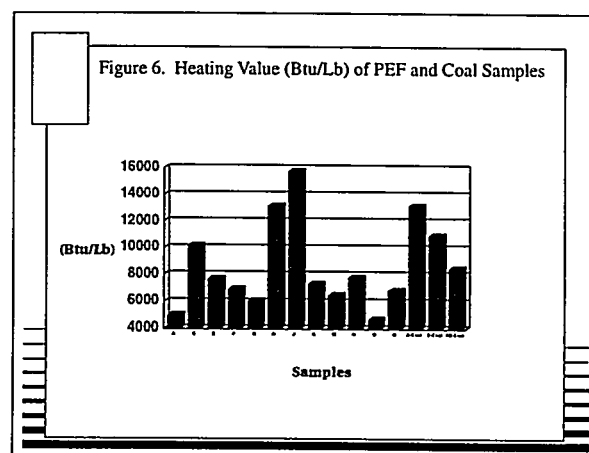
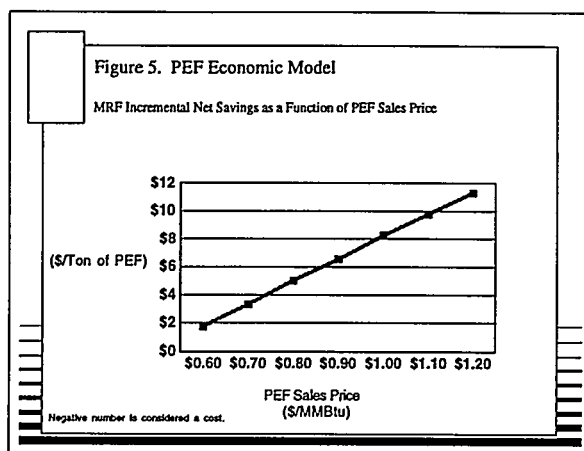
Table 4. Fuel Characterization - INEL Test Burn

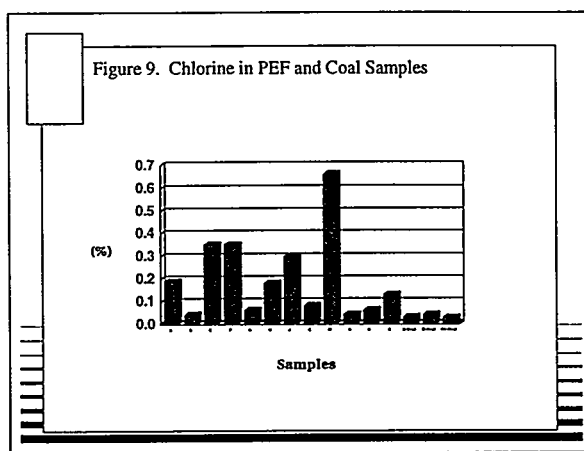
Fuel Type	C (%)	H (%)	O (%)	N (%)	S (%)	HHV (Btu/lb)
Coal	73.33	4.78	10.75	1.20	0.37	12,582
PEF	43.31	5.74	35.40	0.32	0.18	7,449

Table 5. INEL emissions data.

Coal/PEF Ratio	100%/0%	90%/10%	80%/20%	75%/25%
CO ₂ , %	9.58	9.60	9.57	9.00
NO _x , ppm @ 7% O ₂	239	210	197	212
SO ₂ , ppm @ 7% O ₂	29	34	43	45







EPA's Mercury Report To Congress:
A Basis for Decision-Making?

Frank Ferraro
Vice President, Environmental, Health and Safety Management
Wheelabrator Technologies Inc.
4 Liberty Lane West
Hampton, NH 03842

INTRODUCTION

Section 112 (n)(1)(B) of the Clean Air Act Amendments of 1990 directed the US EPA to conduct and transmit to Congress by November 1994, a study of mercury emissions from electric utility steam generating units, municipal waste combustion (MWC) units, and other sources including area sources. The study was to consider the rate and mass of the emissions, the health and environmental effects of these emissions, technologies to control them, and the costs of the controls.

While the Report was intended to inform Congress concerning mercury emissions, it is also intended to serve as a basis for future Federal policy and regulatory decisions. The purpose of this paper is to review and assess the status of the Report and identify its weaknesses and deficiencies. It is the studied opinion of this author that the Report, in its current format, suffers from a number of "fatal flaws" which bring into question its usefulness both as an accurate information document for Congressional review, and as a basis for future policy and regulatory decisions.

The discussion below begins with a brief look at the history of the Report. Specific sections of the Report are identified where perhaps fatal flaws exist in the areas of sources, fate and transport models, and some of the controversy over mercury exposure, health effects, and the chosen reference dose. Some observations are incorporated concerning the Science Advisory Board's comments to EPA in a recent review panel. Finally, these comments address flaws in the current Report, but also identify and address flaws in the EPA Report preparation process.

MERCURY REPORT TO CONGRESS

History

For a number of years beginning around 1987, representatives of EPA's Offices of Air Quality Planning & Standards (OAQPS) and Research and Development (ORD) had been involved with collecting data on mercury emissions from MWCs under the Clean Air Act Section 111 New Source Performance Standards development activities. In gathering emissions data, these EPA representatives interacted with MWC owners and operators individually and through groups such as the Integrated Waste Services Association (the MWC industry trade association), the Conference of Mayors/Municipal Waste Management Association (MWMA), Solid Waste Association of North America (SWANA), and the American Society of Mechanical Engineers (ASME).

As part of this continuing effort and dialog, OAQPS held a two-day Public Meeting in February 1990, at their offices at Research Triangle Park, NC to review the status of their NSPS data collection activities for mercury from MWCs. This information and subsequent data eventually lead to promulgation of an emissions standard for new and existing MWCs (40 CFR 60.50b and 60.30b) in December 1995.

After the passage of the 1990 CAAA, EPA's OAQPS's Emission Factor and Inventory Group also began collecting various emissions information to prepare a series of reports on pollutant emissions, e.g., Locating and Estimating Air Emissions from Sources of Mercury and Mercury Compounds. However, the individuals within this branch of OAQPS were not the same ones as those working on the MWC NSPS.

The MWC industry first became aware of EPA's work in preparing the Locating and Estimating Report in June 1993. The Integrated Waste Services Association (IWSA) provided comments to EPA on MWC

sources and emission rates of mercury. In September 1993, EPA issued the Locating and Estimating Mercury report, ignoring the majority of IWSA's work. Three months later, EPA issued a draft report entitled: National Emissions Inventory of Mercury and Mercury Compounds: Interim Final Report and solicited comments on selected sections of it. IWSA responded by referring the Agency to its previous detailed comments to the Locating and Estimating report.

Over the next year, there was no further communication from EPA on the Mercury reports. Then, in January 1995, EPA published a notice in the Federal Register that there would be a two-day Peer Review workshop to discuss the results of the draft Mercury Report to Congress. While the workshop was open to the public, EPA was not inclined to accept any public comments.

At the January meeting, it was learned that EPA had proceeded with the development of the Mercury Report to Congress, and while one of the major stakeholders, the electric utility industry, had been integrally involved in the preparation and review of the Report, the MWC industry was not even informed of the existence of a draft report until the Public Notice. In addition, no one from EPA's OAQPS or ORD that had been working for the past several years on the MWC NSPS and data collection had been involved in the preparation or review of the draft Report.

The draft Report was provided to the public, including IWSA, for the first time on the morning of the first day of the Workshop. The Public was asked to review and comment on the seven volume draft report on the same day they received it. IWSA was granted only an "observer" status and was offered ten minutes to present any comments at the Workshop.

While EPA was not inclined to accept any public comments on the draft Report, IWSA was subsequently allowed to submit a comment document which cited factual errors in data as well as errors and problems with many of EPA's assumptions in the report. One of the most fundamental flaws in the draft report was that the basic emissions data in the report had been drawn from the incorrect Locating and Estimating - Mercury Report. EPA had ignored the data submitted by IWSA, some of which was based upon testing conducted by EPA's OAQPS and ORD.

Problems with the Draft Report

The draft Report contained inaccuracies and erroneous and ultraconservative assumptions which could lead a reader to believe that mercury emissions from MWCs were seriously impacting the environment and threatening human health. The three primary problem areas in the draft Report are: 1) Sources of mercury emissions, 2) Fate and Transport Models and Assumptions, and 3) Toxicologic information and assumptions.

Sources. As stated above, the branch of EPA that collected emissions data for the draft Mercury Report relied on old data. All of the actual stack test results of mercury emissions from MWCs that had been generated for State air permit compliance tests and by EPA/ORD and OAQPS for development of the MWC NSPS was ignored. These data were readily available and much of it had been provided to EPA by IWSA in comments on the Locating & Estimating and National Inventory reports.

Also, even though the draft report was released in January 1995, EPA based the source data in the Report on data as it existed in 1990. In the draft Mercury Report, EPA's estimate of mercury emissions from MWCs was 64 tons per year (tpy), even though in 1993, IWSA provided EPA with data demonstrating that 1993 emissions were no more than 44 tpy and that value was decreasing rapidly. The Agency's own most recent inventory estimate for MWCs for 1995 is 29 tpy.

The 1995 draft Mercury Report states that MWCs account for 12% of the emissions inventory. However, in 1995, EPA issued a Fact Sheet along with the release of the MACT Emissions Standards for MWCs which stated that MWCs will represent only 3% of the total mercury emissions nationwide once the MACT standards are fully implemented. The inference here is that current MWC emissions are four times what they will be by December 2000. This is patently untrue as is clearly shown in the MWC emissions database that is maintained by EPA.

EPA also ignored other sources of mercury emissions, references for which were readily available in reports prepared by states such as New Jersey and Florida, and underestimated other sources even when they did include them. For example, EPA underestimated the potential mercury releases from fluorescent lights by an order of magnitude, totally ignored the potentially large source of mercury emissions from open field burning, and used inaccurate mercury speciation data in characterizing emissions from MWCs.

Fate and Transport Models and Assumptions. In the draft Mercury Report, EPA relied on series of equations and models to estimate the potential impact of emissions of mercury from U.S. sources. The two air quality models were a regional prediction model and a source specific model. The rudimentary multiple pathway model, IEM2, which is primarily a series of equations, was also used. Comments on the inadequacies of these models and the problems with the associated assumptions made by EPA were provided to EPA by IWSA. The following are some of the more critical points made by IWSA.

RELMAP. To predict regional concentrations of mercury from sources of mercury emissions, EPA used the Regional Lagrangian Model of Air Pollution (RELMAP), and attempted to verify the results of the RELMAP predictions by comparing them to specific observations and sampling events. However, the actual measured results prove the RELMAP-predicted values consistently overestimate actual wet deposition data by a factor of two. EPA states in the Report that actual results "agree well" with predictions, even though EPA's data proves this to be incorrect. For example, EPA states in the Report that at one location in Vermont, the observed measurements were 9.3 ug/m², whereas the RELMAP model predicted up to 20 ug/m². For another location, the RELMAP model predicted deposition at up to 10 ug/m² when actual deposition was 5.7 ug/m².

The RELMAP model predicted local maximum values for mercury wet deposition as 60 ug/m², while EPA cites the highest measured value of actual data as 30 ug/m² in the Florida Everglades. As shown by the data in EPA's report, predicted impacts using RELMAP are approximately twice the actual measurements in every case. In the Report, the Agency even admits that the RELMAP results were "significantly larger" than the measured values. However, no attempt to adjust the RELMAP results were made.

While a factor of two may not seem large enough to be of concern, the impact of the RELMAP predicted values *is* significant on the overall assessment of potential risk. In EPA's hypothetical risk assessment, RELMAP results contribute to a mercury concentration in fish of 0.5 ppm, *one-half* the FDA action level. Consequently, a factor of two becomes very significant, dropping the regional contribution to 0.25 ppm in fish.

COMPMERC. To estimate the impact from specific sources of mercury emissions, EPA used COMPMERC, a modified version of a dispersion and deposition model called COMPDEP. Air quality models are usually developed for or by OAQPS's Air Modeling branch in Research Triangle Park, NC (RTP). The COMPDEP model, however, was developed by EPA's Environmental Assessment office in

Washington, D.C. The DC office, recognizing that COMPDEP had not been validated nor peer reviewed asked the RTP modeling group to refine COMPDEP. The RTP office had been developing and was about to promulgate the next version of their dispersion model, ISC3, which had been peer reviewed and was more sophisticated than COMPDEP. The RTP group was unable to refine nor validate the wet deposition algorithms in COMPDEP and, in an effort to respond to the request from the Environmental Assessment group, the Modeling group added the wet deposition portion of COMPDEP to the ISC3 model which also included a dry deposition component. The ISC3 model with the COMPDEP wet deposition algorithms was released to the public by EPA along with the caveat that anyone using the wet deposition portion of ISC3 does so "*at their own risk*" and that the wet deposition portion of ISC3 "*should not be used for regulatory purposes*", e.g., risk assessment or permitting (Personal communication, OAQPS, Sept. 1996).

It is puzzling as to why EPA's Environmental Assessment group chose to use COMPDEP for the Mercury Report. COMPDEP suffers from many flaws, such as lack of source depletion and poor handling of wet and dry deposition. EPA's Science Advisory Board criticized EPA in February 1996 for use of unvalidated modeling, including COMPDEP and IEM2, saying that the models "**violate a fundamental scientific principal, i.e., conservation of mass**" and provide "**little grounding of reality of the overall methodology.**"

While EPA's newer model, ISC3, is not a perfect model, it contains a number of improvements over the COMPDEP model, including a plume depletion algorithm designed to conserve mass. Unfortunately, the wet deposition algorithms in ISC3 are the COMPDEP algorithms that have still not received the validation necessary to allow its use as a regulatory tool.

The wet deposition portion of COMPDEP is seriously flawed. For modeling of wet deposition, COMPDEP estimates the maximum wet flux rate and assumes that this occurs at the same point as the maximum dry deposition. It is well known that wet deposition flux rates drop off quickly with distance from the stack, and maximum impacts typically occur within several hundred meters of the stack. The maximum dry deposition impact point, however, occurs much further away from the stack. The wet flux rates can decrease by more than an order of magnitude within a few kilometers of the maximum point. The maximum wet flux rate may be more than 100 times higher than the average flux rate across a 10-km modeled area. Use of the maximum impact point wet flux rate will overestimate long term risks by up to two orders of magnitude.

Air Quality Model Input Parameter Assumptions. EPA also made many assumptions in using the RELMAP and COMPDEP models. The base-case mercury speciation profiles for MWCs were contradictory and without reference. For the RELMAP modeling of MWCs, one table in the Report indicated a base case speciation of 15% elemental, 85% ionic, and 20% particle bound, while another table had the base-case speciation for the same source listed as 20% elemental, 60% ionic, and, 20% particle bound. For the COMPDEP modeling of MWCs, the speciation was assumed to be 15% elemental, 85% ionic, with no particle bound mercury. Thus, three different base-case speciations are listed for the same plant type, all without reference.

The mercury speciation assumed in the draft Report of 15% elemental and 85% ionic for MWCs is also inconsistent with other published data. According to work completed in 1991 by Dr. Nicolas Bloom at the Stanislaus, California waste-to-energy plant, a more accurate percentage is 70% elemental and 30% ionic for an MWC with a scrubber and fabric filter baghouse.

Within the next two to three years, most MWCs will be injecting powdered activated carbon into the flue gas as a mercury emission control method to comply with the 1995 MACT standard. Results of testing conducted by EPA and others show that powdered activated carbon is extremely effective in capturing ionic mercury. Actual results using carbon to control mercury emissions demonstrate at least 90% removal of mercury from MWC flue gases. After MACT controls reduce total mercury emission rates by 90% or greater, the remaining species will be between 70%-90% elemental mercury and between 10%-30% ionic mercury. Therefore, the use of elemental to ionic ratios of less than 70:30 is misleading.

EPA did acknowledge that **"due to the high degree of uncertainty regarding the emission speciation and possible rapid chemical and physical transformations immediately after emission, it is recommended that these maximum simulated deposition values should be considered highly uncertain until further research is conducted to reduce these uncertainties."** Despite this acknowledged "high degree of uncertainty," EPA continued to use speciation values without reference when, in fact, actual field data is available.

Using unvalidated air models and models that consistently over predict along with invalid assumptions can yield projected impact results from specific sources that are orders of magnitude higher than they really are.

Water Quality and Terrestrial Models. The model used to predict concentrations in the aquatic and terrestrial compartments, the Indirect Exposure Methodology (IEM2) model, is based on a series of equations initially developed for organic chemicals and is not directly transferable to inorganic mercury compounds. In addition, there are errors in the equations that were used in IEM2. For example, the equation used to predict the gas phase mass transfer coefficient was derived for surface spills of organic liquids and is determined based on the area of the spilled material. This equation is not appropriate for mercury, especially in the case of an ionic species such as Hg(II) or monomethylmercury.

The diffusion of mercury from air to the ground surface or water should be governed by a concentration gradient, but the IEM2 model does not address this factor. The IEM2 model equations also do not address any chemical transformations affecting mercury in soil, water or sediments (oxidation, reduction, methylation, demethylation), nor do they address physicochemical properties important to inorganic chemicals (complex equilibrium, dissolution, precipitation). The chemistry of mercury is complex and dynamic and must be accounted for if a reasonably accurate picture is to be developed concerning mercury's behavior in the environment.

EPA also notes that the model "cannot be used to predict response to reduction or elimination of loadings." Thus, the IEM2 model treats lakes like a bathtub without a drain. If a source reduces its emission or stops emitting altogether, there is no decrease in deposition over time. This is an obvious critical flaw in the model. This disconnect between reality and the IEM2 modeling methodology results in an inaccurate depiction of the potential impacts of mercury.

In addition, the models used to predict sediment concentrations have not been validated, and are likely to produce unrealistic results. Based upon the above, it is estimated that EPA's use of IEM2 and the associated assumptions result in a one to two orders of magnitude overestimation of mercury impacts.

Impacts on Fish. The methodology used to calculate concentrations of mercury in water does not adequately address the complex nature of the mercury biogeochemical cycle in the aquatic environment. The EPA model structure is overly simplified, with the soil-water partition coefficient assuming

inordinate importance in predicting mercury behavior. Many other equally or more important factors and reactions affecting mercury behavior in reality are not addressed in the model, including acid-base reactions, oxidation-reduction reactions, methylation, complexation, water temperature, pH and dissolved organic carbon. Models that incorporate the factors affecting the behavior of mercury are important adjuncts to predicting bioaccumulation. EPA, however, rejected the use of more refined approaches such as the mercury cycling model (MCM) outlined in Hudson et al. (1994), choosing instead "to accept that considerable variation exists in mercury bioaccumulation in fish". The result of these decisions is a low degree of confidence in the results from the IEM2 model. Numerous alternative aquatic models (e.g., REDEOL, WATE02, MINEOL, MEXAMS) exist that can be used to deal with the equilibria of mercury in aquatic systems. These models incorporate pH effects, redox chemistry, precipitation, surface adsorption, ligand exchange and formation of ternary complexes.

The methodology that EPA used to address mercury bioaccumulation in fish also suffers from uncertainty. The Agency notes in the draft Report that there is a "substantial level of uncertainty" in the bioaccumulation values for the two trophic levels of fish studied, and shows that both the derived bioaccumulation factor values and the bioaccumulation factor values based on estimates derived from the literature vary by *more than two orders of magnitude*. The Agency nevertheless uses point estimates for bioaccumulation factors to predict deterministic exposures in the Report without ever analyzing the precise level of uncertainty.

CONGRESS and FEDERAL AGENCIES

Voicing concern over the conclusions in the draft Report, several federal agencies, including the Food and Drug Administration and the Departments of Agriculture, Commerce and Energy, requested that they be allowed to review the Report before it was released (Environment Reporter, April 1996).

One of the primary concerns expressed was how little mention there was in the Report of the National Institute of Environmental Health Sciences (NIEHS)-funded study of the Seychelles Islands. This comprehensive multi-year study was an attempt to overcome the problems of all of the other epidemiologic studies of the health impacts of mercury exposure. EPA based its human health impact analyses in large part upon the results of the study of the mercury contaminated grain episode in Iraq in 1971. The Iraqi study, which was after-the-fact and anecdotal, indicated that fetal exposure to very low levels of mercury would lead to developmental problems. However, many researchers, including the researchers that conducted the Iraqi study have cautioned that the Iraqi study should not be used to derive toxicological assumptions for mercury. EPA also reviewed other mercury-related human health studies, but in most of these case studies, there were limitations and/or confounding factors.

The Seychelles' study is being conducted by a team from the University of Rochester and includes members of the team that conducted the Iraqi study. According to NIEHS, the Seychelles Islands study, "a study of children of heavy, daily fish consumers, demonstrated no developmental damage from the same levels of mercury exposure that was found in the Iraqi study." (NIEHS Press Release, 1996.)

Subsequent to the release of the 1995 draft Report, EPA did make some changes in the Report which did address some of IWSA's comments. For example, EPA included three mercury emission speciation scenarios for MWCs: the original speciation assumption and two assumptions which more closely relate to actual measured data from MWCs. The modeling results using these alternative scenarios, which showed insignificant impacts, were not discussed in the Executive Summary nor the Summary and

Conclusions of the revised Report. These speciation scenarios are found on one page of text and three tables in the middle of the 100-plus page Volume III of the revised draft Report.

SCIENCE ADVISORY BOARD

Concerned that EPA might complete the Mercury Report before the important Seychelles work was published, a bipartisan group of Senators and members of Congress asked EPA to delay finalizing the Report until the Seychelles study was released and could be incorporated into the EPA Report. This group also asked EPA to submit the draft Report to EPA's Science Advisory Board (SAB) for review. On June 18, 1996, EPA announced that it was delaying the release of the Report and had sent the revised draft Mercury Report to the SAB to begin its review.

On February 26 and 27, 1997, the Mercury Subcommittee of the SAB held a Public Meeting to review their findings and receive comments from the public on the draft Report. According to published accounts (Daily Environment Report, February 1997) the Subcommittee strongly criticized the computer risk assessment models used by EPA as inadequate and unable to predict impacts from specific sources, and that EPA should not imply that the models are capable of accurately predicting impacts on humans, wildlife or aquatic life. The SAB panel pointed to EPA's own admission that the models are incapable of predicting the change in impacts on human health or wildlife due to decreases in any particular source.

The panel also reiterated EPA's own statements that the report and the estimates of risk are based on **qualitative** and not **quantitative** analyses. The panel suggested that EPA either remove the predictive models altogether from the report or make improvements and rerun the models with the qualifier that the results are still qualitative and should not be used for regulatory or risk assessment purposes.

The Subcommittee also pointed out that there is a large amount of mercury in the environment today that is the result of historic practices as well as ongoing activities such as gold and copper mining in South America and Asia that the U.S. has little ability to control. As this reservoir of mercury is re-emitted into the environment, it may equal the total current anthropogenic emissions. Therefore, additional controls on current mercury emissions in the U.S. may have little impact on the amount of mercury deposited in the U.S.

The Subcommittee nonetheless endorsed the Report's overall conclusion that exposure to methylmercury is harmful even at relatively low doses based upon the Iraqi and other studies cited in the draft Report. The Seychelles' studies included a small number of outlier results which the Seychelles' researchers felt could justifiably be removed from the evaluation. Without these outliers, the Seychelles' study showed no health impacts at the low levels reported in the previous studies. With the outliers, the results were unclear. The Panel believed that there was insufficient justification for discarding the outliers, and that meaningful results from Seychelles studies were still two years off.

The Panel found that EPA's current reference dose (Rfd), based on the Iraqi study, was within an order of magnitude of that suggested the other studies EPA reviewed and the Seychelles' study, and that this is within an acceptable margin of safety. Therefore, the Panel determined that EPA should not revise its Rfd.

SUMMARY

There are so many errors and questionable assumptions in the draft Mercury Report to Congress that it would take many more pages to discuss them all in detail than can be done so here. Some of the errors don't even pass a logic test, e.g., in the Report, EPA predicted that a single large municipal waste combustor could cause a mercury concentration of 26 ug/g in fish in a nearby lake, and yet, the highest concentration of mercury in fish in EPA's database is 8.9 ug/g. No fish sampled near an operating MWC have ever yielded a mercury level of even approaching 8 ug/g.

In many parts of the report, EPA states that there is substantial uncertainty or variability inherent in the modeling input parameters, such as the deposition flux rate or the fish bioaccumulation factor and fish ingestion rates. However, these caveats are not adequately carried through to the results of the analysis and therefore do not allow the reader to place the information into a reasonable context.

EPA has taken the approach of speculating on the worst case, hypothetical, potential impact that might ever occur using the most rudimentary and convenient models and assumptions. The failure to carry acknowledged uncertainties through into the main body of the analysis will lead to misinterpretation of results. These errors and assumptions can result in overestimating predictions of potential risk by several orders of magnitude.

The EPA Science Advisory Board Mercury Subcommittee has criticized EPA for many of the same reasons that others have, e.g., that characterizing the risk to human health and wildlife cannot be done in a quantitative fashion since the various models do not have the ability to accurately predict the health impacts of anthropogenic source emissions and their indirect exposure pathways. However, the SAB did not suggest that EPA increase the Rfd based upon the results of the Seychelles study. The studies that EPA relied upon were flawed and contain confounding factors which make it difficult to specifically attribute a cause/effect relationship to mercury. Even though the results of the Seychelles study show that the Rfd is within an order of magnitude of the one proposed by EPA, the Rfd for mercury should still be increased since it is based upon a series of studies with questionable results.

Nevertheless, EPA now must address the errors in the Report before a final version is released to Congress and the public.

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Should Regional Municipal Solid Waste Consortia Enter
Incentive Based Service Contracts for Professional Management Services?

John A. Merritt
Merritt Environmental Solutions
152 North Main Street
Natick, MA 01760-2725

INTRODUCTION

There are myriad challenges facing any regional municipal solid waste management consortium today. Consortia of the sort discussed here include any regional municipal waste authority, board, committee or other governing body. The challenges are especially acute when a waste-to-energy facility is part of the integrated solid waste system. With increasing challenges in the regulatory, technical and financial arenas as well as over-worked staffs, managers of many consortia are turning to professional consultants for a variety of support services. Today, these include, not only the more traditional services, such as engineering, accounting and legal, but also often include business management services, as well.

There are many areas in which solid waste management consultants are asked to provide specialized support to public, waste-to-energy consortia. Three commonly sought services are: a) negotiating contracts and other potentially adversarial matters, b) procuring specialized goods and services and c) marketing facility capacity. In each of these areas, taxpayer dollars can be saved or squandered. Some argue that “success based” or incentivized contracts provide management consultants very strong motivation to get the best deal possible for the client. Remuneration is based on pre-determined benchmarks, and escalates as the client’s benefit increases. In some cases, management consultants charge lower than standard rates during a given project, in return for a larger total return if successful.

When appropriate, these contracts can provide excellent results. However, there are circumstances when such arrangements can lead to unexpected, negative consequences. This is particularly true when the client consists of many autonomous municipalities. This paper reviews typical, support services a waste-to-energy consortium might seek from a management consultant. It also discusses incentive based contracts and how to avoid their potential problems.

TYPICAL MANAGEMENT SERVICES

Negotiation Services

Consortium Formation -- Contractual relationships among municipal consortium members, typically include governing, as well as, operational by-laws. These by-laws need to be developed and executed to form the group in the first place. The appropriate regional relationships can, and do, vary dramatically. Some consortia are relatively informal, ad hoc, committees or commissions, focusing upon relatively narrow goals. At the other end of the spectrum are formal, solid waste districts with powers to take land, develop significant facilities and assess taxes. Management consultants, with appropriate experience, can help negotiate agreements that will provide the structure required to accomplish shared goals, without adding unneeded bureaucracy. The significance of a consortium’s by-laws, with respect to incentive based contracts, is discussed below.

Contracts – Contracts, for goods and services, between a waste-to-energy consortium and a wide variety of vendors, typically represent millions of dollars. Initial agreements must be negotiated aggressively, in the consortium’s interest. After being executed, conditions frequently change, requiring re-negotiation or dispute resolution. The highly specialized nature of many of these goods and services has led some consortia to seek focused assistance to negotiate such contracts. Such service can help develop

appropriate specifications, provide additional oversight and save money by negotiating favorable terms. Re-negotiation, particularly in adversarial circumstances, requires a strong understanding of available leverage. Sometimes, that leverage is chiefly financial. Often, it can also include components of law, technology and public opinion. A complicated negotiation, like restructuring a consortium's basic service agreement with a facility owner and/or operator, would benefit from the services of professionals in several fields. There are circumstances where incentive based contracts for these services may be appropriate.

Regulatory Issues -- Negotiations to resolve compliance or other regulatory issues, arising from operations or changes in law, require a thorough understanding of the relevant agencies and issues. Since these matters often arise in a very public and, therefore, political climate, it is critical to identify management consultants with proven communication and dispute resolution skills. The cost of not mitigating these issues immediately and effectively can be significant.

Incentive based contracts are rarely appropriate in these circumstances. While there often is a financial component to these issues, they also introduce the notion of the public interest. The appearance of the consultant arguing against the public interest, for financial gain, is unseemly.

Procurement Services

Procuring ash management/recycling services, waste handling/processing equipment or exotic chemicals are typical responsibilities of a waste-to-energy consortium. It is critical to draft clear, focused RFPs/RFQs to maximize competition for the consortium's business. When possible, holding pre-proposal conferences, reviewing potential vendors' assessments of the current market and revising procurement documents accordingly, when appropriate, are valuable steps. It is important to be familiar with similar, recent procurements elsewhere, while tailoring a particular consortium's procurement scope to its unique characteristics. Management consultants, with strong technical and business expertise, can strengthen these efforts. There are some fairly clear instances, where incentive based contracts can be appropriate for these services, discussed below.

Marketing Services

With highly competitive waste markets in many areas, selling excess capacity is critical to the bottom line of many consortia. Unfilled capacity can mean increases in tip fees to offset revenue loss. Management consultants, with effective waste market identification and penetration strategies can help maintain maximum throughput.

This is a very natural area for incentive based contracts. Goals and current baselines can be readily established and are clear. Improvements are reasonably easy to measure.

INCENTIVE BASED CONTRACTS FOR MANAGEMENT SERVICES

As mentioned in the introduction, a great deal of money is at risk in each of the areas just described. In cases where an objective is clear and unequivocal, an incentive based contract can make a lot of sense. For example, a given consortium's facility currently recovers 50% of the ferrous and receives a contractually established rate for the metal. An incentive based contract could be entered which would pay a management consultant an escalating amount for net financial improvement. If the management

consultant increases the metal recovery rate and/or the rate received for the material to an agreed benchmark, after cost, then a known return will accrue.

In the current example, there are many initial parameters and potential variables that must be pinned down. How much metal is in the stream currently? Will that amount change because of recycling or other external parameters? What actual percentage is currently being recovered? Once they have been established, with provision for externally imposed variables, the project goal can be fairly clearly defined. More importantly, the benefit to all consortium members is clear and mutual.

Generally, procuring well-delineated goods and services can also be appropriate for incentivized arrangements. Management consultants will be motivated to generate the broadest competitive interest and negotiate the most favorable contracts. As long as the client's interest is well known, adequately defined and quantified, these contracts can produce good results.

It is always important, however, to assure that there is no ethical conflict for the management consultant. For example, scenarios where consultants could establish inadequate specifications for the sought goods or services, to keep cost low and maximize their incentives, must be avoided. In cases where there is any question as to the availability of generally accepted standards, independent review of the process should be a component of any incentivized contractual arrangement.

Problem Areas For Incentive Based Contracts

Finally, there are circumstances in which incentivized contracts should generally be avoided altogether. As discussed above, regulatory negotiations present special problems. More generally, however, problems arise when the goal, which defines the client's interest, cannot be clearly and adequately defined.

In a complex negotiation to restructure a consortium's service agreement, for example, it may be difficult to determine, in advance, what will be in the best interest of all the municipalities impacted. The governing rules of the consortium become critically important in cases where those interests diverge as the process develops. It may seem, at the beginning of a large project, that all member communities share the same final goal. However, as time passes, conditions can change dramatically, and all communities may not believe the direction of the project is in their best interest.

Important questions of fairness and equity can arise. For example, should a community, in the minority, continue to be responsible for paying incentives to a management consultant, serving the majority's interest against their own? What mechanism exists for a minority community to escape such expenditure of its funds?

If a consortium decides to enter an incentive based contract, in such complex circumstances, anyway, there are some steps that can be taken to minimize, if not remove, problems of the sort described above:

- Require unanimous votes on matters that can encumber incentive payments to the management consultant
- Establish, in advance, a mechanism allowing dissenting communities to opt out of a process, not in their best interest.

- Spend the time and energy necessary to discuss and define any complex consortium goals as explicitly and clearly as possible.

If it turns out these discussions are troubled and don't result in well defined goals, it is a pretty good sign that an incentive based contract for services would not be advisable. It would make more sense to contract for consultant services, at ordinary rates, to help clarify and define those objectives. If clear, unanimous goals emerge from that process and sufficient safeguards are established to protect minority interests, then incentive based contracts might be considered.

CONCLUSIONS

There are many very good reasons for regional consortia managers to seek specialized assistance with the many challenges they face. In some, well-defined projects, incentive based contracts with service providers can promote excellent results for the consortium. However, when the project is very large and complex, with goals that aren't sufficiently clear, regional consortia must be very careful before executing such contracts. At a minimum, contractual safeguards and remedies must be implemented. They must guard against any member ever having to pay incentives to a management consultant, to work against their own interest. If such safeguards are not possible or practicable, the incentive based contract should be avoided altogether.

The Waste-to-Energy Sector and
the Mitigation of Greenhouse Gas Emissions

Stephen C. Fotis
Van Ness Feldman
1050 Thomas Jefferson Street, N.W.
Washington, DC 20007

David Sussman
Poubelle Associates
704 6th Street, S.W.
Washington, DC 20024

INTRODUCTION

The waste-to-energy sector provides one important avenue for the United States to reduce greenhouse gas (GHG) emissions. The purpose of this paper is to highlight the significant GHG reductions capable of being achieved by the waste-to-energy (WTE) sector through avoided fossil generation and reduced municipal landfills. The paper begins with a review of the current voluntary reporting mechanism for “registering” GHG reduction credits under section 1605(b) of the Energy Policy Act of 1992. The paper then provides an overview of possible emerging international and domestic trends that could ultimately lead to mandatory targets and timetables for GHG mitigation in the United States and other countries. The paper ends with an analysis of the GHG benefits achievable by the WTE sector, based on the section 1605(b) report filed by the Integrated Waste Services Association (IWSA) on the GHG emissions avoided for year 1995.

MECHANISM FOR REPORTING GREENHOUSE GAS EMISSIONS REDUCTIONS

On October 19, 1994, the Department of Energy (DOE) released final guidelines for reporting GHG emissions as required by section 1605(b) of the Energy Policy Act of 1992. These guidelines include six technical support documents for accounting and reporting GHG reductions from each of the following sectors: electricity supply, residential and commercial buildings, transportation, forestry, and agriculture. Entities may wish to report GHG emissions in order to gain recognition, to establish a public record for emissions and reductions for future reference, and to demonstrate support for voluntary approaches to achieving environmental policy goals. Participation in the voluntary reporting program could help to document the significant contribution that the waste-to-energy sector makes to meeting the United States' commitment to reducing GHG emissions.

Although DOE has created an extremely flexible program with many options for the voluntary reporting of GHG emissions and reductions, the agency also encourages the submission of as comprehensive a report as possible. A comprehensive report would include information about: the entire organization and all its GHG activities, historic baseline emissions data for 1987 through 1990, annual emissions, emissions reductions and carbon sequestration projects, other participants in the project, emissions factors used to determine reductions, data on secondary and indirect impacts of the mitigation project, assumptions about the project, and data sources.

DOE pressure for comprehensive reporting poses some risks for section 1605(b) participants. The failure to submit a comprehensive report could undermine the creditability of the underlying mitigation activity. Specifically, it is possible that participants will not receive the full credit and recognition for GHG reductions achieved if they submit only the minimum data required under the section 1605(b) program.

EPAct Section 1605(b) Reporting

Overview of Guidelines.

The guidelines are mandated under section 1605(b) of the Energy Policy Act of 1992, which requires DOE to provide guidance for the voluntary reporting of GHG emissions, their reduction, and carbon fixation achieved through any measure. The guidelines provide information on who may report, what

information may be reported, and how projects should be analyzed for reporting. As a general matter, the guidelines are extremely flexible and are structured in such a way as to promote broad participation. This flexibility should enable utilities to receive credit for GHG reductions achieved through a wide range of measures for mitigating GHG emissions.

Forms for reporting have been designed to suit the guidelines' flexibility. Form EIA-1605 allows individuals to give a detailed account of GHG emissions, reductions, and carbon sequestrations for the entire entity (e.g., corporation, facility) or for specific GHG mitigation projects (e.g., GHG reductions achieved through supply-side efficiency improvements). To accommodate those entities wishing to minimize the reporting burdens, DOE has developed Form EIA-1605EZ, a simplified form that only requires a brief synopsis of the GHG emissions reductions achieved by a specific project in the most recent calendar year. Completed forms are submitted to DOE's Energy Information Agency (EIA), which is charged with the responsibility of administering the section 1605(b) reporting program and maintaining the GHG registry (e.g., database).

As indicated above, the guidelines are separated into eight sections: a general guidelines section and six technical support documents dedicated to issues particular to a specific sector or activity area. The discussion below provides a brief summary analysis of the general guidelines and the technical support documents related to the electric supply sector.

Method of Reporting.

Who May Report. The guidelines provide that the following groups or individuals may report: any U.S. citizen or resident alien; any company, organization, or incorporated group; and any federal, state, or local governmental entity. These entities may report their reductions or sequestration efforts as long as they can "define a project and report physical data in enough detail to quantify results of the activity." No minimum reporting threshold is established in order to encourage broad participation and participation by small-scale initiatives.

The DOE rule permits the reporting of activities undertaken in association with others, such as efforts by a utility to implement demand-side efficiency improvements at industrial or commercial facilities (e.g., installation of high-efficiency electric motors or green lighting). In order to avoid double counting, reporters must identify other parties participating in the activity. The rule also allows the reporting by a third party or trade association. As will be discussed below, IWSA has submitted a section 1605(b) report for the entire WTE sector.

What Information May Be Reported. Gases covered in the DOE reporting program include carbon dioxide (CO₂), nitrous oxide, methane, and halogenated carbon substances (e.g., CFCs, HCFCs, PFCs). DOE will count both direct and indirect emissions reduction and sequestration activities related to these four gases. DOE decided against limiting the program solely to direct emissions (which arguably would be more manageable and transparent) in favor of the flexible approach reflected in the guidelines. Direct emissions are those which result from fuel combustion or other processes that release greenhouse gases on-site. Indirect emissions are those which occur off-site from the party whose activities caused the emissions to be generated elsewhere. For example, a manufacturer would report as indirect the emissions associated with the electricity purchased from a utility used to light its assembly plant, since

the production of that electricity had caused emissions elsewhere. In the case of the WTE industry, the principal indirect GHG effect is the avoidance of CO₂ and methane from landfills.

International activities are included in the types of activities that may be reported. The same criteria will be applied to international activities as domestic activities. Difficulties may arise in analyzing the international activity, such as determining the reference case or obtaining credible data, so special attention should be given to direct and indirect effects of these activities.

How to analyze projects for reporting. The project may consist of all emission-producing activities of an organization, several activities, or only one activity. Every report must: (1) define the reference case to use as a basis for comparison with the project, utilizing historic data and/or use projected or modeled data; (2) identify the project's major or minor primary and secondary effects; (3) choose an estimation method using default data or measured/estimated data for the reference case and the project; and (4) report reductions. The general guidelines illustrate the project analysis process in three case studies: an industrial cogeneration project, an energy-efficient project in a large office building complex, and the purchase of new solar-powered electricity generating equipment. These case studies illustrate the varying levels of detail and analysis that can be included in the reports.

Baseline or Reference Case. In order to define the reference case (e.g., the emissions level against which to measure the effects of the project), DOE suggests using either historical data or projected data. Historical data would involve averaging emissions for some previous year(s). An average could be taken from the 1987 to 1990 period, or from some year(s) more accurately reflecting normal operations. Projected data would involve extrapolating the reference case from past trends and external data to determine what emissions would have been in the year in which the project's effects are being measured. This process may involve modeling and adjusting for growth over time. DOE also suggests estimating the emissions per unit of production using historic or current-year data and adjusting for future growth by multiplying this emission rate by the rate of production in the reporting year.

Estimation Methods. DOE provides guidance for choosing the method for estimating emissions levels for both the reference case and the project case to determine emissions reductions. The guidelines and supporting documents recognize three categories of data: physical data, default data, and reporter-generated data. Physical data describes the activities involved in the project. Default data includes emissions factors and stipulated factors. Stipulated factors allow the conversion of physical data about the project into estimates of changes in energy use, GHG emissions, or carbon sequestration. Emissions factors are provided in the specific sector supporting documents, described below.

Projected Mitigation Future Years. In certain cases, the mitigation activity may result in greater GHG reductions in future years than in the current reporting year. One obvious example is a forestry project that will sequester carbon dioxide over a thirty-year period. Although some carbon sequestration may be achieved during the initial year, most of the sequestration will accrue over the life of the forestry project. This is also the case for most WTE projects. As explained in the last section of this paper, the combustion of municipal solid waste provides the greatest GHG benefit by avoiding landfill methane and CO₂ over a 20-to-30 year period. In the final guidance, DOE recognized the problems that could ensue from a purely retrospective GHG reporting system (e.g., reporting only GHG emissions actually

reduced, avoided, or sequestered during the current reporting year). As a result, the final guidelines allow for the reporting of the GHG emissions mitigated for future years as well as the current reporting year.

Electricity Supply Sector. Utilities have the flexibility of reporting for their entire system, one specific project, or at some level in between. The "supply sector" technical document is intended to assist utilities in determining an appropriate scope for the reporting of their projects.

The DOE identifies the following types of emissions reduction measures that will be creditable under the section 1605(b) program:

- fuel substitution;
- direct carbon removal by "cleaning" the fuel prior to combustion or by "scrubbing" the emission stream following combustion;
- energy efficiency improvements in electricity generation, conversion, and transfer; and
- energy efficiency improvements in the end-use equipment (e.g., reducing energy demand).

The guidelines presents a standard methodology for estimating reductions from such projects, activities, and measures. The method is applicable to both carbon dioxide and non-carbon dioxide greenhouse gases and can be used to compute emissions from carbon content or from various technologies employed in the electricity supply sector.

FUTURE TRENDS

International

The Framework Convention on Climate Change is an international agreement that was signed by the U.S. and more than 150 nations at the Earth Summit in Rio de Janeiro in June 1992. The agreement committed signatory nations to take non-binding actions to reduce GHG emissions to 1990 levels by 2000. Emission levels for post-2000 were to be determined through subsequent negotiations following the Rio Convention.

The first of these negotiations -- the First Conference of the Parties of the Framework Convention on Climate Change -- occurred in Berlin in April 1995. At this conference, the parties agreed to launch a two year process to define actions and advance commitments to reduce GHG emissions in the post-2000 time frame. This agreement later became known as the "Berlin Mandate." The Second Conference of the Parties was held in Geneva from July 8-19, 1996. The Third Conference of the Parties is scheduled for December 1997 in Kyoto, Japan.

Geneva Conference. At the Geneva Conference, U.S. officials announced that for the first time the U.S. will seek to set verifiable and binding targets to reduce GHG emissions through an international agreement. On July 17, in a speech at the Second Conference of the Parties of the Framework

Convention on Climate Change in Geneva, Tim Wirth, Under Secretary of State for Global Affairs, stated that the U.S. is committed to reducing greenhouse gases, and that only through the setting of binding targets can progress toward emissions reductions be assured. Further, the setting of targets to reduce greenhouse gases must be achieved through maximum flexibility of implementation, which may include joint implementation and trading mechanisms. However, the U.S. proposal does not outline specific targets or goals for emission reductions -- specific numbers are to be decided through international negotiations at a later date.

In his speech, Wirth outlined the goals of the U.S. policy in seeking a binding agreement:

- the U.S. will focus on outcomes that are “real and achievable” and that will seek measured adjustments so that all nations may reduce emissions in an “economically sensible manner”;
- the U.S. will seek market-based solutions that are flexible and fair and will not accept proposals that seek to gain an economic competitive advantage;
- the U.S. will seek a proposal that will require the participation of all nations, developing and developed, to take steps to limit emissions (the U.S. will continue to provide technical assistance to nations to help them reduce greenhouse emissions); and,
- the U.S. will seek to set verifiable and binding medium-term targets to reduce greenhouse gases.

In addition to outlining the guidelines for the U.S. proposal, Wirth criticized other proposals that have been submitted as being neither “realistic nor achievable.” Further, Wirth underscored the importance of flexibility in the implementation of global emission reductions and that governments should be able to decide how they will achieve the reductions.

International Panel on Climate Change Report. Also presented in Geneva was a report by the Intergovernmental Panel on Climate Change (IPCC) on the environmental and socioeconomic impacts of climate change. Released in 1995, the IPCC report concluded that human activities have an adverse affect on climate change. These findings were officially accepted and supported by the Clinton Administration during the Geneva Conference.

Ministerial Declaration and Future Climate Change Activities. On the last day of the Geneva Convention, a ministerial declaration was adopted that calls for, or encourages, the development and establishment of legally binding post-2000 limits on GHG emissions. Provisions within this agreement, the “Geneva Declaration,” encourage the development of legally binding emissions targets for developed countries and emissions reduction commitments from developing countries; endorse the conclusions of the IPCC report; support a U.S. recommendation that legally binding medium-term emission targets be pursued; and, urge expedited development, application, diffusion and transfer of climate friendly technology.

In December 1996, the Ad Hoc Group on the Berlin Mandate (AGBM) met to begin negotiations for emission reduction targets suggested in the Declaration. At that meeting, Parties to the Convention were asked to submit draft proposals for the climate change agreement for review at the next round of negotiations.

Move Towards Post 2000 Targets. The next negotiation session on the U.N. Framework on Climate Change was again held under the auspices of the AGBM in Bonn, Germany from February 25 to March 7. At that time, all draft proposals for a protocol, or other legally binding instrument, were reviewed. The 150 nations participating in the meeting failed to outline the bases for a Protocol to the U.N. Framework on Climate Change. There was no agreement on a timetable for reduction of GHG emissions, a CO₂ reduction target, or on whether reductions should be achieved through coordinated international policies or through policies determined by the individual countries. In the next step, the proposals will be combined into one document which will be distributed by June 1 and reviewed at the next AGBM meeting, scheduled to be held on July 28 - August 7 in Bonn, Germany.

Several different proposals were submitted for treaty negotiations. In January, the United States unveiled its proposal for tradeable emissions budgets to reduce the level of GHG emissions (see discussion below). In a move which surprised observers, the European Union (EU) agreed to call on industrial nations to cut GHG emissions by 15% by 2010. However, member countries were able to agree on country-by-country targets for only a 10% reduction. The remaining 5% reduction would be negotiated later. Other countries, notably the Pacific island states under threat from a rising sea level caused by global warming, are demanding a 20% reduction by 2005.

All of these proposals were criticized. The United States' proposal to create a system of tradeable GHG emission credits received a cool response from delegates and was attacked by environmental groups as "unintelligible, unpopular and extremely complicated." The United States and Japan claimed that the EU's proposal was not a firm commitment, but was simply an international negotiating position. In addition, the proposal was criticized because the proposed 15% reduction would be met by the EU as a whole, allowing some member countries to actually increase their emission levels. Industrialized nations reject the possibility of a 20% reduction on GHG emissions. Some industrialized nations continue to oppose the imposition of binding targets only on developed nations, claiming such a regime would allow developing countries an unfair trade imbalance because of the additional cost of goods produced under an emissions cap.

After the Bonn meeting, the United States proposed that Japan and the United States form a bilateral joint initiative to lead the world community in solving the global warming problem. Specific details of such a proposal have not been released, but Vice President Al Gore has stated that the proposal could be the basis for climate change negotiations later this year.

One final negotiating session is scheduled for October 20-21 before the Third Conference of the Parties to the UN Framework Convention on Climate Change meeting scheduled for December 1-12, 1997 in Kyoto, Japan. At the Third Conference of the Parties, the Parties will decide on what provisions will be included in a final agreement on climate change. The United Nations has insisted that the final agreement must include binding commitments to limit greenhouse gases.

National

U.S. Draft Climate Change Proposal. On January 17, the U.S. submitted its draft protocol to the United Nations for consideration in the climate change negotiations. The U.S. draft document proposes a number of provisions that the U.S. would like included in the final climate change agreement, including the strengthening of commitments by developing countries and the creation of emission trading provisions for developed countries.

The U.S. draft proposal includes a “trigger mechanism” that calls for the creation of a negotiation process that would include binding provisions for developing countries to reduce emissions to be completed by the year 2005. This negotiation process would take place through a separate round of negotiations after the Third Conference of the Parties is complete. The current climate change proposal under consideration by the Parties requires developed nations to take mandatory steps to reduce emissions, while developing countries are encouraged on a voluntary basis.

Further, the U.S. draft proposal would require developing countries to undertake the following:

- prepare annual reports on emissions inventories and report on steps to reduce emissions; and,
- identify and implement measures, not yet specified, to mitigate emissions.

For developed nations, the draft protocol proposes:

- to establish an “emission budget” for each country. The emission budget would encompass a multiple year period (or “budget period”) in which a country would be allowed to “bank” emissions credits not used during the current period for future use, to “borrow” emissions credits (with a penalty) from a subsequent budget period, or trade emissions. The draft does not specify the size of the emission budgets (*i.e.* emissions allowances) or the duration of the budget periods (yet to be determined). The U.S. is currently considering budget periods between 3-10 years. In addition, the U.S. draft proposal states that after the first budget period and corresponding emission budget allowance, subsequent emission budgets must be less than or equal to the previous emission budget;
- to establish a process for reviewing developing country reports and improve emission reduction strategies;
- to allow emissions trading between countries with emissions budgets;
- to permit joint implementation between developed and developing countries, through which developed countries would receive emission credits for transferring energy efficient technology to developing countries; and,
- to create a national system for measuring emissions and reporting annually on measurement, compliance and enforcement practices for the relevant budget period.

Current political climate. In response to the U.S. policy shift toward verifiable and binding targets to reduce GHG emissions, both the Senate and House Commerce Committees held hearings in September on the status of the climate change negotiations.

At the hearings, House and Senate Members expressed concern regarding the Administration's position in the climate change negotiations. Several Members criticized the Administration for acting hastily on this issue without sufficient scientific data and for supporting positions that could harm the American economy and cost American jobs. Further, Members of Congress disagreed with any policy that would set binding emissions reduction targets for developed, but not for developing, countries.

The response to the new draft protocol has been lukewarm in the United States. Environmentalists feel that the unanticipated move toward flexibility in reaching emissions targets is a step backward. They also claim that the logistics of implementing an emissions trading plan, and then verifying its success or failure, will prove to be difficult. Industry, on the other hand, urges the administration to analyze the economic impacts of current climate change policy before committing itself to targets and time tables. However, in February more than 2,000 economists, including six Nobel Laureates, signed a statement declaring that preventive, market-based steps are necessary in light of the significant environmental, economic, social and geopolitical risks of global climate change. Such consensus may influence U.S. policy makers.

Committees in the House and Senate have stated that they intend to hold hearings on global climate change during the current Congressional session. Senator John Chafee, Chair of the Environment and Public Works Committee, is calling for nations to meet flexible but binding emissions targets for greenhouse gases. While observers question whether a Republican-controlled Congress would ratify a treaty containing legally binding targets, the United States may be under increasing international pressure to make such a commitment in light of the ranking by the World Wildlife Fund of U.S. efforts to reduce CO₂ emissions as the absolute worst of the 20 major industrialized nations.

WASTE-TO-ENERGY IS CAPABLE OF ACHIEVING SUBSTANTIAL GREENHOUSE GAS EMISSIONS REDUCTIONS

There are approximately 135 municipal waste combustion (MWC) facilities currently operating in the United States. Most of the MWC facilities (91) are waste-to-energy plants that generate electricity or steam by feeding mixed municipal waste into large furnaces dedicated solely to burning trash. In a limited number of cases (23), the MWC facility generates electricity or steam by burning a refuse-derived fuel (RDF) that has removed recyclable and unburnable materials and then shredded or processed the remaining trash into a uniform fuel. In addition, there exist 11 RDF processing plants that provide RDF not only for furnaces dedicated to burn RDF, but also boilers that burn fossil fuel or other waste fuels.^{1/}

^{1/}

In 21 cases, the MWC facility is an incinerator that combusts trash but does not recover energy from waste.

This section discusses several ways in which one might expect waste-to-energy facilities to mitigate GHG emissions. The first is the CO₂ that would have been emitted from the combustion of fossil fuel in order to generate electricity or steam. The second is the avoidance of methane and CO₂ that would have been emitted if the municipal solid waste had been disposed in a landfill instead of burned in MWC facility. As the discussion below indicates, the greatest opportunity for GHG mitigation exists from avoiding landfill gas emissions as well as ash reuse for various commercial purposes. The discussion below is based on IWSA's section 1605(b) report submitted to the EIA on GHG emissions avoided by the WTE industry for the year 1995.^{2/}

Avoided Fossil Generation.

One important benefit of waste-to-energy facilities is that they displace the use of fossil fuel for generating electrical power and steam. In 1995, for example, the waste-to-energy sector combusted over 31 million tons of municipal waste. The combustion of this fuel source resulted in the generation of 2650 megawatts of electricity every hour^{3/} and the export of nearly 1.4 million pounds of steam every hour. As a point of reference, this energy output is sufficient to meet the power needs of 1.2 million homes and businesses across the country. In addition, the combustion of this municipal waste avoided the use of about 30 million barrels of crude oil or almost 9 million tons of bituminous coal that would be necessary to generate an equivalent energy output.

The avoidance of fossil fuels in such a substantial amount has many clear energy, economic, and environmental benefits for the nation. Unfortunately, a direct net reduction in GHG emissions is not one of them. Using year 1995 as an example, waste-to-energy facilities emitted 31.3 million tons of CO₂ emissions to generate 2650 megawatts per hour. This represents a CO₂ emissions increase of slightly over 9 million tons, when compared against the CO₂ levels that would have been emitted from replacement coal-fired generation.^{4/} In assessing the total GHG consequences of WTE facilities, the analysis does not end with a simple comparison of WTE and power plant emissions. As the next subsection indicates, WTE facilities also produce a number of indirect GHG benefits by reducing the amount of MSW deposited in landfills. These benefits more than offset any marginal increase in CO₂ emissions resulting from MSW combustion at WTE facilities.

Avoided Landfill Gases.

CO₂ and methane are two greenhouse gases emitted from landfills as the organic waste decomposes over a 20 to 30 year period. The decomposition begins with aerobic bacteria consuming oxygen while converting organic substances to CO₂, heat and water. This process continues until all available oxygen is depleted. After oxygen depletion, decomposition of organic material continues under anaerobic

^{2/} The authors would like to recognize the efforts of Maria Zannes, President of IWSA, and Greg Gesell, American Ref-Fuel, in preparing the section 1605(b) report submitted on behalf of the WTE sector for year 1995.

^{3/} Assuming parasitic usage of 20 percent, the net power exported into the grid is estimated to be approximately 2120 megawatts of electricity per hour.

^{4/} The combustion of 31.3 million tons of waste by WTE facilities results in about 31.3 million tons in CO₂ emissions. In contrast, coal-fired generation of an equivalent energy output results in 21.1 million tons of CO. The reasons for this decrease of slightly over 9 million tons result from more a favorable heating value, heat rate, and CO₂ conversion factor for fossil fuel sources than waste-to-energy facilities.

conditions. In the absence of oxygen, anaerobic bacteria begin digesting the waste and producing methane. Over the life of the landfill, organic materials will be broken down into CO₂ and methane at ratio of approximately 45:55.

The combustion of MSW avoids the release of both CO₂ and methane from landfills. In the case of 33.3 million tons of MSW combusted in 1995, this translates into the avoidance of about 9 million tons of CO₂ over the life of the landfill. Similarly, landfill methane will be reduced by about 4 million tons over the same time frame. It should be noted that methane has substantially higher global warming potential than CO₂. According to latest estimates, methane has a "heat-trapping" capacity that is some 24.5 times greater than that of CO₂. Applying this factor to instant example, the avoidance of 4 million tons of methane is equivalent to a CO₂ emissions reduction of 98 million tons. Table 1 provides a summary of these GHG benefits. It should be noted that some landfills collect and combust a portion of the emitted methane. A few landfills use this methane for the generation of electricity. (See below.)

The Environmental Protection Agency (EPA) has promulgated New Source Performance Standards (NSPS) and Emissions Guidelines (EG) for landfills under Title I of the Clean Air Act.^{5/} The requirements of the NSPS and EG are basically the same, with the main difference being the timing of implementation and the lead agency. Specifically, EPA administers the NSPS which takes place immediately for affected new landfills, while states implement the EG for affecting existing landfills once States have completed and received EPA approval of their implementation plans. As a general matter, the NSPS and EG standards require the collection and destruction of landfill gases at those facilities with a design capacity of 2.5 million metric tons and with annual non-methane organic compound emissions of at least 50 megagrams per year. Once fully implemented, affected landfills will consist of approximately two thirds of the nation's total landfill capacity. Although some landfills may install an energy recovery system, most facilities are expected to install a flare system that will burn off the collected methane. Although such flaring systems will reduce the amount of methane released into the atmosphere from regulated landfills, the methane combusted by flaring will result in a CO₂ emissions increase of 24.1 million tons. Table 2 provides a summary of these GHG benefits assuming all (e.g., affected and nonaffected) landfills comply with EPA's NSPS and EG requirements.

Ash Reuse.

In recent years, the use of MSW combustion ash has begun to increase for the WTE sector. Fifteen facilities currently are using a portion of their ash either as landfill cover, road building material or artificial reefs. Ash reuse is underway in projects from Florida to Maryland, Minnesota, Pennsylvania, Massachusetts, Tennessee and New York. There exist many additional safe applications of MSW combustion ash, which could provide a useful solid by-product and result in avoidance of GHG emissions. One example is use of WTE ash by-products in many cement and concrete applications as a substitute for portland cement and natural aggregates. The manufacture of portland cement and the mining of natural aggregates require considerable amounts of fossil energy and produce CO₂ emissions. Replacing portland cement or natural aggregates with WTE ash will offset the amount of fossil energy consumed and associated GHG emissions.

^{5/}

See 61 Fed. Reg. 49,9905 (March 12, 1996).

Although not included in IWSA's section 1605(b) report, the use of MSW combustion ash represents another important GHG mitigation benefit resulting from WTE facilities. This mitigation opportunity, however, will only be taken on greater importance as potential barriers to ash reuse are removed.^{6/}

CONCLUSION

WTE facilities have the capability of achieving substantial GHG benefits for the environment. This becomes especially evident when avoided landfill gases are factored into the GHG mitigation analysis. Using 1995 as an example, WTE facilities are capable of achieving what is equivalent to a net CO₂ reduction of up to 98 million tons. If the amount of MSW combusted annually were to triple over the near term, the amount of CO₂-equivalent emissions avoided could increase up to almost 300 million tons per year. Such reductions would substantially contribute to the Clinton Administration's efforts to meet current and future GHG mitigation obligations being negotiated by international treaty.

^{6/} Many of these barriers are related to safety concerns about the MSW combustion ash. These concerns, however, are largely unfounded. Specifically, the WTE sector has been testing for the safe management of MSW combustion ash for over a decade. These studies consistently show that leachate from ash landfills is similar to salty ocean water, with metals content at about the same level as the standards set for safe drinking water. MSW combustion ash tested under federal guidelines has consistently shown to be non-hazardous.

Table 1. NET GHG Benefit for 1995.

Greenhouse Gas	Emissions in Equivalent CO ₂
Avoided Emissions Resulting from WTE Sector	
Fossil Generation CO ₂	22 million tons
Landfill Methane	98 million tons
Landfill CO ₂	9 million tons
Total	129 million tons
Emissions from WTE Sector	
Fossil Generation CO ₂	31 million tons
Net CO₂ Benefit	98 million tons

Table 2. NET GHG Benefit for 1995 (assuming all landfills comply with EPA's NSPS and EG requirements).

Greenhouse Gas	Emissions in Equivalent CO ₂
Avoided Emissions Resulting from WTE Sector	
Fossil Generation CO ₂	22 million tons
Landfill CO ₂	24 million tons
Total	46 million tons
Emissions from WTE Sector	
Fossil Generation CO ₂	31 million tons
Net CO₂ Benefit	15 million tons

TECHNICAL SESSION III

Fluidized Bed Combustion

Detection Of Lateral Non-Uniformities In Fluidized Bed Combustors

A. Venkata Ramayya
Department of Mechanical Engineering
Vellore Engineering College
Vellore
Pin-632 014
Tamilnadu, India

A.Thiyagarajan and S.Amjad Ahmed
Graduate students
Vellore Engineering College
Vellore
Pin-632 014
Tamilnadu, India

ABSTRACT

This paper addresses the detection of lateral non-Uniformities in fluidized bed combustors by a novel probe technique not reported so far, by using the horizontal differential pressure fluctuations associated with bubble flow. The salient features of these fluctuations are highlighted utilizing the simulated records obtained by considering the Davidson's pressure field around a bubble. The simulation approach is validated by a comparison with the measured vertical and horizontal differential fluctuations in a freely bubbling fluidized bed.

INTRODUCTION

The concept of 'fluidization' finds wide application in combustors and incinerators, and from an environmental view point they find wide acceptance. At present they are being pursued vigorously to handle a wide array of fuels including municipal solid waste.

The onset of bubbling in a fluidized bed followed by continuous growth and subsequent eruption at the bed surface, greatly influences solid circulation patterns and gas phase mixing which in turn affects various in-bed processes like heat and mass transfer, erosion of in-bed surfaces, attrition and elutriation. In addition the mobility of a fluidized bed is also affected by distribution of bubbles across the bed cross-section, for the presence of any lateral non-uniformities in bubbling can severely affect the yield of a reactor or a combustor. These non-uniformities can arise on account of uneven distribution of the fluid or partial blockage of distributor plate including the disposition of various internals present in the combustor. It is always desirable to monitor the development of such non-uniformities in the course of operation of large units.

There are various techniques¹ that have been developed for the determination of local bubble characteristics but most of them are limited either to a small depth of observation or are impractical in large beds or hot and corrosive environments of industrial fluidized beds or combustors.² Of late, the interpretation of differential pressure fluctuations in terms of fluidization parameters is receiving considerable attention because of its potential application in demanding environments. Some of the advantageous features of this technique include the inherent robustness of such probes, their amenability for cooling in high temperature applications, the enormous amount of information contained in the response of such probes³, their relative insensitivity to mechanical damage or fouling, the possibility of locating them even outside the system.⁴

Any probe system meant to detect lateral non-uniformities must be able to reveal the presence of bubbles on both sides of its location using as minimum a number of sensors as possible. In this context the present study focusses on the development of a novel probe technique utilizing horizontal pressure differential record which is highly sensitive to the directionality of bubble approach (i.e) from left or right, and, which so far has not been reported.⁵ Specifically this paper addresses the prediction and simulation of horizontal differential pressure fluctuations under the freely bubbling conditions. The effect of growth of bubbles and the presence of other bubbles are considered along with the randomness of the bubble traversing path by considering the pressure field around a Davidson's bubble.⁶ The resulting trends are discussed in relation to those obtained experimentally from a freely bubbling 2-D bed.

SIMULATION OF HORIZONTAL DIFFERENTIAL PRESSURE FLUCTUATIONS

Figure 1 shows a schematic of a typical bubble flow sequence past the horizontal differential pressure probe and the resultant response. Since it is difficult to quantify the pressure distribution around a bubble with wake in terms of an usable model, circular bubbles are considered here. It will be shown later that even with this approach the predicted patterns resemble very closely with the measured records taken under freely bubbling conditions.

Considering the pressure field around a Davidson's bubble⁶ the excess pressure distribution relative to that in the dense phase remote from the bubble can be written as

$$\Delta P_e = \Delta P_s [r/S] \cos\theta \quad r \leq R \quad (1)$$

$$= \Delta P_s [R^3/Sr^2] \cos\theta \quad r > R \quad (2)$$

where

$$\Delta P_s = (\rho_s - \rho_f) (1 - \epsilon_{mf}) g S$$

The normalized pressure gradient recorded by the horizontal differential pressure probe can be related as

$$[\Delta P_e / \Delta P_s] = [\Delta P_e / \Delta P_s]_{right} - [\Delta P_e / \Delta P_s]_{left} \quad (3)$$

(either of the two can be taken as reference) and the variations of this for a random bubble trajectory depicted in Fig.2 can be predicted in time co-ordinates by

$$Y = U_y t \quad (4)$$

$$U_{br} = 2/3 \sqrt{g R} \quad (5)$$

$$\tan\beta = U_x / U_y \quad (6)$$

$$r = \sqrt{E^2 + Y^2} \quad (7)$$

$$\text{and } E = e - Y \tan\beta \quad (8)$$

The effect of bubble growth is simulated by assuming

$$D = D_i + Y^{1.64} \quad (9)$$

to account for a high rate of growth to study the effect of rapid growth on the simulated differential pressure change patterns (This extreme limit corresponds to a growth in size of 60mm across a bed height of 180mm as found in actual measurements⁷). The presence of an another bubble on the pressure change recorded at the probe tip is considered by a summation of the pressure field due to each one when the other is absent and vice versa. This approach is found to be able to predict the pressure patterns satisfactorily under vigorously bubbling conditions as also verified by high speed photography.⁸

The effect of bubble interactions on the velocity of individual bubbles is taken through Clift and Grace model⁹, where for bubbles in vertical alignment.

$$U_1 = U_{\infty 1} + U_2 R_2^3 / (x_d + R_1)^3 \quad (10)$$

$$\begin{aligned} U_2 &= U_{\infty 2} + U_1 R_1^3 / (x_d - R_2)^3 & x_d &\geq R_1 + R_2 \\ &= U_1 + U_{\infty 2} & x_d &< R_1 + R_2 \end{aligned} \quad (11)$$

EXPERIMENTAL

To compare the simulated horizontal pressure differential fluctuations under freely bubbling conditions, measured records⁸ obtained using wall pressure taps on a two-dimensional bed (0.4m x 0.028m) with sand in the size range of 360µm to 550µm are used here. The excess gas velocity range is from 0.03 to 0.23 m/s. Two pressure transducers (HBM PD 0.1, SCANIVALVE 5PSID) coupled to carrier frequency amplifiers (HBM KTS-5) and connected to a microprocessor based signal analyzer (SM 2100B IWATSU) complete the instrumentation setup. The size of the pressure taps is 0.8mm I.D and they are arranged to record simultaneously vertical and horizontal pressure gradients and the adequacy of the time constant verified by changing the data sampling time interval. The data collected correspond to a transducer interrogation frequency of 409 HZ.

RESULTS & DISCUSSION

Effect of bubble growth and obliquity

The effect of bubble growth on the resultant horizontal pressure fluctuation is presented in Fig.3. For a vertically rising bubble, as is the case here, there is a transition from negative to positive gradients followed in between by a dwell period during which the gradient is zero. This dwell period actually represents the time interval during which both the sensors of the probe are engulfed by the bubble. The sensitivity of the probe response to the directionality of the bubble approach (i.e.) from left or right is amply clear by the fact that in the second case the transition is from positive to negative gradient, during the period of bubble to probe interaction. If the bubble starts growing considerably during its ascent and past the probe, its net affect is to alter the time scales involved rather than the nature of fluctuation.

Fig.4(a). depicts the effect of bubble growth for an oblique bubble to probe hit wherein the pressure gradients are always negative for a bubble approaching from left. Again the effect of bubble growth is only to alter the time scales associated with the bubble residence at the probe. For a bubble approaching the probe from right side, the resultant pressure gradients turn out to be always positive, as indicated in Fig. 4(b) for the case with bubble growth . This in conjunction with Fig.3 brings out the extra - ordinary sensitivity of a horizontal pressure gradient record to the directionality and obliquity of the bubble traverse. The deviation from this trend observed for the one without growth

corresponds to a case where the bubble while crossing the probe obliquely does not completely engulf the two sensors of the probe. This can be easily understood by referring to Fig.2 where in

$$L1 = (e+S) \cos\beta > R \quad (12)$$

and

$$L2 = e \cos\beta < R \quad (13)$$

Only when both $L1$ and $L2$ are less than R , the gradients would be either entirely positive like in Fig.4(b) or entirely negative as in Fig.4(a). However the obliquity can be easily discerned from the fact that there is an additional incursion from negative to positive as denoted by the region 'abc' which however is not going to be there for a vertically rising bubble.

Effect of the presence of other bubbles

A comparison of the simulated vertical and horizontal pressure gradient fluctuations for successive bubble flow sequence past the probe is given in Fig .5. This simultaneous comparison of both vertical and horizontal gradients will be used to validate the soundness and utility of the simulation approach by a comparison with experimental records for the same probe configuration.

Figure 5 shows that for an oblique traversing path horizontal gradients are positive as expected and discussed earlier. The vertical pressure gradients are well known and discussed elsewhere.¹⁰ The important point to note here is that when the peak in vertical gradient is lower, the peak in horizontal gradient would be higher and vice versa, as can be seen at time intervals A-a and B-b. In the simulation the bubble interaction is suitably taken into account.

Comparison with experimental records

An experimental record of vertical and horizontal pressure differential changes simultaneously taken is presented in Fig .6. along with the probe configuration. For all the three bubbles marked by vertical gradient pulses A,B and C it can be clearly observed that when vertical gradient peak is larger, the horizontal gradient peak is lower and vice versa. The fact that the horizontal differentials are always positive tends to indicate that it is for an oblique hit with the bubble completely engulfing both the sensors of the probe on its way past the probe. The bubble approach path which can be inferred is from left of the probe. For this path and probes, the direct similarity confirms the simulated patterns are the ones resembling closely with those to be expected in freely bubbling beds.

The effect of closely spaced bubbles on the simulated gradients in both directions is noted in Fig.7. It reveals that for close spacing, the gradients at the nose of the following (trailing) bubble will be higher. The flow path is such that the trailing bubble completely engulfs the probe while the leading bubble tends to avoid one sensor of the horizontal differential probe. The sort of deviation observed here is already discussed in the context of Fig 4(b).

Figure 8 depicts the experimental recordings for close spaced bubbles in a freely bubbling bed. A comparison with the vertical gradient pulse marked D brings in the strong similarity for bubbles in

the process of coalescence. The gradient at the nose of the trailing bubble is greater for both the gradients. The only difference between Fig.7 and Fig.8 is that the size of the leading bubble is smaller for simulated records whereas it is larger for experimental case. Similarly the pulses marked A,B,C and E are for bubbles at various stages of coalescence.

Sensitivity of horizontal differential probe response

Figure 9 tends to show the various utility of horizontal differential trace in the sense that it contains much more information than that contained in a vertical gradient record. For the vertical probe (sensor spacing = 6mm as that for horizontal) the flow path corresponds to a bubble flowing obliquely but roughly midway through the two sensors. The resultant gradient is almost symmetric but the point to be noted here is that, it can't reveal whether the bubble approached from right or left since in both cases the pattern would be same. However, the horizontal gradient while revealing that the bubble completely intercepted the probe while rising obliquely (as the gradients are either completely negative or completely positive) in addition gives the information that it approached from right side of the probe. For a bubble flowing exactly midway through the two sensors of the probe the two peaks in the horizontal gradient pulse will be equal to each other.

It is this feature which facilitates the detection of lateral non-uniformities by requiring the presence of bubbles on both sides of the probe for uniformity in bubbling. The salient features of the horizontal pressure gradient fluctuations could be incorporated in a bubble detection and fluidization quality monitoring program for on line detection of lateral non-uniformities.

Unambiguous bubble detection

By a suitable positioning of the sensors of the probe and taking advantage of the sensitivity of the horizontal gradients to bubble flowpath, it is possible to detect the bubble rather unambiguously. For example, Fig.10 considers a probe system employed by Dent et al¹¹ in a fluidized bed combustor. For a vertically rising bubble midway through the two sensors, the horizontal differential is zero and this feature can be used directly to measure the bubble diameter in conjunction with the vertical gradient information for this probe configuration. For a bubble flowing eccentrically but vertically past the probe, the horizontal differential resembles that of a point pressure fluctuation when it avoids one or both the sensors of the probe.

CONCLUSION

Lateral non-uniformities in fluidized bed combustors can be detected with the help of horizontal differential pressure fluctuations with least number of sensors. A single horizontal differential probe can be used to judge whether or not bubbling is there on both sides of the probe by incorporating the unique sensitivity of this probe response to bubble traversing path in a detection program. Whether the bubble approached from left or right side of the probe can be easily detected since there is a complete transition from one type of pattern to other which are easily distinguishable and can be taken into account. In addition it is also possible to generate more information regarding bubble properties, which is rather authentic and unambiguous.

The technique can be applied in a commercial unit either by making the horizontal differential pressure probes as part of the bed internals or by locating them just on the walls of the combustor. Detection of the presence of lateral non -Uniformities will lead to corrective actions and hence with a better degree of uniformity, the average bubble size can be reduced. This will help in a lower level of elutriation from the top of the bed surface.

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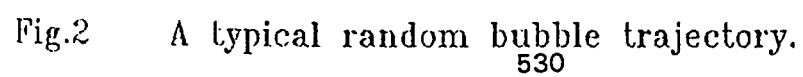
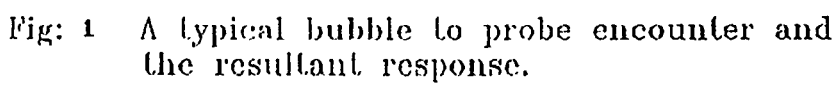
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NOMENCLATURE

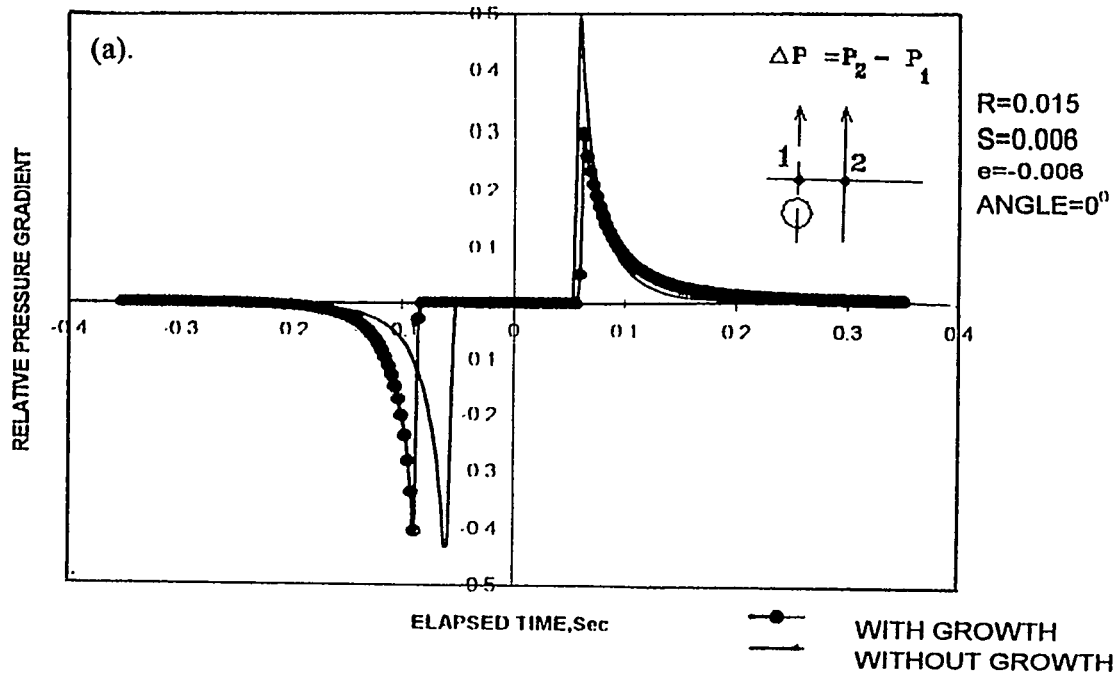
D_p	Particle diameter,m
E	Eccentricity of bubble centre from the sensor,m
e	Eccentricity at the instant bubble nose crossing the probe,m
H_s	Static bed height,m
R	Bubble radius,m
r	Distance between bubble centre and the point of interest,m
S	Sensor spacing of the probe,m
t	Time,s
U	Superficial gas velocity,m/s
U_{br}	Bubble rise velocity ,m/s
U_{boc}	Bubble rise velocity in isolation,m/s
X_d	Vertical distance between two bubble centres,m
Y	Vertical distance between bubble centre and plane of the probe,m
Z	Vertical distance from distributor plate,m
β	Obliquity of bubble centre with probe,degree
Θ	Angle subtended by the line joining the bubble centre and the sensor at a particular instant,degree
ϵ	Voidage
ρ	Density,Kg/m ³

Subscripts

f	Gas
s	Solid
m_f	Minimum fluidization
1	Leading bubble
2	Trailing bubble
X	X Component
Y	Y Component



SINGLE BUBBLE



SINGLE BUBBLE

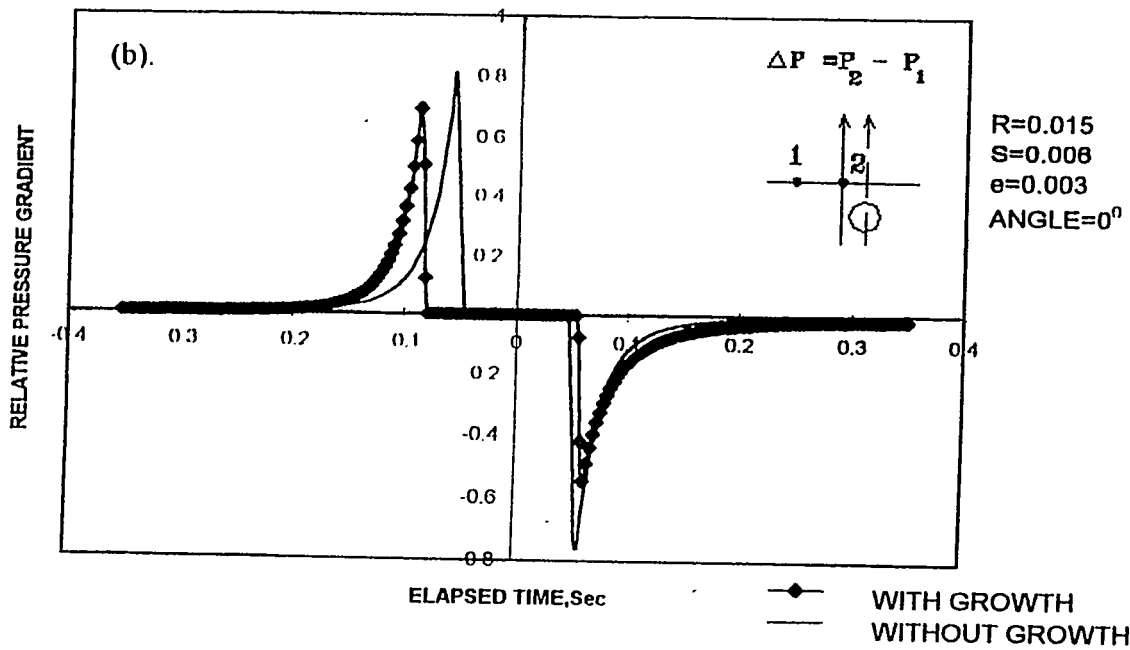
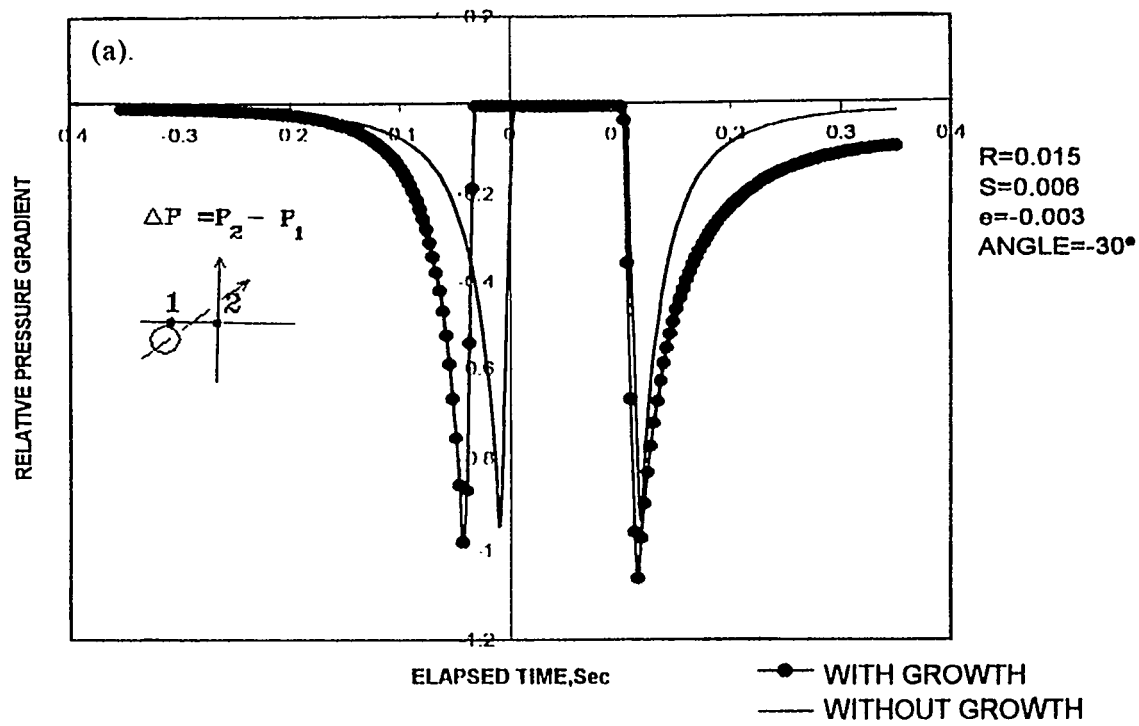


Fig . 3 : The effect of bubble growth on the horizontal pressure gradient record for a vertically rising bubble.

SINGLE BUBBLE



SINGLE BUBBLE

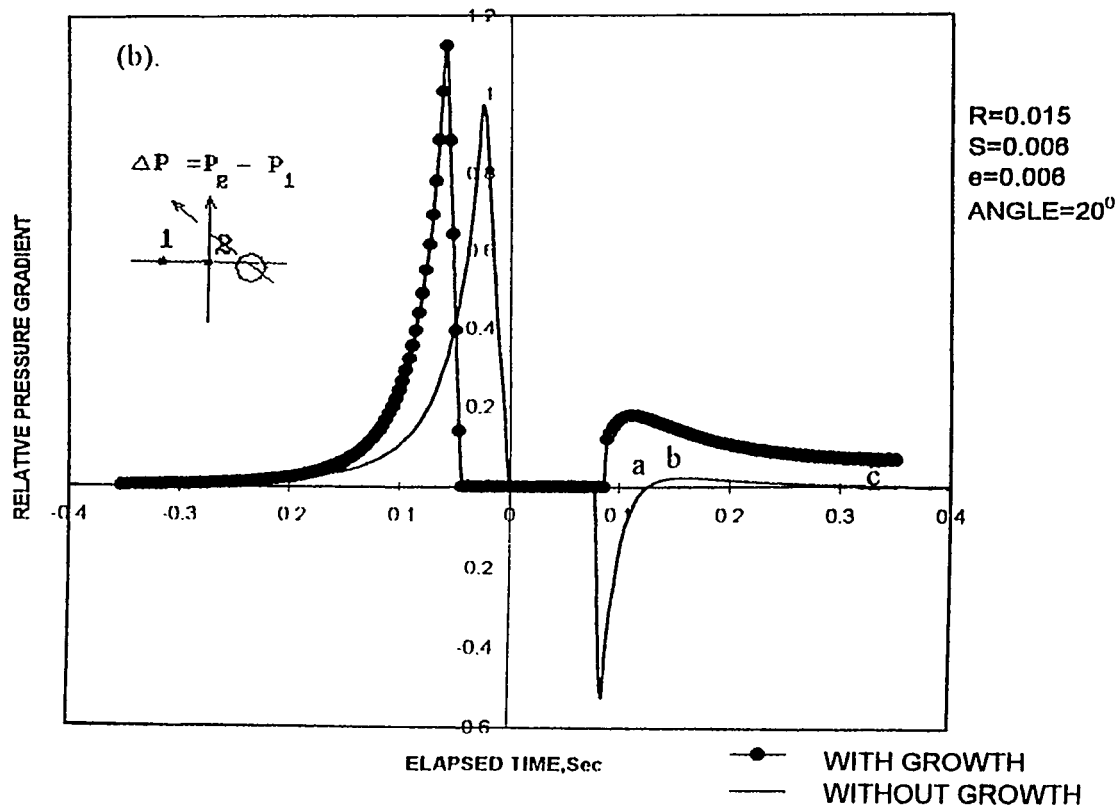


Fig 4 The effect of obliquity and bubble growth on horizontal pressure gradient fluctuation.

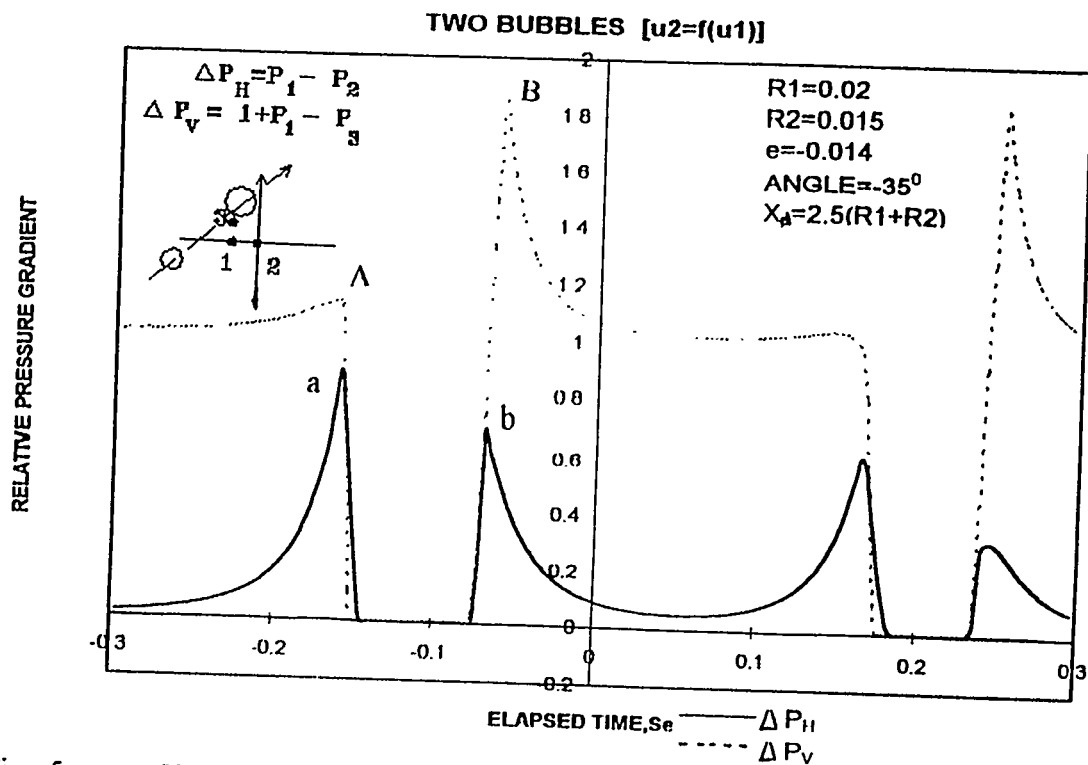


Fig. 5 Simulated vertical and horizontal pressure gradient fluctuations for wide spaced bubbles

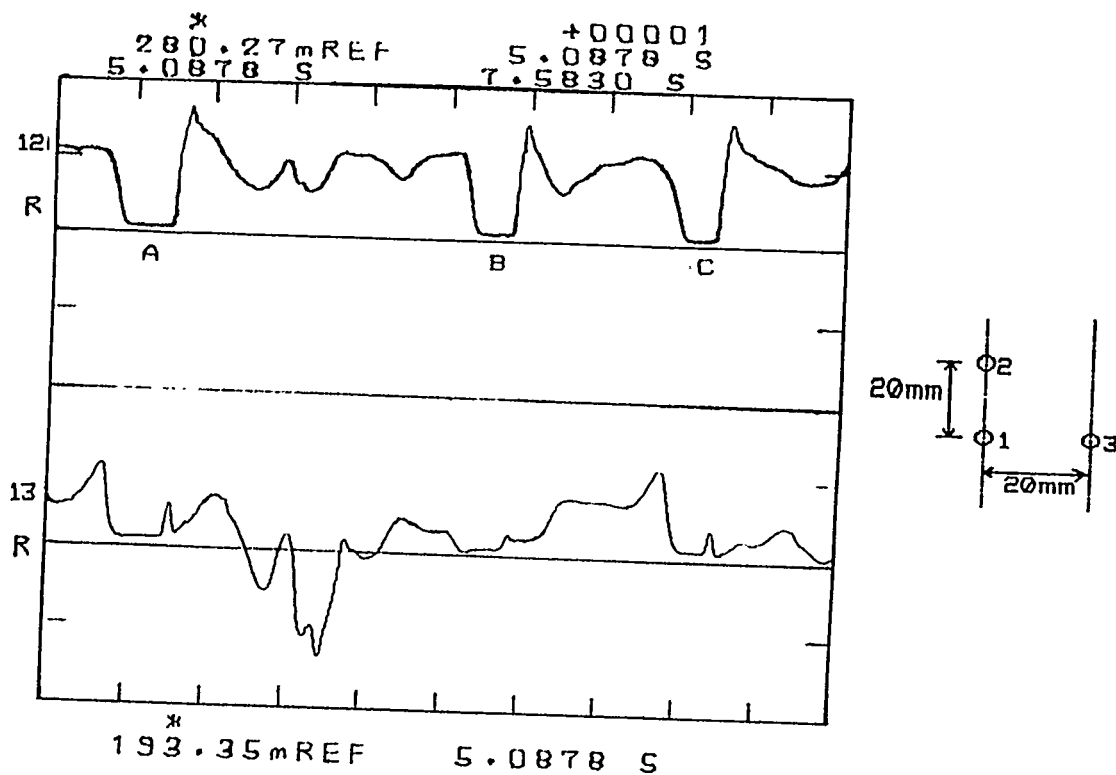


Fig. 6 Experimental recordings of the vertical and horizontal differential pressure changes in a freely bubbling 2-D bed (Sand, $D_p = 402 \mu\text{m}$, $H_s = 0.55 \text{ m}$, $Z = 0.32 \text{ m}$, $U - U_{mf} = 0.15 \text{ m/s}$) from 5.0878 s to 7.5830 s. At 5.0878 s, the vertical pressure differential is 280.27 mREF while that of horizontal pressure differential is 193.35 mREF.

TWO BUBBLES

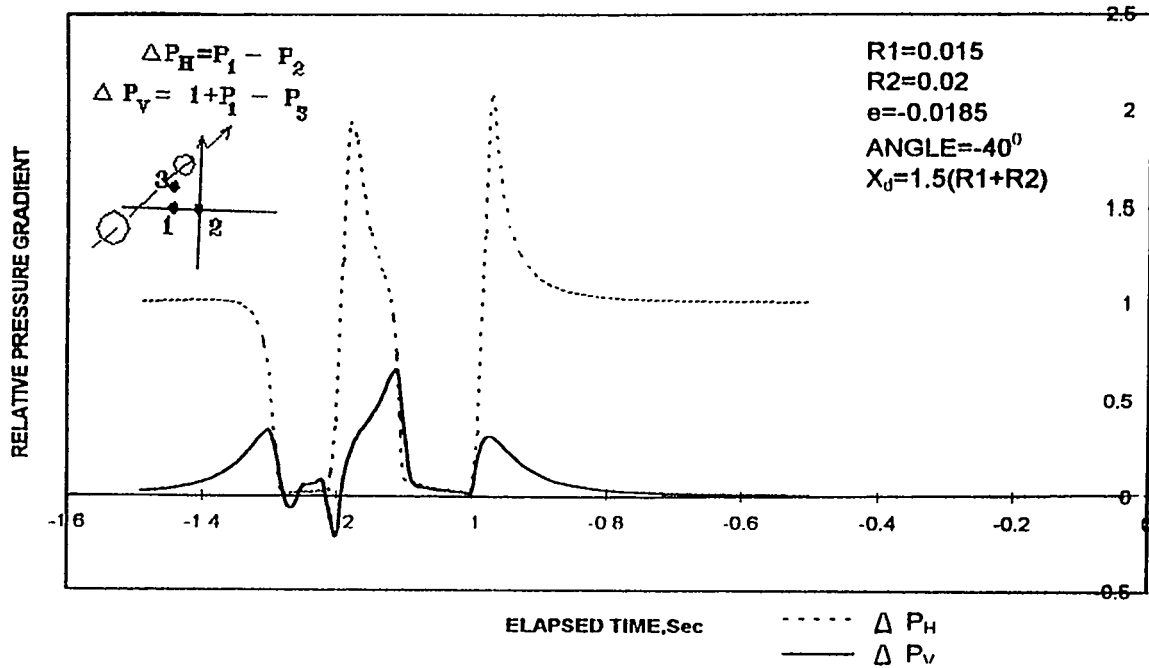


Fig . 7 Simulated vertical and horizontal pressure gradients for close spaced bubbles.

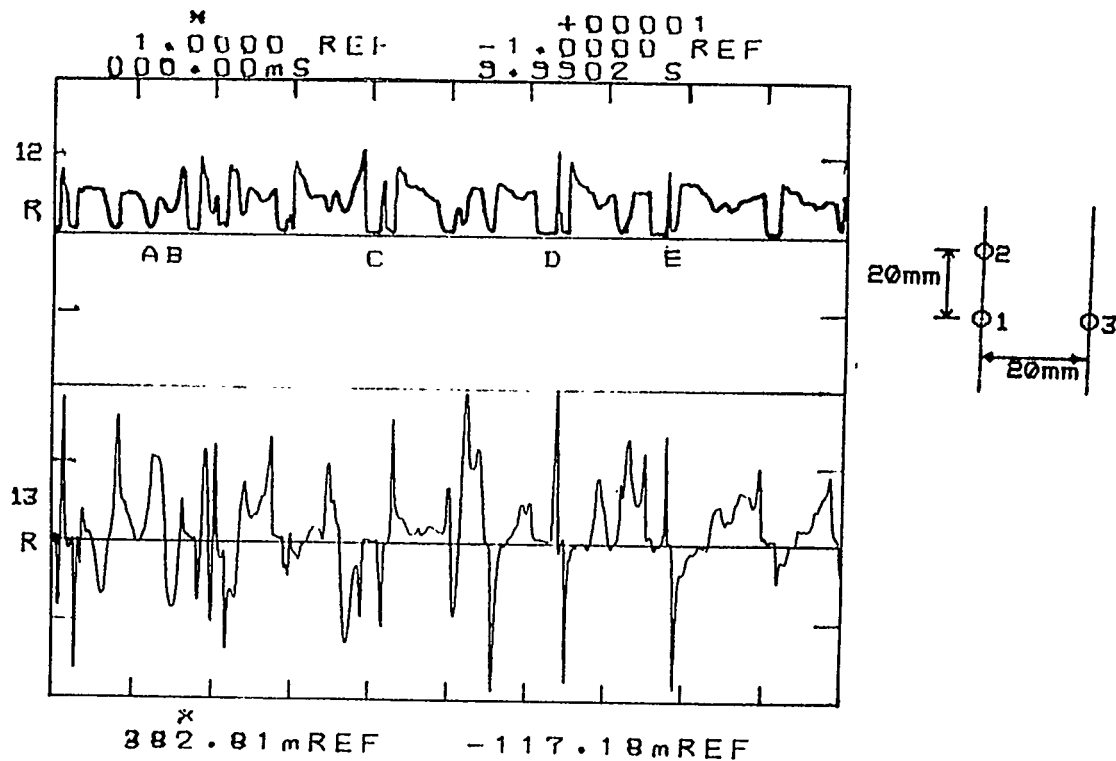


Fig . 8 Experimental recordings of vertical and horizontal differential pressures across a time interval of 9.9902 s in a freely bubbling 2-D bed (Sand , $D_p = 402 \mu m$, $H_c = 0.55 m$, $Z = 0.32 m$, and $U - U_{mf} = 0.18 m/s$). The scale is from 1 REF to -1 REF for vertical and between 382.81 mREF and -117.18 mREF for horizontal differential.

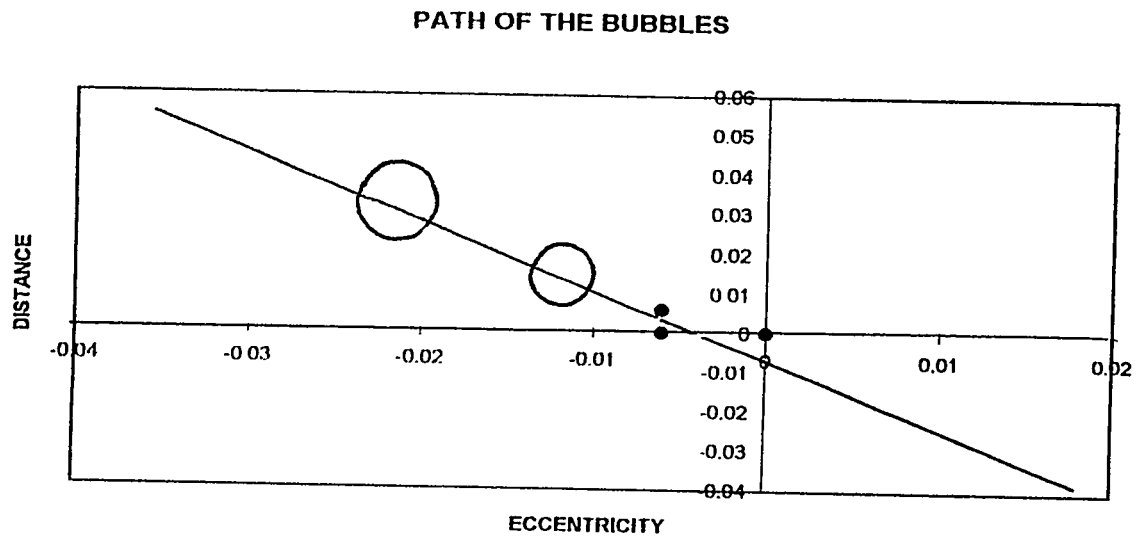
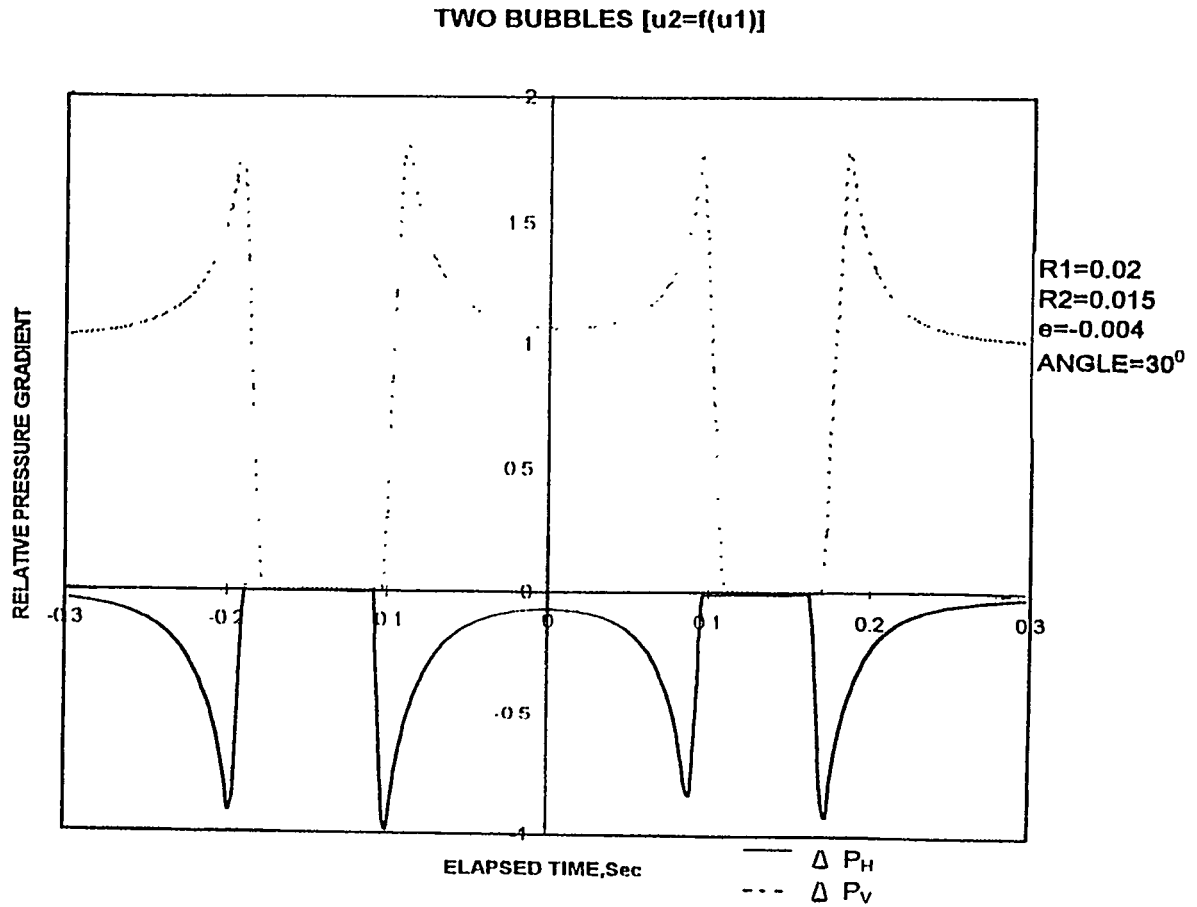
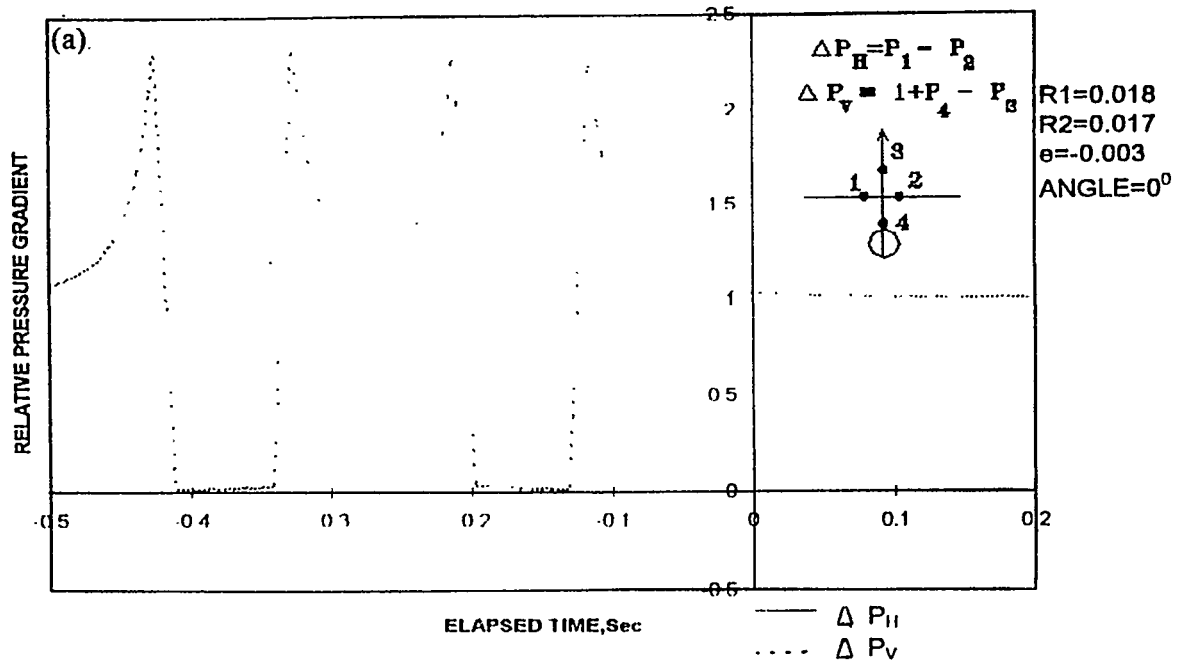


Fig. 9 . Simulated vertical and horizontal pressure gradient fluctuations for a bubble flowing obliquely and midway through the vertical differential probe.

TWO BUBBLES [u2=f(u1)]



TWO BUBBLES [u2=f(u1)]

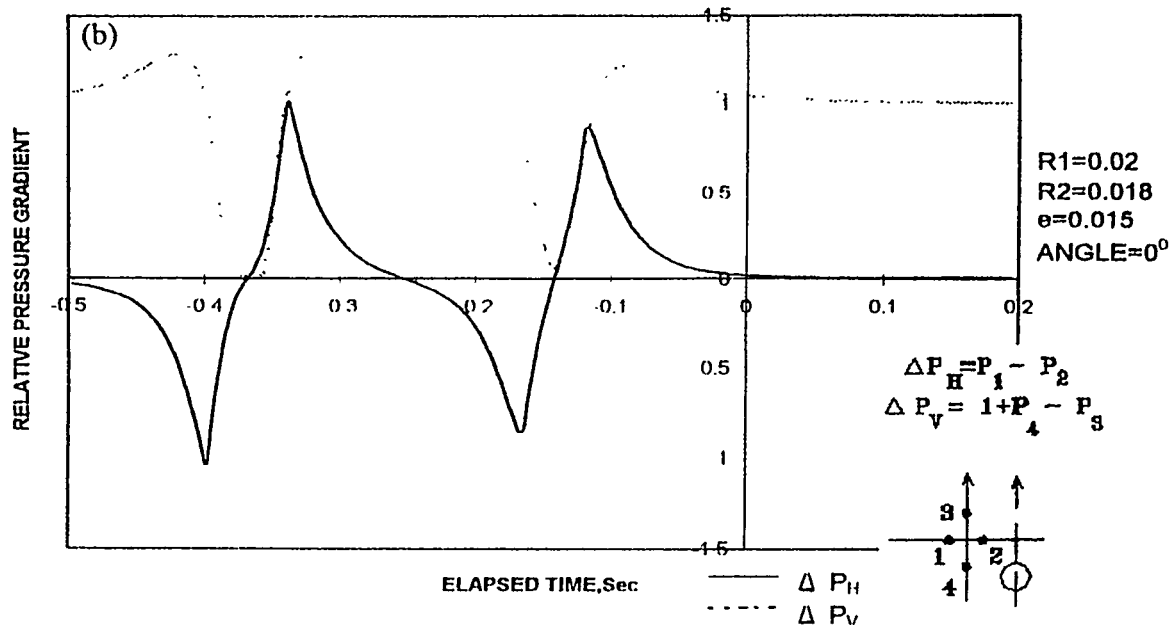


Fig .10 Simulated vertical and horizontal pressure gradient fluctuations for (a) co-axial bubble hit and (b) eccentric hit.

Lime Enhances Moving Bed Filters for Mercury and Dioxin Control

Anthony Licata, Technical Advisor
Dravo Lime Company
345 Concord Road
Yonkers, N.Y. 10710

Ed Goetz
Dravo Lime Company
Research Center
3600 Neville Road
Pittsburgh, PA 15225

Lutz-Peter Nethe
Märker Umwelttechnik GmbH
Oskar Märker Strasse 24
Harburg/Schwaben D-86655, Germany

ABSTRACT

Moving bed carbon filters were developed and used in Europe to control mercury and dioxin emissions from municipal waste combustors (MWCs), crematories, hazardous waste incinerators and power plants. Although some operating problems such as a potential for fires to form in the carbon beds have caused operators some concern, more stable bed materials are presently being produced which can maintain the moving bed filter's capability in reducing mercury and dioxin emissions to very low levels while providing safe operations.

Märker Umwelttechnik GmbH (Märker) and Dravo Lime Company (Dravo) have developed a pelletized form of Sorbalit® that replaces the carbon in moving bed filters and is effective in removing mercury, dioxins, and acid gases without the inherent problems of using a carbon only adsorbent system. Sorbalit pellets are a formulation of portland cement, lime, carbon, and sulfur compounds. These pellets are currently being successfully applied in a hazardous waste incinerator, a foundry, a crematory, and a contaminated soil treatment plant.

This paper discusses the development of pellet technology and its application in moving bed filters. Safety aspects for the use of composite carbon/lime pellets will be discussed and a review of removal efficiencies among carbon alone, a composite carbon/lime material in a powder form, and composite carbon/lime adsorbents in a pellet form will be provided.

INTRODUCTION

The German air pollution regulations, like those in most of Europe, are intended to reduce pollution to the lowest technologically achievable value regardless of economic considerations. This contrasts sharply with U.S. EPA's approach which is to balance the economics of the waste combustor and health benefits of the country. The rationale for the stricter standards in Europe lies in the closer proximity of sources of pollution to residences and business centers, and accordingly requires them to be extremely good neighbors. It is not at all uncommon for local air pollution control regulators and owners of facilities to demand much lower emission limits than those required by the already strict German Federal regulations in order to facilitate community acceptance of the proposed project during permitting. This mind-set to reduce air emissions to the maximum has resulted in cases wherein air pollution control technology systems required as many as five separate control methods/elements to achieve very stringent and contractually required air emissions reductions. To illustrate, Table 2 presents a summary of the emission standards in the 17th BImSchV (present German Federal law) and compares these regulations with the U.S. EPA standards for MWCs with all values converted to metric units for ease of review.

As a positive consequence of this regulatory philosophy, major advancements to the technology of air pollution control were developed in Germany which have resulted in significant reductions in emissions of certain key pollutants such as dioxins, mercury, and acid gases. One innovative approach that was developed in response to the goal of requiring the lowest possible emissions was the use of a moving bed filter as part of a multi-component pollution control system. The moving bed filter, located in the final position, is referred to as a "police" or "polishing filter". The term "polishing filter" is used because the device completes the pollution control process by reducing already low levels of pollutants to extremely low values while catching any potential breakthroughs. Generally, such a device would not be practical, efficient

or economic in reducing high levels of pollutant emissions to code requirements. However, when used to reduce low levels of pollutant emissions, extraordinary results can be achieved. For example, say an upstream pollution control device such as a dry scrubber / fabric filter has reduced SO₂ emissions from 250 ppm to 10 ppm, then typically, the addition of a moving bed filter to the pollution control train downstream of the dry scrubber could reduce or polish the SO₂ emissions from 10 ppm to <1 ppm before discharging the flue gases to the atmosphere. Such results, although unimaginable only a few years ago, are indicative of the progress that can be made when the public demands and is willing to pay for state-of-the-art technology when the possibility, however remote, of negative effects on human health are the alternative and money is viewed as an unlimited resource.

As illustrated in the above example, this innovative multi-component approach to air pollution control utilizing a moving bed filter technology has produced reductions in some pollutant levels on an order of magnitude lower than the already very low levels required by the regulations established in Germany by the 17th BImSchV, the Federal law in Germany which regulates the air emission standards for all waste management facilities.

The following is a summary of typical permit limits required by local government for various waste management projects implemented and built in Germany in the early 1990's. This summary illustrates the relentless ratcheting of German permit limits and contract specifications beyond those required by the 17th BImSchV.

Summary of Typical Permit Limits

Emissions @ 11% O ₂	17th BImSchV	Permit Limits	Contract Specifications
Dioxins ng/Nm ³	0.1		
Range	-	0.05 - 0.1	0.01 - 0.05
Typical	-	-	0.05
Mercury µg/Nm ³	50		
Range	-	5 - 50	1 - 25
Typical	-	20	10
NO _x mg/Nm ³	200		
Range	-	70 - 200	50 - 200
Typical	-	200	70 - 100

TECHNOLOGY OF MOVING BED FILTERS

Moving bed filters have been successfully applied to the control of both particulate and gas phase contaminants in flue gas streams from a host of industrial and municipal processes. Particulate matter is removed by impaction on the bed media which is generally spherical with diameters in the range of 2mm to 8mm. Gas phase components are removed by the selection of a chemically reactive filter medium appropriate to the gas phase component to be removed.

For example, carbon media has been proven effective in the control of heavy metals and organic emissions. In this configuration, moving bed filters have two primary elements, the filter media (activated carbon or lignite coke) to adsorb pollutants from the flue gas and a housing or moving bed filter to contain the carbon. In the moving bed filters, the carbon is constantly fed into the top of the housing structure and is removed from the bottom. Both cross-flow and counter-flow moving bed filter system configurations are available. In the cross-flow design, the contaminated flue gases flow across the vertically downward moving bed in a horizontal direction. In the counter-flow design, the contaminated flue gases flow in an upward direction through the vertically downward moving bed. Hybrid configurations which apply both cross-flow and counter-flow schemes have also been built. Accordingly, moving bed filters can be built in a variety of ways to be used as a single stage or as a multi-stage control system. These stages can consist either of a single vessel with multiple bed levels or of multiple vessels each dedicated to the control of a single contaminant or group of contaminants.

Figure 1 illustrates the above described configurations for moving bed filter systems for air pollution control. Typically in an initial stage, dioxin, mercury, HCl and SO₂ are removed. In a secondary stage and after ammonia (NH₃) is injected into the flue gases, NO_x can be removed by the carbon. As described previously, moving bed filters are often used after the primary acid gas (SO₂, HCl) control device such as a wet scrubber or spray dryer/fabric filter. This is to remove the majority of the acid gas (90 - 99%) using a calcium based reagent (\$80/ton) and thus minimize the usage of the very costly carbon (\$300 - \$900/ton) for acid gas control. Thus, as a practical matter and in terms of economics, moving bed filters are not used as a primary air pollution control system. They should only be used as the polishing component in multiple component system.

Moving bed filters offer the following advantages as pollution control devices:

- 1) Multiple pollutants can be removed in a single application.
- 2) They do not require a large pressure drop and can be retrofitted into many sites.
- 3) Carbon provides an excellent medium for the reduction of dioxins, organics, and mercury to well below permit limits.
- 4) In most cases, the used carbon can be injected back into the furnace and burned, thus eliminating a disposal problem and the associated disposal cost.

As pollution control devices, moving bed filters offer the following disadvantages:

- 1) The massive volume of carbon present in the filter is a potential fire hazard.
- 2) Good SO₂ controls are required prior to the moving bed carbon filter. Since carbon has a high adsorption affinity for SO₂, this affinity coupled with the much higher amounts of SO₂ present in the gas stream from combustion sources will quickly use up the available carbon thereby letting mercury and dioxins pass through.

- 3) NO_x reduction capability is not as good as that of other control methods such as selective catalytic reduction technology (SCR). If high levels of NO_x control are required, (below 100 mg/Nm³) other more effective technologies such as SCR technology should be employed.
- 4) Handling granular carbon is messy and requires additional housekeeping. The use of composite carbon/lime pellets can almost completely mitigate this problem.

A SORBALIT CASE HISTORY

Märker was called by the owner of an industrial sludge incinerator and asked for help in solving several operating problems at the sludge plant connected with the plant's air pollution control system. The air pollution control system consisted of a dry scrubber with a fabric filter followed by a moving bed carbon filter. After careful review, the sludge at this facility proved to have a higher than normal sulfur and chlorine content which increased the acid gas quantities exiting the dry scrubber and entering the moving bed filter system. This resulted in a very high carbon usage rate since the moving bed filter system had been originally designed to control only mercury and dioxins. There were additional material handling problems at the plant resulting from the use of carbon.

To solve the problem, Märker developed a plan to replace the granular carbon (4mm) in the filter and replace it with a pelletized form of their Sorbalit technology. Sorbalit is a formulation of lime, activated carbon or lignite coke, and proprietary sulfur compounds. A binder such as portland cement or bentonite is used to strengthen the formulation in order to form pellets. The activated carbon component in the composite carbon/lime pellets ranges from 5% to 35% by weight. Photos of typical pellets are presented in Figure 2.

Composite carbon/lime pellets can be manufactured in a variety of sizes and shapes to meet the size of the filter media material handling requirements for the different manufactures of moving beds. The pellets in Figure 2 were produced by the "spinning disks" or "snow balling" technique. The nominal 4mm pellets on the left were made in Märker's laboratory in Germany using portland cement as a binder with composite carbon/lime. Dravo Lime made the 10mm pellets using bentonite as the binder. Both portland cement and bentonite have proven to be effective binders. They provide sufficient surface strength so that the pellets do not crush using screw feeder in the material handling process. The second property of the binder is that it is porous and permits flue gases to enter the pellet so that the carbon and lime can adsorb or absorb their respective pollutants.

The concept for the use of the composite carbon/lime pellets was that the lime would absorb the acid gases while the carbon adsorbed the dioxins and mercury. The only modification made to the moving bed filter was to replace the granular carbon with the composite carbon/lime pellets in the feed hopper. Test results of the air pollution control system demonstrated that the use of the composite carbon/lime pellets reduced the emissions to within specified levels on a sustained basis at expected composite carbon/lime usage rates. The composite carbon/lime formulation used for this application based on laboratory testing consisted of 10% lignite coke, 10% portland cement, and 0.25% sulfur compounds, and the balance hydrated lime.

Of prime interest to all parties during the development of the pellet technology was the confirmation that the binders would not affect the ability of adsorbents to control dioxin and mercury emissions. Unfortunately, Märker cannot presently test dioxin removal in the laboratory. However, Märker does have the capability to determine the effectiveness of different adsorbents with HgCl₂. Consequently in their

research laboratory, Märker compared formulations of their regular adsorbents containing 5% carbon and 95% hydrated lime with Dravo's pellet formulation which contained the same mixture plus a 5% bentonite binder. The test results show that there were no negative effects caused by the presence of the binder in the pellets on the Hg adsorption capacity of the composite carbon/lime. The test data are presented in Table 1.

These results are also encouraging as to dioxin adsorption in that Märker's past experience has been that Hg capture with carbon or carbon based sorbents is more difficult than dioxin capture under any given set of flue gas conditions. The literature is replete with many examples of field test data typically showing >95% capture rates of dioxins at concentration levels in the low ng/dscm range with concurrent and somewhat lower Hg capture rates of 85 - 95% when the Hg concentration levels were in the $\mu\text{g/dscm}$ range. As a result, testing of the sorbents for dioxin removal are expected to show higher levels of dioxin removal than Hg removal.

THE CARBON ADSORPTION PROCESS

The adsorption of mercury and organic materials such as dioxin into activated carbon and coke is controlled by the properties of both the carbon and the adsorbate, and by the conditions under which they are contacted. This phenomenon is generally believed to result from the diffusion of vapor molecules into the surface of the carbon. These molecules are retained at the surface in the liquid state because of intermolecular or Van der Waals forces.

As the temperature falls, or as the partial pressure of the vapor above the carbon rises, the average time that a molecule resides on the surface increases. So does the fraction of the available surface covered by the adsorbate. However, the carbon surface is not uniform and consists of sites whose activities vary. More active sites will become occupied first and, as the activity of the remaining available sites decreases, the adsorption energy will change.

The physical structure of activated carbon and coke is not known in detail, but it is believed to contain randomly distributed pores in the carbon, between which lies a complex network of irregular interconnected passages. Pores range in diameter down to a few angstroms, and provide a internal surface area from 300 to 1,000 m^2/gram of carbon. The volume of pores at each diameter is an important variable that directly affects carbon performance.

Since adsorption takes place at the carbon-gas interface, the surface area of the carbon is one of the most important factors to consider. The second factor is the pore radius. However, the surface area must be available in the proper range of pore sizes. If too much of the area is available in pores smaller than 5 Å, many molecules will be unable to penetrate the pores and that area of the carbon will essentially be unavailable for adsorption. For most pollution-control applications, the surface areas of pores whose diameters range between 5 and 50 Å yield good efficiency rates because the relative pressure of the vapor is usually too low for the larger pores to become filled. At high relative pressures, however, the total pore volume becomes important because the macropores also become active.

The size of a molecule of mercury is approximately 3.6 Å and the dioxin molecule is 10 Å x 3 Å. Both molecules are adsorbed in different parts of the carbon particle. In theory, dioxins are collected in the

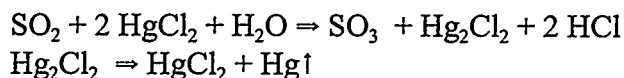
macropores ($r > 25\text{nm}$ [$250\text{\AA}$]) while the mercury is collected in the micropores (0.4nm [$4\text{\AA}$] $< r < 1\text{nm}$ [$10\text{\AA}$]). Dioxin, being larger, blocks the passages, preventing mercury from entering the micropores. To increase the mercury capture rate the amount of carbon used must be significantly increased, the surface area of the carbon must be increased, or sulfur added.

SULFUR'S ROLE IN MERCURY ADSORPTION

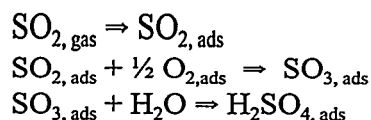
The addition of sulfur compounds to the process plays a major role in the adsorption of mercury but not in the adsorption of dioxin. Sulfur's role in the adsorption is two-fold:

- First, the sulfur compounds maintain the active state of the carbon. Activity is defined as the amount of open pores in the carbon. Sulfur's role is to keep these pores open and to allow the mercury to get into the sub-structure pores. The exact process in which the sulfur keeps the pores open has not been defined. One theory is that the sulfur reacts with water which is adsorbed or is on the surface of the carbon particles to form an acid that penetrates the pores.
- The second role for sulfur is to convert elemental mercury (Hg°) to a sulfate. Hg° is more difficult to capture than Hg_2Cl_2 (which is the predominant species in MWC emissions) or Hg_2SO_4 .

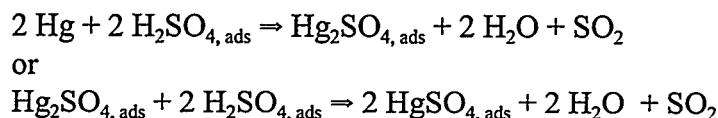
Hg° accounts for 5 to 10% of the total mercury emissions from an MWC. For HWIs and fossil fuel fired power plants as well as other combustion sources however, elemental mercury can be 50% of the total mercury emission. Flue gas constituents such as SO_2 can further increase the elemental mercury content by reducing the dissolved HgCl_2 in wet scrubber liquors to Hg° which is consequently driven into the gas stream due to its poor solubility.



The adsorption capacity of carbon is affected by formation of sulfuric acid on the carbon owing to adsorption of the flue gas constituents SO_2 and H_2O :



Elemental mercury then reacts with the sulfuric acid to form mercurous sulfate (Hg_2SO_4) or in the presence of excess acid to form mercuric sulfate (HgSO_4):



Since the lime component of composite carbon/lime removes the SO_2 from the flue gas, some adsorption capacity of the carbon for Hg° is diminished. The sulfur component in Sorbalit added during

manufacturing, replaces the missing SO_2 and enhances the adsorption of Hg° . Mercuric chloride does not react with the sulfuric acid, but is dissolved in sulfuric acid.

FIELD TEST RESULTS

To date, composite carbon/lime pellets have replaced granular carbon in moving bed filters at a sludge incinerator (hazardous waste), a "green food" dryer, a foundry, and a soil treatment plant. Due to the competitive business these plants are in and the contractual obligations associated with the manufactures of the moving bed filters, Märker cannot presently publish the actual emission data. However, we can acknowledge that these facilities are currently meeting the strict German Federal emission regulations. For informational purposes Table 2 is a comparison in European units of Germany's emission regulation for waste management facilities and U.S. EPA's emission standards for new large MWC's. Table 3 is a tabulation of emission standard for hazardous waste facilities in Europe and Table 4 is a summary of U.S. EPA's proposed emission standards for hazardous waste facilities. Based on the test data currently available, the composite carbon/lime pellets used in a moving bed filter as a police filter will easily meet the U.S. EPA emissions regulations as well as the more stringent German and European standards.

The Institute of Gas Technology (IGT) has undertaken a development program of converting contaminated sludges from U.S. harbors and turn them into saleable "tiles". IGT has several combustion technologies that they employ to slag the harbor dredging and to destroy the organics which include PCB's and dioxins. In IGT's pilot plant test program, they wanted to ensure that they had effective methods to capture organics that were a result of incomplete combustion. IGT evaluated both a fixed carbon bed and a fixed bed of composite carbon/lime pellets to control the off gases from their process. At the time of the writing of this paper, the pilot plant test has been complete, however, the laboratory work still requires several months to confirm that European and U.S. experience coincide.

CONCLUSIONS

Carbon adsorption has been developed into a proven and effective method of controlling various hazardous pollutants to extremely low levels. The use of carbon as a collection medium in a moving bed filter has resulted in operating problems at various facilities. Typically for combustion sources, temperature excursions have resulted fires. Consequently, the selection and use of pelletized adsorbent formulations such as composite carbon/lime pellets has demonstrated the capability to replace activated carbon and to mitigate their safety and material handling problems although still in the developmental stage.

There are many other potential applications yet to be developed for composite carbon/lime's use as the adsorbent medium in a police or polishing filter as technology develops. At a U.S. EPA workshop on Dioxins held in Washington in December, 1996 a number of industrial and combustion sources of dioxin emissions were identified. Moving bed filters using carbon based sorbents could be potentially utilized widely in many of these industrial applications.

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Table 1. Sorbalit research test data.

Test No.	Reaction Conditions (Adsorbent Weight, mg)	Adsorbent	Reactor Temp °C	HgCl ₂ Solution					% Hg Removal
				Hg Content µg/g	HCl Content mg/g	Solution Metered g	Hg Total Quantity In µg	Hg Total Quantity Out µg	
1A	250		180	1.7	125	4	6.8	0.49	92.8%
1B	250	Sorbalit with	180	1.7	125	4	6.8	0.19	97.2%
1C	250	5% lignite	180	1.7	125	4	6.8	0.13	98.1%
Average Test 1		coke	180	1.7	125	4	6.8	0.27	96.0%
2A	250	Dravo Lime	180	1.7	125	4	6.8	0.32	95.3%
2B	250	pellets: 5% Carbon	180	1.7	125	4	6.8	0.14	97.9%
2C	250	0.5% Sulfur	180	1.7	125	4	6.8	0.13	98.1%
Average Test 2		5% Bentonite	180	1.7	125	4	6.8	0.20	97.1%

Table 2. German and U.S. EPA standards for MWCs

⁽¹⁾ (metric units corrected to 11% O₂).

Pollutant		Germany Bundesgesetzblatt - 1990 All Sized Units		U.S. EPA Promulgated 12/95 New Large Units
SO ₂	mg/Nm ³	200	50	61 or
	% reduction	N/A	N/A	80%
	Avg. time-hrs.	0.5	24	24
HCl	mg/Nm ³	60	10	28 or
	% reduction	N/A	N/A	95%
	Avg. time-hrs.	0.5	24	24
PM	mg/Nm ³	30	10	18.3
	Avg. time-hrs.	0.5	24	-
Cd	mg/Nm ³	Included in Class I Metals ⁽²⁾	0.05	0.0153
Pb	mg/Nm ³	Included in Class III Metals	0.5	0.153
Hg	mg/Nm ³	Included in Class	0.05	0.061 or
	% reduction	II Metals	N/A	85%
	Avg. time-hrs.	-	>60 min.	-
Dioxin Furan ⁽³⁾				
	ng/Nm ³ TEQ	-	0.1 ⁽⁴⁾	≈0.2 ⁽⁵⁾
	ng/Nm ³ mass	-	N/A	13
	Avg. time-hrs.	-	>500 min.	-
NOx	mg/Nm ³	400	200	219
	Avg. time-hrs.	0.5	24	24
CO	mg/Nm ³	100	50	89
	Avg. time-hrs.	1	24	4

⁽¹⁾ All emission data based on mass burn water wall technology

⁽²⁾ Class I Heavy Metals: Cd & Tl

Class II Heavy Metals: Hg

Class III Heavy Metals: As, Co, Cr, Cu, Mn, Ni, Pb, Sb, Sn, & V

⁽³⁾ U.S. EPA dioxin standards are on a mass basis. There is no direct correlation to TEQs and only an approximate conversion can be made with a ± error.

⁽⁴⁾ Germany requires a minimum combustion zone temperature of 850°C for 2 seconds.

⁽⁵⁾ U.S. EPA requires control of temperature at APC system.

Table 3. HWI emission guidelines for some European countries (mg/Nm³ dry at 11% O₂) .

Basis	Federal Republic of Germany 17th BImSchV 11/90		Netherlands BLA 1993	EC Directive	
	Corrected only when >11% O ₂		Corrected at All Times	max. ½ hr.	24 hr. Max
Measurement	24 hr. avg	max. ½ hr.	max. 1 hr. mean		
HCl	10	60	10	10	5
SO (SO ₂ + SO ₃)	50	200	40	50	25
HF	1	4	1	2	1
NO _x (NO ₂)	200	400	70	-	-
CO	50	(hr.) 100	(Boiler) 50	-	50
C (organic)	10	20	10	10	5
Particulate	10	30	(8 hr. avg.) 5	10	5
Heavy Metals					
Class I	Cd + Tl Σ = 0.05 (>.5 hr.)		Hg = 0.05 (8 hr. avg.)	Cd + Tl Σ = 0.05 (>.5 hr.)	
Class II	Hg = 0.05 (>.5 hr.)		Cd = 0.05 (8 hr. avg.)	Hg = 0.05 (>.5 hr.)	
Class III	Sb,As,Pb,Co,Cr,Cu, Mn,V,Sn,Ni Σ = 0.5 (>.5 hr.)		Sb,As,Pb,Co,Cr, Cu,Mn,V,Sn,Ni, Te, Se Σ = 1.0 (8 hr. avg.)	Sb,As,Pb,Co,Cr,Cu, Mn,V,Sn,Ni Σ = 0.5 (>.5 hr.)	
PCDD/PCDF (ng/Nm ³)	0.1 I-TEQ > 500 min.		0.1 I-TEQ (8 hr. avg.)	0.1 I-TEQ ⁽⁶⁾ (8 hr. avg.)	
Combustion Temperature	1200°C >2 sec.		850°C at >6%O ₂ >2 sec.	850°C at >6%O ₂ >2 sec.	

⁽⁶⁾ Guideline only.

Table 4. U.S. EPA Emission Limits for Hazardous Waste Combustors (Proposed 4/96)

Pollutant	Averaging Time ⁽⁵⁾	Units	Emission Limit ⁽¹⁾			
			Incinerator		Cement Kiln	
			Existing	New	Existing	New
PM ⁽⁷⁾	CEMS - 2 hours	mg/dscm (gr/dscf)	69 (0.030)	69 (0.030)	69 (0.030)	69 (0.030)
Dioxins / Furans ⁽²⁾⁽⁶⁾	stack test	ng/dscm	0.20	0.20	0.20	0.20
Hydrocarbons ⁽⁷⁾	CEMS - hourly	ppmv	12	12	20 ⁽³⁾	14
CO ⁽⁷⁾	CEMS - hourly	ppmv	100	100	⁽⁴⁾	100
HCl + Cl ₂ ⁽⁷⁾	CEMS - hourly	ppmv	280	67	630	67
Hg ⁽⁷⁾	CEMS - 10 hours	μg/dscm	50	50	50	50
Semivolatile Metals (Pb, Cd) (sum) ⁽⁷⁾	stack test or	μg/dscm	-	-	-	5.2
	CEMS - averaging times vary	μg/dscm	270 12 hours	62 10 hours	57 10 hours	60 10 hours
Low Volatility Metals (As, Be, Cr, Sb) (sum) ⁽⁷⁾	stack test or	μg/dscm	-	60	-	55
	CEMS - 10 hours	μg/dscm	210	80	130	80

(1) All limits are corrected to 7% oxygen and 20°C.

(2) TEQ basis.

(3) The limit given is for the main stack, with the option of meeting a 6.7 ppmv by-pass duct limit.

(4) The limit for the by-pass duct is 100 ppmv; there is no applicable CO limit for cement kiln main stacks.

(5) Average time based on "rolling averages."

(6) Based on confirmatory test under normal conditions.

(7) Determined during comprehensive test (an operating condition that will result in higher than normal emissions).

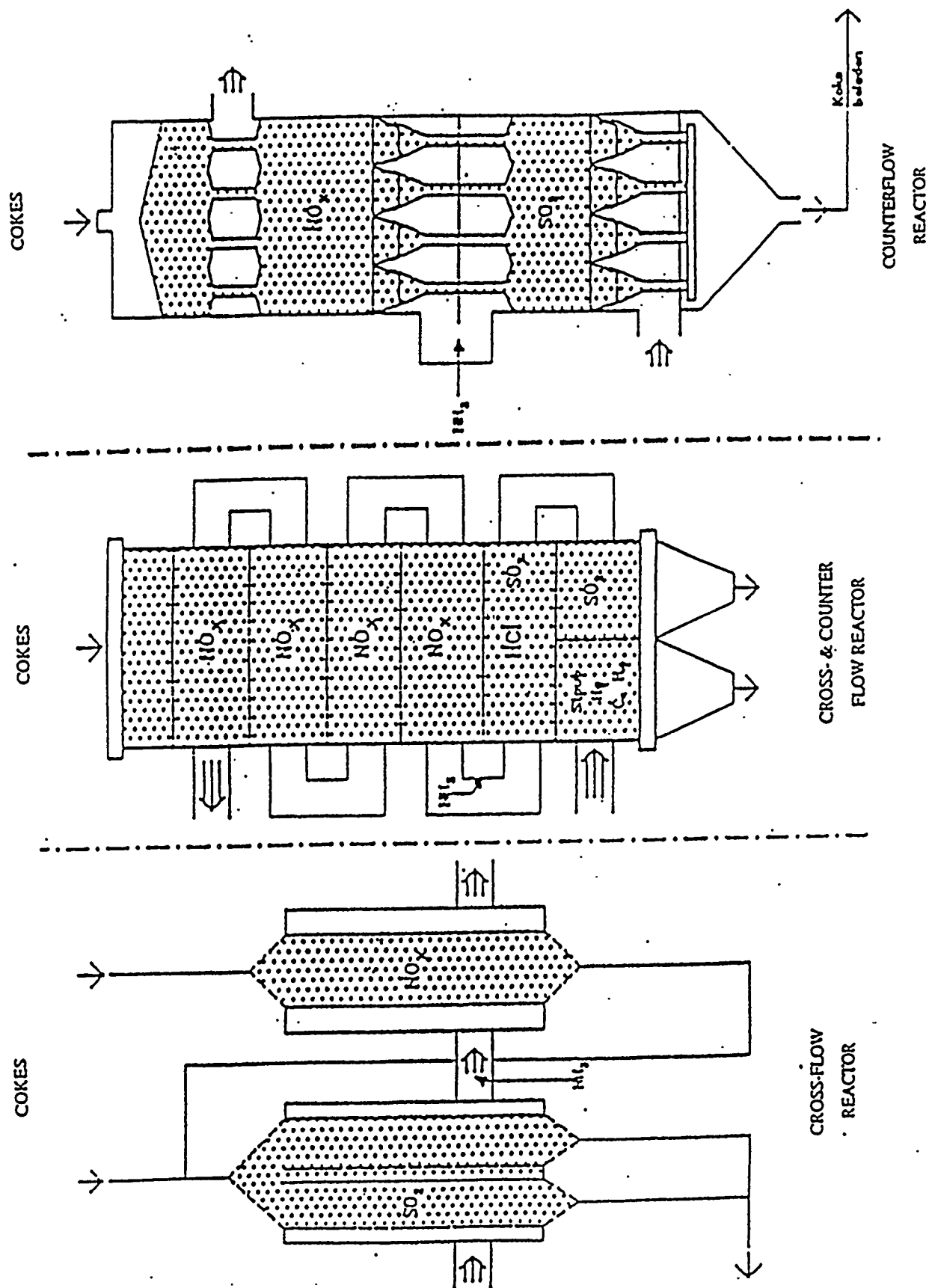


Figure 1. Various moving bed filter configurations.

PEER-REVIEW

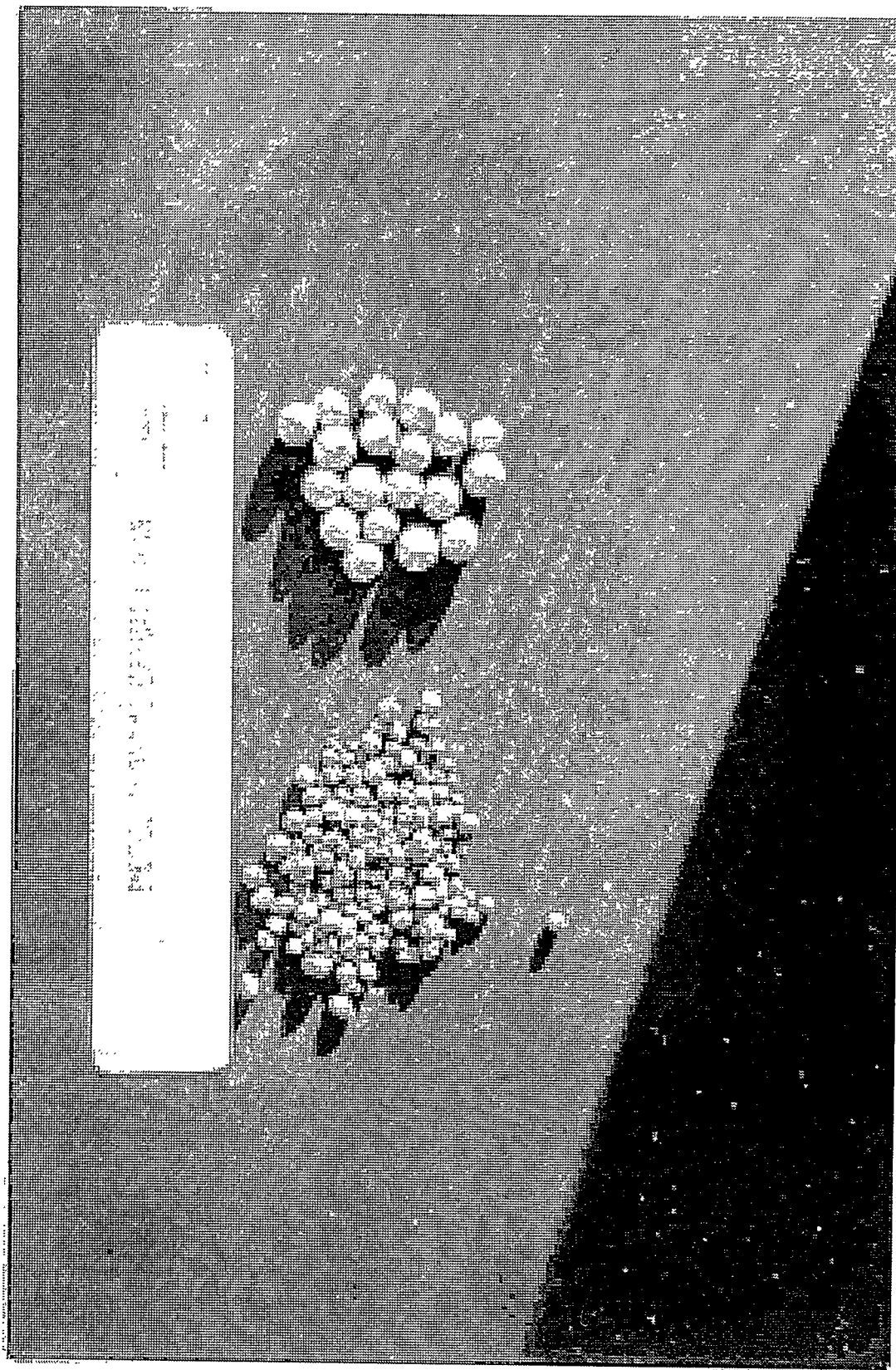


Figure 2. Photograph of Sorbalit Pellets

PEER-REVIEW

Scrap tire pyrolysis: experiment and modelling

A. Napoli, Y. Soudais, D. Lecomte
Ecole des Mines d'Albi - Carmaux
Centre Energétique-Environnement
Campus Jarlard - route de Teillet
81 013 Albi - FRANCE

S. Castillo
Laboratoire Matériaux et Energie
Université Paul Sabatier
118, route de Narbonne
31 062 Toulouse - FRANCE

INTRODUCTION

Pyrolysis of waste, usually organic solids like tires, plastics or composite materials, is an alternative thermal waste treatment technology. Three main physical and chemical mechanisms -i.e.: chemical kinetics, internal heat transfer and external heat transfer - have to be considered when modelling the degradation of solid waste particles. Because of the lack of physical properties for wastes most of the models described in the literature use basic data obtained on the pyrolysis of coal, wood and biomass. In this work, we report basic information on the thermal degradation of tire samples at small scale: Thermogravimetric analyser (TGA) and differential scanning calorimeter (DSC), as well as direct and indirect measurements of thermal and physical properties (thermal conductivity of the tire and of the char, porosity, density, specific heat). Pyrolysis experiments on tire samples are performed in an imaging furnace. The experimental results are compared to theoretical values deduced from models that take into account physical property measurements.

ANALYSIS

Works on the pyrolysis of coal, wood and biomass have led to numerous model descriptions taking into account heat and mass transfer in large solid particles undergoing pyrolysis reactions. Pyle and Zaror¹ studied two major dimensionless groups: the Biot number (Bi) which compares external convection and internal conduction and the Pyrolysis number (Py), which compares internal heat conduction transfer and chemical kinetics. Internal convection is assumed negligible and external heat transfer (convection and radiation) may be described by a third-order boundary condition. Based on this analysis, simplified models can be developed for design or modelling of reactors. A fundamental study of wood pyrolysis by Kansa and co-authors² takes into account heat conduction, internal convection, mass, energy and momentum equations for the solid and the released gas. The influence of the Peclet number (Pe), which compares internal conduction and internal convection, is studied. In most pyrolysis models, internal convection is neglected.

Chemical kinetics

The pyrolysis reaction in a solid (wood, biomass particle, coal, etc.) is described by many authors^{1,3-5} as a source term in the local energy equation:

$$p = -\Delta H \frac{\partial \rho_s}{\partial t} \quad (1)$$

where

$$\begin{aligned} p &= \text{source term in W.m}^{-3} \\ \Delta H &= \text{overall heat of reaction during the pyrolysis process in J.kg}^{-1} \\ \frac{\partial \rho_s}{\partial t} &= \text{local mass loss in kg.m}^{-3}.\text{s}^{-1} \end{aligned}$$

The local mass loss is determined from the overall mass loss obtained by TGA. Several methods are described to determine the kinetic law from non-isothermal thermogravimetric analyser (TGA) measurements⁶. Other authors¹⁻² assume a simple Arrhenius decomposition equation :

$$\frac{\partial \rho_s}{\partial t} = -A e^{\frac{-E}{RT}} (\rho_s - \rho_{s\infty})^n \quad (2)$$

where

A	=	frequency factor in s ⁻¹
E	=	activation energy in J.mol ⁻¹
R	=	gas constant in J.mol ⁻¹ .K ⁻¹
T	=	temperature in K
ρ _s	=	density of the solid at a time t in kg.m ⁻³
ρ _{s∞}	=	density of the solid at the end of the pyrolysis reaction in kg.m ⁻³
n	=	order of the reaction

In the case of waste, which are multi-component and heterogeneous materials, little information is available on the chemical reactions involved in pyrolysis. The basic TGA and DSC measurement methods provide a global information about heat and mass balance on a small sample of the material. Some of the reactions may be exothermic, others endothermic, according to the temperature range. Yang and co-authors⁷ studied the degradation of the elastomers which are the main degradable components of waste tires : styrene-butadiene rubber (SBR), polybutadiene rubber (BR) and natural rubber (NR). The mass loss is the algebraic sum of the mass losses of the elastomers:

$$\frac{\partial \rho_s}{\partial t} = \sum_i \frac{\partial \rho_i}{\partial t} \quad (3)$$

where

$$\frac{\partial \rho_i}{\partial t} = \text{local mass loss of component } i \text{ in kg.m}^{-3}.\text{s}^{-1}$$

A first order kinetic equation is used to describe the reaction kinetics :

$$\frac{\partial \rho_i}{\partial t} = -A_i e^{\frac{-E_i}{RT}} \rho_i = K_i \rho_i \quad (4)$$

where

A _i	=	frequency factor of the component i in s ⁻¹
E _i	=	activation energy of the component i in J.mol ⁻¹
K _i	=	rate constant of the component i in s ⁻¹
ρ _i	=	density of the component i at a time t in kg.m ⁻³

Kim and co-authors⁸ calculate K_i and $\frac{\partial \rho_s}{\partial t}$ by fitting the TGA data with Equation (3). The method requires no preliminary investigation about the initial material composition. It is assumed that tire rubber is constituted of various compounds which undergo independant decomposition reaction in characteristic individual temperature regions. Each decomposition is governed by a first order irreversible independant reaction and the kinetic parameters were obtained by differential methods⁹⁻¹⁰. Even with a realistic description of the mass loss term as a function of temperature, Equation (1) does not take into account the thermal effects at different temperatures.

For waste tire pyrolysis, degradation exhibits an exothermic reaction between two endothermic stages¹¹⁻¹². Mass loss occurs at 200°C, but thermal degradation (softening and liquefaction) starts almost at ambient temperature. It is thus important to have a better description of the source term used in the energy equation.

Yang and co-authors¹¹ make a clear distinction between the source term induced by thermal degradation (no mass loss) and the source term induced by volatilization of the elastomers. The heat release process is described by a simulative curve of the DTA and DSC enthalpy measurements. The decomposition source term without mass loss is expressed as :

$$p_d = \sum h_{di} \rho_i \frac{d\alpha_i}{dt} \quad (5)$$

where

$$\begin{aligned} h_{di} &= \text{heat of reaction of component } i \text{ in } \text{J.kg}^{-1} \\ \frac{d\alpha_i}{dt} &= \text{rate of decomposition of component } i \text{ in } \text{s}^{-1} \\ \rho_i &= \text{density of component } i \text{ in } \text{kg.m}^{-3} \end{aligned}$$

The evaporation source term is expressed as :

$$p_v = \sum h_{gi} \frac{d\rho_i}{dt} \quad (6)$$

where

$$\begin{aligned} h_{gi} &= \text{latent heat of component } i \text{ in } \text{J.kg}^{-1} \\ \frac{d\rho_i}{dt} &= \text{rate of weight loss of component } i \text{ in } \text{kg.m}^{-3}\text{s}^{-1} \end{aligned}$$

Heat transfer

When the Pyrolysis number is small, the pyrolysis process is controlled by internal or external heat transfer. The heat transfer problem is often treated as a moving boundary problem¹³. Among the models which were developed for wood and biomass pyrolysis, integral balance techniques provide approximate analytical solutions¹⁴. For internal controlled processes (small Biot number), pyrolysis rate is very sensitive to thermal conductivity and a good prediction of the pyrolysis time requires an accurate knowledge of the conductivity of the material and of the char. In the case of waste or heterogeneous materials, little information on the thermal conductivity is available. For the char, the conductivity is dependant on the structural properties of the material itself. The wood-cell arrangement generates a pseudo-periodic porous char. For tire particles, evaporation occurs in two-phase porous medium made of liquid elastomers and solid carbon black. This 'bubbling' mechanism¹⁵ generates microporosity in the char.

The conduction term in the energy equation can be written :

$$q = -\nabla \cdot (k^* \nabla T) \quad (7)$$

where

$$\begin{aligned} k^* &= \text{apparent thermal conductivity in } \text{W.m}^{-1}.\text{K}^{-1} \\ \nabla &= \text{gradient (vector) differential operator equivalent to a partial derivative in a one dimensional system} \end{aligned}$$

A review of thermal conductivity models in porous media was made by Azizi¹⁶. The apparent thermal conductivity is influenced by the conductivity of the two phases and the proportion of the phases (porosity). But the influence of geometry is important and more information about the microscopic arrangement of the carbon black in the porous structure is needed for a correct description of conductive heat flow. In the literature about pyrolysis models, the parallel model in which the thermal conductivity

is assumed to be linearly dependent of the various phases conductivity, is often used without justification¹¹. For large temperature gradients, internal radiative transfer must be considered.

EXPERIMENTS

Kinetics

The experiments were performed with a Calvet-type heat flow Differential Scanning Calorimeter (Setaram DSC 111) coupled with a thermobalance (Setaram ATG 92). The reference material was a fixed amount of α -alumina. The powder tire samples were obtained by cryogenic grinding device (SPEX 6700 Freezer/Mill) giving a particle size range of 100-250 μm small enough to ensure internal isothermal conditions during experiments. A flow of purified argon in both the reference and the sample tube was used to maintain an inert atmosphere and to remove the volatile products. The tire samples were studied from 30°C to 800 °C at a heating rate of 5°C.min⁻¹. The final temperature was maintained for one hour to obtain a complete pyrolysed solid (char). Two experiments were realized in the same conditions with the char and the empty crucible respectively in order to record the char and blank signals. Mass loss curves and mass loss rate curves were continuously measured in each experiment.

Thermal diffusivity measurements

The flash method¹⁷⁻¹⁸ was used to measure the thermal diffusivity of tire and char. A brief thermal impulsion is absorbed on the upper side of the sample and the consequent temperature increasing on the back side is recorded. The sample is maintained in a tubular furnace and measurements can be obtained at various temperature from ambient temperature to 300°C. The measurement requires a disc sample of 30 mm diameter, 4 mm thickness with the two faces parallel (Figure 1).

Imaging furnace

An imaging furnace described elsewhere¹⁹ (Figure 2) was used as the experimental device to study the internal thermophysical tire properties. A Xenon arc lamp (4,5 kW) is the radiative source of energy. Spheric and elliptic mirrors concentrate the flux at the focus of the furnace. The sample (12 mm diameter, 3 mm thickness pellet) lies on the top of a sliding support allowing to lead it to the focus where its upper side is exposed to the high radiative flux while its lower side is insulated. The carrier gas (N₂, 200 mL.min⁻¹) is swept under the quartz cover (60 mm diameter, 60 mm high) to maintain neutral atmosphere (Figure 3). The time of treatment is easily controlled by the mean of the sliding support. The high energy supplied by the imaging furnace allows a great gradient of temperature to establish inside the solid; otherwise, as a high temperature is quickly reached in the solid, we can assume that the pyrolysis kinetic is not a limitative factor. So, the boundary conditions are easily controlled in this furnace and the reaction rate may be neglected regarding to the internal heat transfer. This experimental device allows to study the internal heat transfer in a solid chip submitted to a pyrolysis reaction.

MODEL

The mass and energy balance equations for a material undergoing pyrolysis reactions may be written :

mass balance

$$\frac{\partial \rho_s}{\partial t} + \nabla \cdot (\rho_g \mathbf{v}) = 0 \quad (8)$$

energy balance

$$\frac{\partial}{\partial t}[\rho_g u_g + \rho_s u_s] + \nabla \cdot (\rho_g u_g \mathbf{v}) = \nabla \cdot (k^* \nabla T) + \frac{-\partial \rho_s}{\partial t} (h_g - h_s) \quad (9)$$

where

$$\begin{aligned} \rho_g &= \text{apparent density of gas in kg.m}^{-3} \\ \rho_s &= \text{apparent density of solid in kg.m}^{-3} \\ u_s, h_s &= \text{internal energy, enthalpy of solid in J.kg}^{-1} \\ u_g, h_g &= \text{internal energy, enthalpy of gas in J.kg}^{-1} \\ \mathbf{v} &= \text{Darcy velocity of gas in m.s}^{-1} \\ k^* &= \text{thermal conductivity of the solid in W.m}^{-1}.\text{K}^{-1} \end{aligned}$$

Assuming convection negligible ($\mathbf{v} = 0$), Equation (9) becomes:

$$\frac{\partial}{\partial t}(\rho_g u_g + \rho_s u_s) = \nabla \cdot (k^* \nabla T) + \left(-\frac{\partial \rho_s}{\partial t}\right)(h_g - h_s) \quad (10)$$

Assuming $\rho_g u_g \ll \rho_s u_s$, we obtain :

$$\frac{\partial(\rho_s u_s)}{\partial t} = \nabla \cdot (k^* \nabla T) + \frac{-\partial \rho_s}{\partial t} (h_g - h_s) \quad (11)$$

The internal energy u_s is the sum of the latent heat L_s and the sensible heat $c_s T$:

$$\frac{\partial(\rho_s c_s T)}{\partial t} = \nabla \cdot (k^* \nabla T) - L_s \rho_s \frac{\partial \alpha}{\partial t} + \frac{-\partial \rho_s}{\partial t} (h_g - h_s) \quad (12)$$

where

$$\frac{\partial \alpha}{\partial t} = \text{rate of solid-liquid transformation of the solid } (0 < \alpha < 1) \text{ in s}^{-1}$$

The Pyrolysis number can be defined by :

$$P_y = \frac{k^*}{K \rho_s c_s l^2} \quad (13)$$

where

$$\begin{aligned} K &= \text{the lowest constant rate for the pyrolysis reactions in s}^{-1} \\ l &= \text{dimension of sample in m} \end{aligned}$$

Assuming $P_y \ll 1$, the controlling factor is heat transfer and thus the quantities α , $h_g - h_s$ and $\frac{\partial \rho_s}{\partial t}$ in

Equation (12) are only dependent on temperature T .

To solve Equation (12), an integral balance method can be used (in the 1 dimensional case)

$$\int_D \frac{\partial \rho_s c_s T}{\partial t} dx = \int_D \nabla \cdot (k^* \nabla T) dx + \int_D -\frac{\partial \rho_s}{\partial t} (h_g - h_s) dx + \int_D -\frac{\partial \alpha}{\partial t} L_s \rho_s dx \quad (14)$$

where

D = domain of integration (thickness of material which changes over time)

A simplified expression of $\int_D -\frac{\partial \rho_s}{\partial t} (h_g - h_s) dx + \int_D -\frac{\partial \alpha}{\partial t} L_s \rho_s dx$ is given by Kanury and Holve¹⁴

assuming a constant pyrolysis temperature T_c with constant bulk enthalpy change ΔH . Equation (14) reduces to :

$$\frac{\partial}{\partial t} \int_D \rho_s c_s T dx = \int_D \nabla \cdot (k \nabla T) dx + (\rho_c - \rho_0) \Delta H \frac{dx_c}{dt} \quad (15)$$

where x_c , ρ_c , ρ_0 are defined in Table 1

The boundary conditions are :

- constant radiative heat flux at $x=0$
- no heat loss at $x=l$

The solution of this integral equation is given by Kanury and Holve¹⁴ with the following assumptions :

- The thermophysical properties are independent of temperature but depending on density. The properties of non reacted solid are noted with subscript 0 whereas the properties of char are noted with subscript c.
- A linear temperature profil is chosen to integrate the energy balance along the x axis.

The model describes the pyrolysis reactions as a three main phase process: a preheated phase (Figure 4a) corresponds to the increase of the temperature from T_i up to T_c into the depth x_t ; an early-charring (Figure 4b) phase where a continuously thickening char layer x_c exists near the exposed surface and a thermal wave x_t propagates into the solid; and a late-charring (Figure 4c) phase where the char front x_c propagates across the solid to the insulated face.

The basic equations of the model are reported in Table 1.

RESULTS AND DISCUSSION

Kinetics

Typical TGA, DTG (derivative thermogravimetry) and DSC results are illustrated on Figure 5 and Figure 6 respectively.

The major composite materials of tire rubber are carbon black, elastomers and processing oils^{7,12}.

Three stages of degradation are easily recognized on the DTG curve. Brazier and al.²⁰ attributed the first stage of degradation (150-310 °C) to the evaporation of oil/plastizer included in the tire. The second and third stages correspond to the degradation of elastomers. The temperature of degradation of natural or polyisoprene rubber is about 373 °C while styrene-butadiene copolymers rubber decompose on the 430-450 °C temperature range depending on styrene content. The total weight loss is more than 60 % of the initial mass and the remaining char is constituted of inert carbon black and ash. The thermal degradation takes place between 280-480 °C and is achieved when the temperature reached 500 °C. A pyrolysis temperature T_c of 380 °C was chosen for the Kanury model¹⁴.

The DSC curve on Figure 6 shows an endothermic process at the beginning of the treatment, an exothermic transition between 300-400 °C and finally an endothermic process up to 500 °C. The endothermic energy may be due to the rupture of chemical bonds in the polymer leading to a viscous

aspect. Sircar and al.¹² attribute the exothermic transition to bond-forming reactions like crosslinking, cyclization. The ΔH reaction energy is calculated in the total range of the study and the value of 713 kJ.kg⁻¹ is used in the model. The specific heat of tire is measured in the degradation region 30°C-200°C and a mean value of $c_0 = 1417 \text{ J.kg}^{-1}.\text{K}^{-1}$ is chosen. The specific heat of char is determined in the high temperature region 380°C-800°C where the solid is completely degraded. The value of $c_c = 1779 \text{ J.kg}^{-1}.\text{K}^{-1}$ is retained for the model.

Thermal diffusivity measurements

Measurements were made with the flash method both for the tire sample and the char. Values are reported in Table 2

To obtain a good measurement, the shape of the sample should be perfectly cylindrical with plane and parallel faces. But during the pyrolysis process, warping and splitting of the sample may be observed especially at high temperature and high heat flux. An important volume change may in some case be observed (up to twice the initial volume). To obtain correct shaped samples, a tubular electrical furnace was used with mild external conditions. The values of thermal diffusivity were given for ambient temperature. Effects of high temperature and radiation were not studied in this experiment.

Imaging furnace

Experimental results are shown on Figure 7. The overall mass loss of a tire sample is plotted versus time when undergoing a high constant heat flux (100 W.cm⁻²) on one face, the other face being insulated. With this very severe external conditions, temperature rise in the sample is very fast and the main limiting phenomenon is internal heat transfer. Comparison between the model and experience points out the influence of thermal conductivity of the solid char on the duration of pyrolysis. The values taken in the model and reported from the experiments described above are recorded in Table 2. The experimental data may be fitted by a theoretical value $k_c = 0.085 \text{ W.m}^{-1}.\text{K}^{-1}$, noticeably different from the measured value $k_c = 0.14 \text{ W.m}^{-1}.\text{K}^{-1}$. Several explanations may be given for this discrepancy : the conditions of pyrolysis were different between the imaging furnace and the electrical tubular furnace which was used to prepare the samples. As a matter of fact, high thermal rates may cause greater volume change ("pop corn effects") and increase porosity inside the char thus lowering the apparent thermal conductivity. The existence of cracks and splits may also have identical effects on the char thermal conductivity.

CONCLUSION

Little data on the thermophysical properties of waste is available. This paper points out the importance of these data in the energy equation : heat of reaction, heat of vaporization, overall enthalpy, reaction kinetics, specific heat, thermal conductivity, temperature range of pyrolysis.

A preliminary set of measurement techniques was presented in the present paper with a special interest on scrap tire pyrolysis. The following results were obtained :

1. Combined DSC and TGA is a powerful technique to take into account mass and energy balances in the pyrolysis reactions. Mass losses, but also overall reaction enthalpy, specific heat of waste and char may be obtained. Thermal effects, endothermic and exothermic, may be observed and put in relation with mass losses.

2. For large tire particles, heat conduction is a dominant effect on the overall behaviour of the pyrolysis reaction, but the determination of thermal diffusivity is not straightforward. According to the experiments described the order of magnitude of the thermal conductivity is $0.085 - 0.14 \text{ W.m}^{-1}.\text{K}^{-1}$ depending on the pyrolysis process. These very low values show that char is a very insulating material.

The results presented show the importance of a thorough characterization of solid wastes with respect to pyrolysis processes. Heat conductivity, specific heat and heat of reactions have a strong influence on the overall energy balance as well as the characteristic times of the process. A complete model including competition between internal and external heat transfer effects, reactions kinetics, temperature range effects, based on accurate determination of thermophysical parameters is currently developed and will be presented soon.

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Table 1. Kanury and al. model

Phase	Mathematical model	Comments
Adimensional variables	$\theta \equiv \frac{T - T_i}{T_c - T_i} \quad \xi \equiv \frac{x}{l} \quad \tau \equiv \frac{\alpha_0 t}{l^2} \quad \sigma \equiv \frac{\rho_c c_c}{\rho_0 c_0}$ $q \equiv \frac{q_s l}{k_0 (T_c - T_i)} \quad \lambda \equiv \frac{\Delta H (\rho_0 - \rho_c)}{\rho_0 c_0 (T_c - T_i)} \quad \kappa \equiv \frac{k_c}{k_0}$	T_i initial temperature in K T_c pyrolysis temperature in K x abscisse in m l depth of solid in m $\alpha_0 = \frac{k_0}{\rho_0 c_0}$ thermal diffusivity of tire in $m^2.s^{-1}$ t time in s k_0 thermal conductivity of tire in $W.m^{-1}.K^{-1}$ k_c thermal conductivity of char in $W.m^{-1}.K^{-1}$
Preheated phase $0 \leq \tau \leq \tau_0$	$\xi_T(\tau) = \sqrt{2\tau}$ $\xi_c(\tau) = 0$	
Early-Charring phase $\tau_0 \leq \tau \leq \tau_s$	$\xi_c(\tau) = \frac{\kappa \lambda}{\sigma \bar{q}} \left(\sqrt{1 + \frac{2\sigma \bar{q}}{\kappa \lambda^2} \left(\bar{q} \tau - \frac{F(\tau)}{2} \right)} - 1 \right)$ with $F(\tau) \equiv \sqrt{4 \left(\tau - \frac{1}{2\bar{q}^2} \right) + \frac{1}{\bar{q}^2}}$	ΔH enthalpy of pyrolysis reaction in $J.kg^{-1}$ q_s heat flux on the upper side of solid in $W.m^{-2}$ ρ_c density of char in $kg.m^{-3}$ ρ_0 density of tire in $kg.m^{-3}$ x_c abscisse of the char front in m
Late-Charring phase $\tau_s \leq \tau$	$\xi_c(\tau) = \frac{\kappa \lambda}{\sigma \bar{q}} \left(\sqrt{1 + \frac{2\sigma \bar{q}}{\kappa \lambda^2} \left(\bar{q} - \frac{1}{1 - \xi_{cs}} \right) (\tau - \tau_s) + \lambda \xi_{cs} + \frac{\sigma \bar{q} \xi^2}{2\kappa} \xi_{cs}} \right) - 1$ with $\xi_{cs} = \xi_c(\tau_s)$	

Table 2. Property values used in the Kanury and al. model

	Tire	Char	Reference
Conductivity ($\text{W.m}^{-1}.\text{K}^{-1}$)	0.35	0.14	Flash method
Specific heat ($\text{J.kg}^{-1}.\text{K}^{-1}$)	1417	1779	DSC
density (kg.m^{-3})	1100	479	Yang ¹¹
Pyrolysis temperature T_c (K)		653	ATG
Heat of Pyrolysis ΔH (kJ.kg^{-1})		713	DSC
Radiative Flux $\dot{q}_s''$ (W.m^{-2})		10^6	
Depth of solid l (m)		$3 \cdot 10^{-3}$	

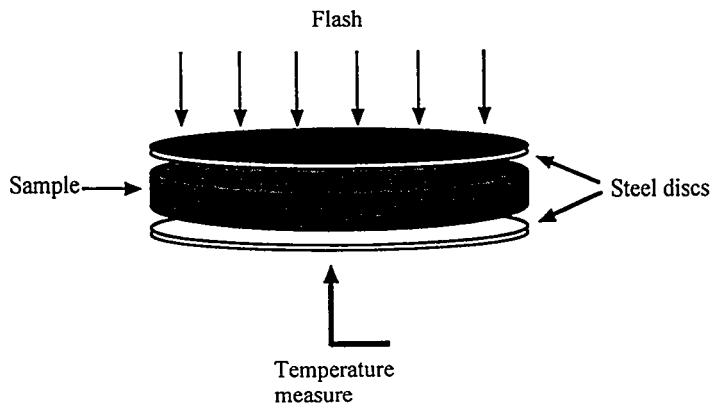


Figure 1. Schematic device of thermal diffusivity measurement by the flash method

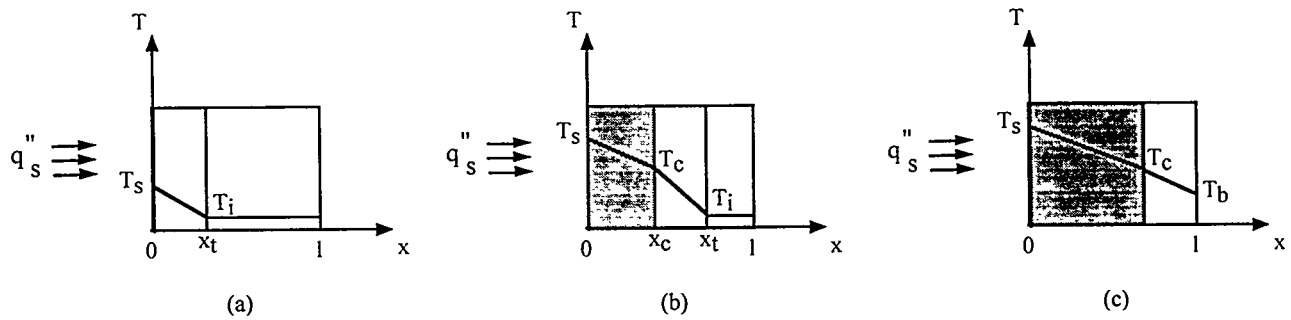


Figure 4. Schematic representation of the Kanury and al. model

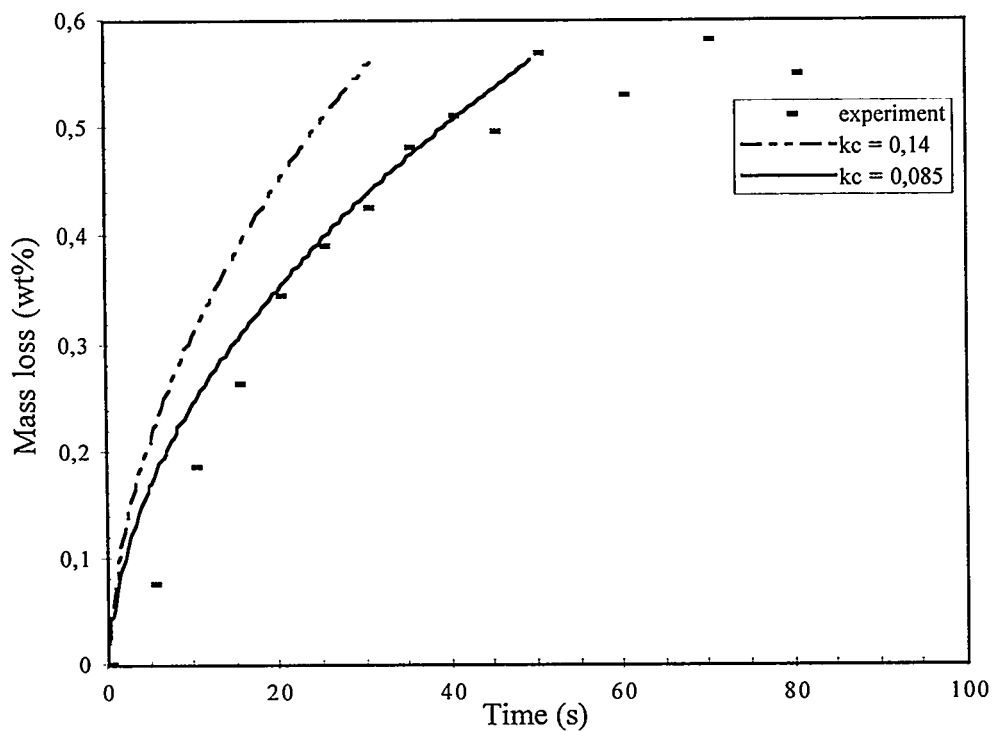


Figure 7. Mass loss vs. time : experimental results (imaging furnace); Kanury and al. model ($kc=0.14$ and $0.085 \text{ W.m}^{-1}.\text{K}^{-1}$)

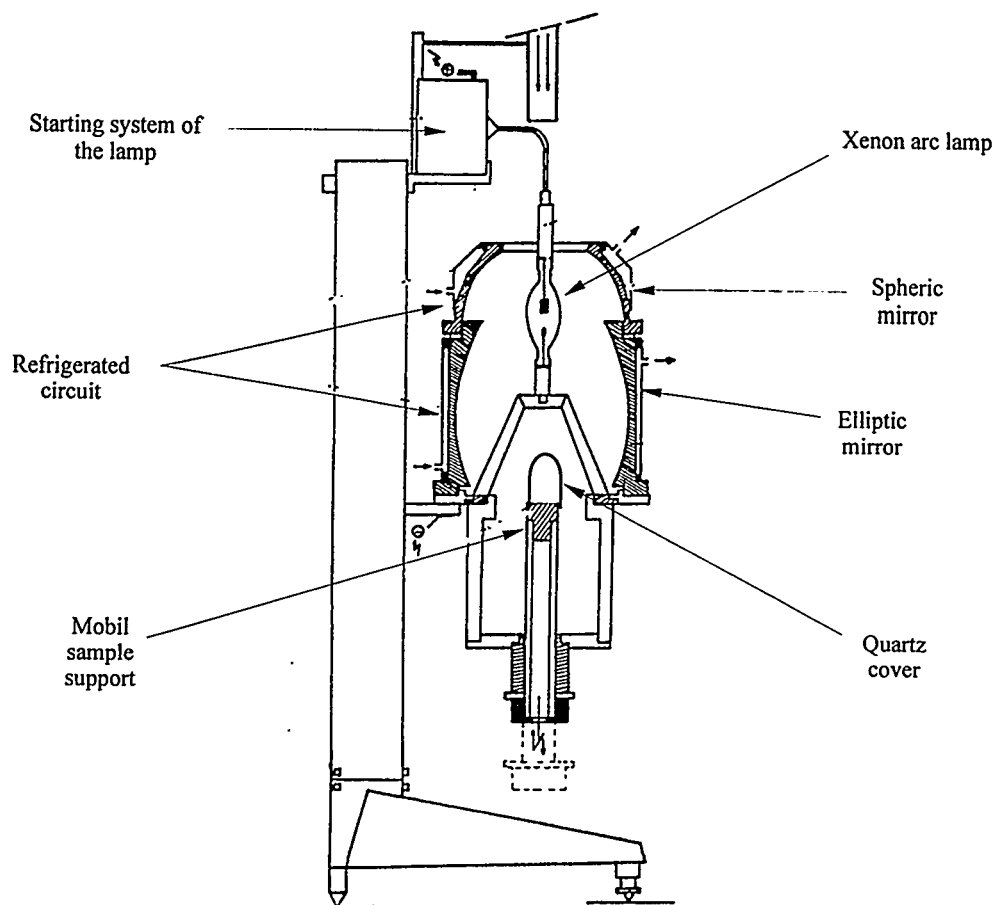


Figure 2. Imaging furnace

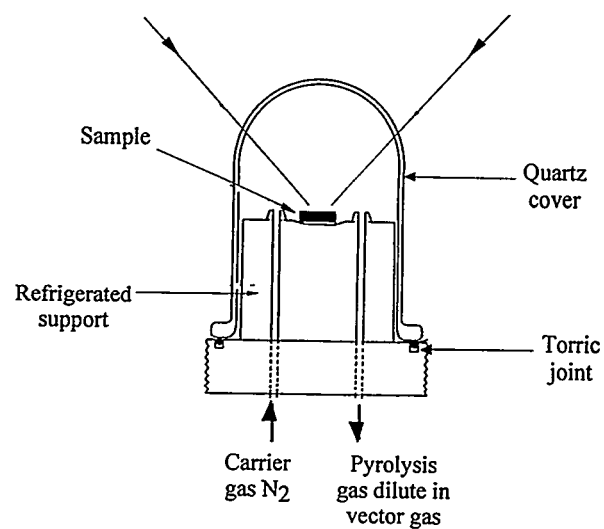


Figure 3. Detailed quartz cover

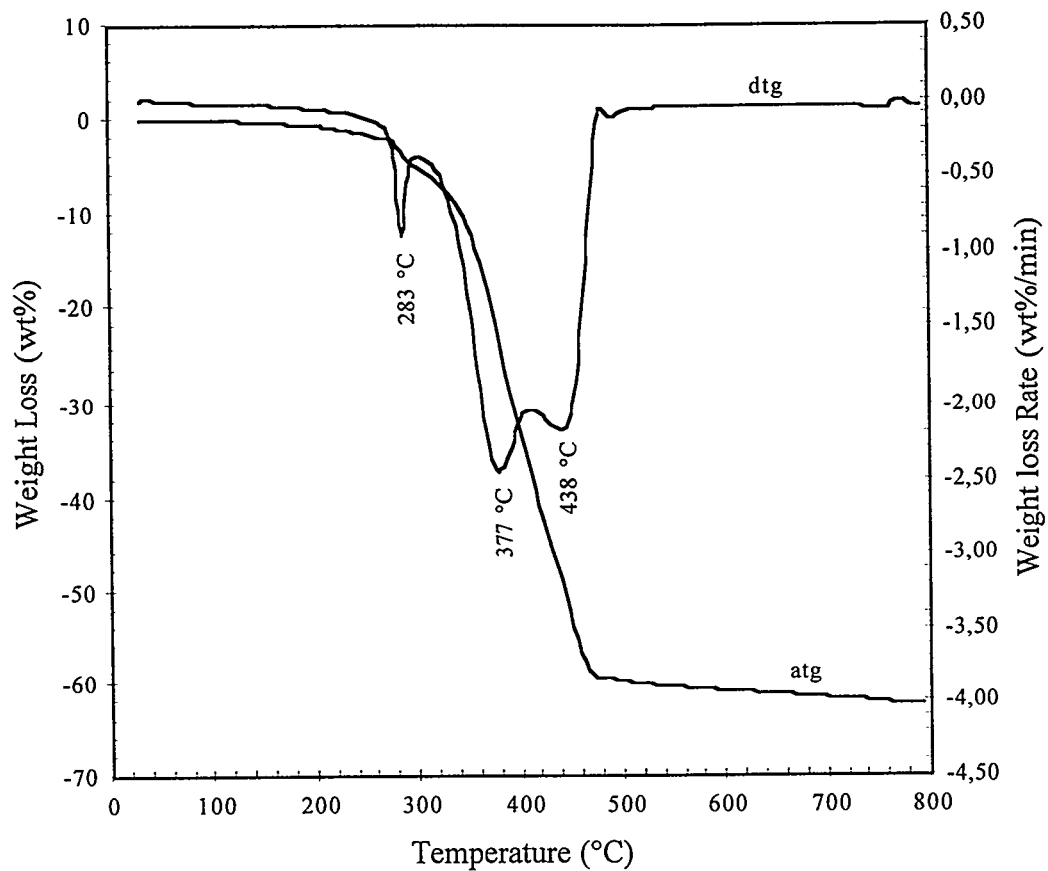


Figure 5. ATG and DTG curves of the pyrolysis of tire

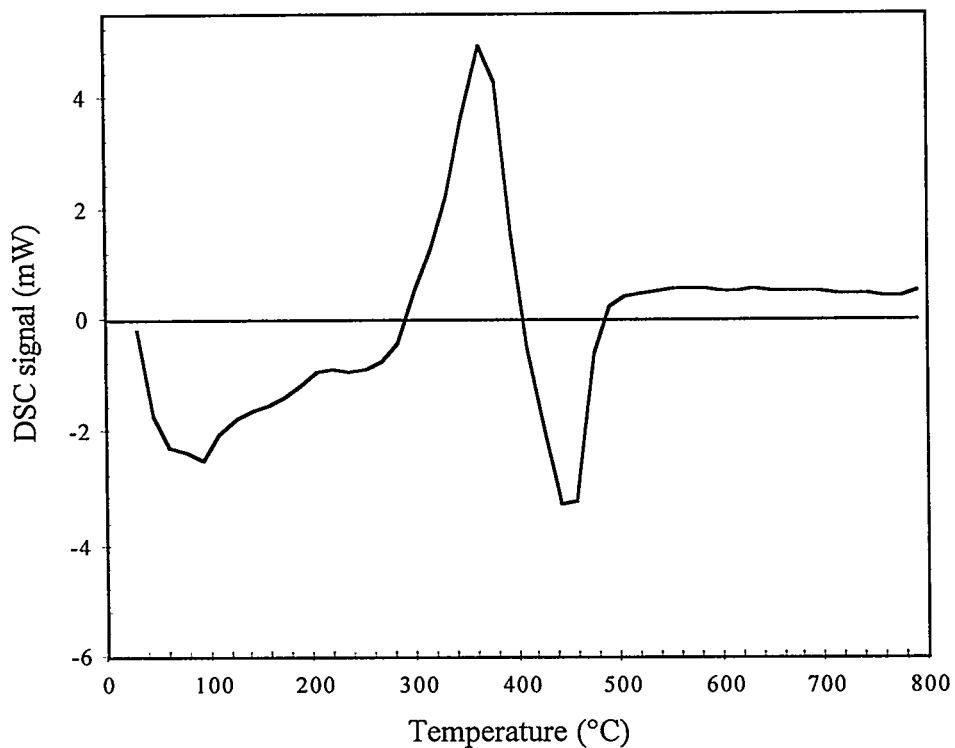


Figure 6. DSC curve of the pyrolysis of tire

Start-up Experience at the Robbins Resource Recovery Facility
while Focusing on the Environment

Bruce C. Studley
Foster Wheeler Power Systems, Inc.
Perryville Corporate Park
Clinton, NJ 08809-4000

Roy H. Moyer
Robbins Resource Recovery Facility
Foster Wheeler Illinois, Inc.
13400 South Kedzie Ave.
Robbins, IL 60472

INTRODUCTION

In early November, 1996, a new generation of advanced combustion technology using circulating fluidized bed (CFB) boilers began continuous operation in Robbins, Illinois, a suburb of Chicago.

The Robbins Waste-to-Energy and Recycling Facility processes a minimum of 1,600 Tons-per-day of Municipal Solid Waste. Approximately 400 tons-per-day of waste will be recycled with the remaining 1200 tons fed to one of two 600 ton-per-day circulating fluidized bed steam generating units.

The Robbins Facility is designed and operates with the most advanced pollution control equipment. Foster Wheeler and facility personnel, in conjunction with the Illinois Environmental Protection Agency and Cook County Department of Environmental Control, have undertaken a number of programs to optimize environmental performance at the facility, including an on-going, aggressive ambient air monitoring program using a chemical mass balance model and ambient air mercury testing.

This paper provides an overview of the design, approach to start-up, actual experiences to date, and the overall operations of the Robbins Facility with emphasis on the monitoring programs and environmental controls.

FACILITY DESCRIPTION

Overview

The Robbins Resource Recovery Facility, as shown in Figures 1 and 2, is a resource recovery plant that is located in the Village of Robbins, southern Cook County, Illinois. The recovery processes involve the separation of recyclable materials (e.g., aluminum, ferrous, glass, compost feed) from the waste stream and the conversion of the remainder to electrical energy. These processes are accomplished in the facility's (RDF) Refuse Derived Fuel Plant and Power Plant. In order to have a high level of reliability and availability, the Plants were designed and constructed with redundant systems and supporting equipment.

The RDF Plant will receive about 2,050 tons of municipal solid waste (MSW) per day (Monday to Friday and half a day on Saturday) from surrounding communities via approximately 200 refuse collection and transfer trucks. The MSW (about 500,000 Tons per year) will be inspected and processed through an automated recovery system to separate out the recyclable materials (about 125,000 tons per year) which will be sold to recycling companies. The material that is larger than 2.5" will be shredded in order to produce RDF (about 375,000 tons per year). The RDF will be screened to recover any ferrous material.

The Power Plant will then burn the RDF in two state-of-the-art circulating fluidized bed (CFB) boilers which will produce steam to power a steam turbine and drive a 55 MWH/hr. electric generator. A simplified process flow diagram of the Facility is shown in Figure 3.

RDF Plant

The RDF Plant consists of the tipping floor, two parallel processing systems, RDF storage building and two truck weigh scales. Each processing line is designed to handle 85 tons of MSW per hour.

MSW collection and transfer trucks will be weighed at the inbound truck weigh scale and then proceed directly to the tipping floor. The trucks will dump the MSW directly on the floor where there is a two (2) day storage capacity. The waste composition of the MSW which was used for design purposes is described in Table 1.

The MSW is inspected with unprocessable materials (e.g. white goods, large furniture, carpet, etc.) removed with mobile grapples and loaded into trailers for disposal to a landfill. Front-end loaders will be used to manage the MSW for efficient storage. The grapples will also be used to mix and load the MSW onto the feed conveyors to the processing lines. The processing lines include primary and secondary trommels. The trommels are large cylindrical drums with thousands of holes of uniform size. The primary trommels have 5.5" diameter holes. The secondary trommels have 1.75" diameter holes at the input end and 2.5" diameter holes at the outlet end. The trommels are on a three (3) degree angle sloping from the inlet to the outlet.

As the trommels rotate, the materials that are less than the size of the holes fall through to the conveyor below. This material from the primary trommel is run under a magnet to remove ferrous material and then is conveyed to the secondary trommel. There the material less than 1.75", is dropped out and is conveyed to the glass system for further segregation and processing. The remaining material that is greater than 1.75" but less than 2.5" is separated out and is conveyed directly to the RDF storage building. The oversize material from the secondary trommels is processed under the eddy current separators to remove aluminum cans. With respect to the glass recovery system, it will yield an organic-free glass product and a compostable organic material. The glass product will be sold for use in concrete aggregate, and the organic material will be processed off-site into compost for use as a soil amendment.

The oversize material from both the primary and secondary trommels is conveyed to the heavy-duty shredders. The shredders reduce the material to 3.5" or smaller. The shredders are enclosed in reinforced concrete structures with a fire suppression and protection system, explosion venting through the roof and relief panels. The shredder enclosures are located outside and adjacent to the processing building. A simplified process flow diagram of the materials recovery and fuel preparation system is shown in Figure 4.

The shredded material is then conveyed to the RDF storage building where it can be used immediately or stored until needed. The RDF storage building provides a 3-day inventory of fuel.

In order to minimize dust and odors within the MSW tipping floor, processing areas and RDF storage area, combustion air for the boilers is drawn from these areas. This causes a slight negative pressure in the buildings which results in air always being drawn in.

Power Plant

The Power Plant consists of two (2) parallel, 600 tons per day (based on a design RDF heat content of 6,170 Btu/lb.) circulating fluidized bed boilers, each producing 229,000 pounds per hour of superheated

steam. They will be operated 24 hours per day, 345 days per year. It is estimated that 20 days of maintenance will be performed on each boiler per year. However, even during periods of major maintenance, one of the boilers will remain in service so that the plant will effectively be in operation 365 days per year.

At the maximum continuous rating (MCR) of the boilers, 458,000 pounds per hour of high pressure superheated steam (900 psig @ 830° F) are generated and directed to one 55 MW turbine generator. The electricity generated by the condensing turbine that is not required for in-plant use is exported to Commonwealth Edison. The furnace system within each boiler is capable of handling fuel with a higher heating value (HHV) range of 4500-7000 Btu/lb. In each boiler, the RDF furnace is fed through the front wall of the furnace. The top supported boiler walls are water-cooled, welded-tube-and-fin construction. During start-up, bed inventory will be sand. The bed inventory silo will later be filled with screened bed ash material and sand, which will be used thereafter to make up lost material.

Following each furnace is a single high-efficiency steam-cooled cyclone. The design effectively handles the thermal variations which occur when burning RDF and will give reliable operation for many years. The cyclone separates entrained solids including unburned carbon from the flue gas and returns them to the furnace, providing excellent carbon burn-out. A cross-section of the boiler is shown in Figure 5.

Downstream of the cyclone is a vestibule that encloses the steam-generating boiler bank and the pendant finishing superheater. The heat-recovery area (HRA) is the final segment of the steam generator. It encloses the primary superheater and economizer. All tubes in the HRA are designed on a large clear spacing with a low inter-tube velocity to minimize any accumulation of sticky ash deposits. Flue gas leaving the economizer will pass through the air emissions control system prior to discharge to the exhaust stack.

Flue gases are cleaned in an air emissions control system which includes dry scrubbers and fabric filters. The air emissions are continuously monitored in accordance with the facility's Air Quality Permit issued by the Illinois Environmental Protection Agency (IEPA). Lime and activated carbon are injected to control the acid gasses and mercury levels. A selective, non-catalytic reduction (SNCR) system, using Urea, is also injected for NOx reduction.

Due to the highly efficient combustion characteristics of the CFB technology at relatively low combustion temperatures (1500° - 1700°F) and high gas residence time, together with staged combustion, NOx emissions have been extremely low. So low that Urea injection has not been necessary to meet permit limits.

To meet the hydrogen chloride and sulfur dioxide emission permit limits, each boiler is equipped with a dry flue-gas scrubber in combination with a fabric-filter baghouse. In the dry flue-gas scrubbers, lime slurry is atomized and injected into the flue-gas stream, neutralizing the acid-gas components. The water in the slurry is evaporated by the hot flue gas producing dry powder reaction products. Additionally, small quantities of activated carbon are mixed with the lime slurry and sprayed into the flue-gas scrubber to reduce emissions of mercury.

The particulate matter, consisting of flyash, dry scrubber reaction products and unreacted lime, is collected on an array of fabric filter bags contained in multiple modular units (with redundant capacity). Approximately 99.6% of the particulate is being removed.

The continuous emissions-monitoring system is being used to control and record flue-gas opacity, sulfur dioxide, carbon dioxide, carbon monoxide, nitrogen oxide, and total hydrocarbons ensuring compliance with applicable environmental standards. All of this data is also available to be telemetered to the IEPA.

Overall, the advanced combustion technology available by using the CFB boilers, coupled with the front end processing of all waste into RDF, and the highly efficient air emissions control system, have resulted in air emissions well below permit limits. The results of recent stack testing, which were performed in mid January, 1997 are compared to the regulatory limits in Table 2. The continuously monitored pollutant values and their limits, are summarized in Table 3.

That portion of bottom ash which is not recycled for use in maintaining CFB inventory, and flyash, are conveyed to their respective storage locations. The flyash can either be conditioned with water, loaded into covered trucks and sent to an approved ash disposal site, or transported dry for possible use by a local cement company. All ash streams are periodically tested and have been classified as non-hazardous.

APPROACH TO START-UP

On November 23, 1994 upon completing financing and with the necessary permits issued, the Project was provided with its official Notice to Proceed. This notice initiated a thirty-three (33) month schedule which was the original duration planned for the engineering, procurement, construction, and start-up of the Facility. As with other Foster Wheeler facilities, which relies on its own family of companies for the engineering, boiler supply, construction and start-up, this project was aggressively pursued and fast tracked to assure on-time completion. This proven approach resulted in completing the Facility seven (7) months ahead of schedule with Commercial Operation declared on January 22, 1997.

Preparation for the Start-up and Operation was initiated by Foster Wheeler Illinois (FWI), a wholly owned subsidiary of Foster Wheeler Power Systems (FWPS), during the early engineering phase of the project. This consisted of reviewing all applicable technical specifications and drawings to assure lessons learned at other FWPS Plants were incorporated. Also, a detailed review of all permits were undertaken to summarize the various programs, plans and reports for which FWI would be responsible. These, along with the programs and plans normally incorporated by FWPS, were then all logically placed into an overall Start-up Activity Schedule. This particular schedule consisted of over 190 tasks. Primary activities included:

- Staffing Plan
- Training Program
- Operations and Maintenance Manual
- Test and Turnover Manual
- Subsystem Startup Schedule
- Startup Plan

- Equipment Purchases and Plant Supplies
- Plant Normal and Emergency Procedures
- Outside Services and Sub-Contractors

The original staffing plan called for 79 employees organized as depicted in Figure 6. Operating Supervisors were placed at the Facility a full year prior to Start-up.

FWI and FWPS developed for the Robbins Resource Recovery Facility a detailed Start-up Plan and Operations and Maintenance Manual. This in-depth set of documents was prepared in accordance with the Construction Permit/PSD, Solid Waste Permit and an environmental Consent Decree with the Illinois Attorney General's Office, along with Foster Wheeler's standard programs and procedures. The manual serves as both a technical and administrative reference and contains the necessary information to assist the plant staff in the start-up, operation and maintenance of the facility. In addition, an entire volume has been dedicated to an overview of all permits with a compliance summary to assure a proper understanding of the permits that exist and their operating criteria. In total, seventeen (17) volumes were required. The Table of Contents for the Robbins Resource Recovery Facility Start-up Plan and Operations and Maintenance Manual is shown in Table 4. The major parts of the manual are listed below and are followed by a brief description of their purpose and contents.

1) System Operating Procedures

The System Operating Procedures are designed and written in accordance with Foster Wheeler's operating philosophy and are based on the plant's unique design as defined in the drawings and equipment specifications. They are also based upon the operating instructions furnished by the various equipment vendors. Each operating procedure contains as a minimum, the following sections:

- System Overview
- Major Components
- Control of Major Components
- System Operating Instructions (SOI)
- Troubleshooting
- Appendix - System Operating Instructions
- Appendix - Initial Valve and Switch Alignment

The system operating, maintenance and start-up procedures presented in volumes 1 to 3 were developed specifically with the end user or plant staff in mind and are a plant specific document. Each section describes a system with an overview, annotated list of components and description of the control system. These are purposely kept concise and when coupled with the Engineering Flow Diagrams in volumes 12 to 17, provide an understanding of each system and its operation. The next part, the system operating instructions (SOI), coupled with the initial valve and switch alignment in the section's appendix explains exactly how each system is to be prepared, started-up, operated (normal), and shutdown. Finally, the last part, the troubleshooting guide, provides the necessary information to analyze and correct malfunctions, abnormalities, etc. to assure the continuous operation of the system.

2) Maintenance

The Maintenance program contained in the manual was designed to provide an effective inspection, maintenance, repair and parts replacement program. Through the implementation of this program, equipment within the plant will receive the appropriate maintenance to assure maximum productivity and reliable performance. Because of the number and complexity of equipment and parts and the need to assure that an organized maintenance program exists, a computerized maintenance management system was implemented. This system allows all necessary information about equipment, including parts, warranties, vendors and labor to be organized and easily accessed. In addition, the system provides the best means of planning for and completing all preventive and predictive maintenance, routine testing and reporting, inspections, etc.

3) Safety

Emphasizing Foster Wheeler's policy to maintain safe working conditions for employees, sub-contractors and visitors, accident prevention can only be achieved by taking a structured approach through a formal plant safety program. Within the Safety Program Manual, the following information and procedures are included:

- Safety Policy
- Safety Program Outline
- Safety Organization and Responsibility
- Safety Miscellaneous Memos/Focus Topics
- Safety Handbook
- Safety Inspections
- OSHA Inspections
- Record Keeping and Reporting
- Medical Exams
- Substance Abuse Program
- Alternate Work Program (Light Duty)
- Employee Training Summary
- Personnel Protective Equipment
- Emergency Planning
- Safe Work Permits
- Electrical Safety Program
- Lock Out/Tag Out Clearance Program
- Confined Space Entry Program
- Contractor Orientation & Safety
- Hazardous Communication Program
- Respiratory Protection Program
- Exposure Monitoring and Control Program
- Hearing Conservation Program
- Bloodborne Pathogens Exposure Control Prog.
- Chemical Hygiene Plan for Chemistry Lab.
- Fall Protection Program
- Walking-Working Surfaces Safety Prog.
- Cranes
- Safe Sling Use
- Industrial Vehicles
- Process Safety Management
- Special Conditions
- Torch Cutting and Welding
- Portable Power Tools
- Abrasive Grinding Machinery
- Signs and Tags

4) Training

To prepare newly hired personnel to assume positions at the Robbins Resource Recovery Facility, a comprehensive training program was developed and implemented. The program consists of several different curriculum, each combining formal classroom instruction with hands-on and on-the-job training. The training program for the Robbins Resource Recovery Facility is comprised of three major areas:

- Operator Training, including appropriate portions of classroom and hands-on instructions.
- Maintenance Training, including specialized classroom instruction and hands-on training.
- Supervisor Training, including specialized training as well as classroom instruction at various times with their respective groups.

The operations training course was designed to cover the theory of plant operation, safety and fire protection, and design and operating principles of the individual equipment, including environmental considerations. Also included was instruction regarding start-up, routine and emergency operation, and shutdown of all systems and components. Similarly, the maintenance courses are developed from material covering subjects such as tools, work practices, methods, safety and fire protection.

These basic training courses which also include specialized safety videotapes and materials are enhanced by the addition of facility specific vendor training during and following start-up of the facility. Within the Training Manual the following topics were included:

- Plant Orientation
- Safety, Security and Emergency Response Plan
- First Aid and CPR
- Fire Fighting and Protection Systems
- Supervisor Training
- Power Plant Principles
- System Operating Procedures
- Maintenance Training
- Vendor Training

5) PERMITS

The Permit Overview and Compliance Summary contained within the manual was developed to help the Robbins Resource Recovery Facility's staff to more easily understand the applicable regulatory compliance issues. Each summary section is based on operation of the facility. Therefore, pre-construction and construction activities are considered completed within the scope of this section. By having the compliance information summarized in a user friendly format, additional emphasis will be placed on always adhering to permit requirements. An actual copy of each permit is included in the manual, each under its own tab, and is periodically used for compliance evaluation. The following permits have been included:

- IEPA Construction Permit/PSD Approval
- IEPA Solid Waste Construction Permit
- NPDES-Storm Water Permit
- Water Pollution Control Permit
- Federal Aviation Administration Permit
- Illinois Department of Transportation Permit (IDOT) - Roadway
- Wetland Permit - Construction
- Sewer Related Permits
- Endangered Species
- Hazardous Waste
- Illinois Historic Preservation Review

In addition to the permits, other documents, which will assure the safe and proper operation of the

facility while minimizing the impact on the environment, include:

- Hazard and Operability Study (HAZOP)
- Emission Test Plan
- Continuous Emissions Monitoring Procedures
- Mercury Optimization Plan
- NOx Abatement/Optimization Plan
- Remedial/Corrective Action Plan
- Ash Management Plan
- Noise Survey
- Ambient Air Monitoring Program

STARTUP ACCOMPLISHMENTS

Through proper planning and the proper allocation of resources, coupled with working very closely with the IEPA and Illinois Attorney General's office, the Robbins Resource Recovery Facility was commissioned and started up ahead of schedule. With construction starting in February, 1995 the electrical switchyard was completed with the back-feeding of power on June 12, 1996. Overall mechanical completion from a construction perspective occurred on September 20, 1996. Through the sequential turnover of subsystems and systems prior to mechanical completion an effective and orderly startup was possible. On September 9, 1996 MSW was first delivered to allow for check-out and startup of the RDF Plant. In parallel with this effort the Power Plant was commissioned with natural gas firing, via the auxiliary burners provided on both boilers, on September 19, 1996. This was followed shortly thereafter by the blowing of steam lines and the initial synchronization of the turbine generator, using natural gas, on October 31, 1996.

With the facility properly commissioned, and all major systems and equipment proven reliable, RDF was introduced and properly fired within the boilers beginning on November 8, 1996. Prior to the introduction of RDF the boilers are first fired using natural gas via auxiliary burners to obtain a cyclone outlet gas temperature of greater than 1500°F. This assures that the RDF will be properly combusted with sufficient temperatures to destroy any organics. A cold start can be accomplished in less than 6 hours with a hot start in under 1.5 hours.

After completing all final checks as the boilers were fired on RDF, the plant was raised to full load operation to allow tuning of the control system for full automatic operation. Once completed, a seven (7) day Facility Acceptance Test was undertaken. This test started on January 14, 1997 and was successfully completed 7 days later on January 21, 1997. Acceptance criteria consisted of:

- RDF Processing Capacity
- RDF Processing Recovery (greater than 25%)
- Boiler/Power Plant Availability
- Boiler/ Power Plant Capacity
- Electrical Generating Rate
- Boiler Residue Rate
- Environmental Compliance

With respect to the RDF plant, recovery overall has exceeded the 25% minimum requirements. Recovery rates for specific recyclable materials are shown below.

- | | |
|------------------------|-----|
| ● Ferrous Material | 90% |
| ● Aluminum Cans | 65% |
| ● Glass Material | 90% |
| ● Compostable Organics | 55% |

CONCLUSIONS

Although only recently started and placed into commercial operation, the Robbins Resource Recovery Facility has not only established new benchmarks of environmental performance, it has already benefited the Village of Robbins. The Robbins Facility by accepting, separating and processing all residential and commercial waste delivered to the plant has allowed the village, and surrounding communities to reduce or eliminate the cost of separate recycling programs and disposal of materials prohibited in landfills.

The pretrommeling of MSW and the glass-recovery system, combined with the proven high efficiency, stable combustion and low emissions of the CFB combustion design give the Robbins Facility several unique attributes when compared to other waste-to-energy projects. These attributes are:

- Low Air Emissions
- High Materials-Recovery Capabilities
- Superior Energy-Recovery Efficiency
- Low Ash Generation
- Low Overall Waste-Disposal Cost

The ambient air monitoring program, which has been in operation at various locations around the suburbs of Chicago for over a year, will continue to collect and analyze air samples now that the facility has been placed into service. Based on the extremely low air emissions from the facility, its impact on the ambient air is expected to be truly non-existent.

As additional operating data and information from the facility and the various programs become available, future papers will be published to allow all interested parties to keep informed on this next generation resource recovery facility.

Table 1. Design Waste Composition.

Material	Percent
Newspaper	10.1
Corrugated Cardboard	8.7
Other Paper	27.3
Plastics	8.1
Wood	4.8
Textiles	3.3
Rubber and Leather	1.5
Food Waste	7.2
Yard Waste	9.7
Glass	9.3
Ferrous	5.2
Aluminum Cans	1.1
Other Aluminum	0.3
Non-Ferrous	1.0
Sand, Stones, etc.	2.4
Total	100.0

Table 2. Comparison of Compliance Stack Test results to the Emission Permit Limits.

Burning 100% RDF				
Pollutants		Unit A	Unit B	Robbins permit
Particulate	gr/dscf	0.0015	0.0056	0.01
SO ₂	ppm	1.0	0.5	30
HCl	ppm	4.6	6.2	25
CO	ppm	4.4	2.2	100
NO _x (1)	ppm	73.1	90.4	130
VOC	ppm	1.5	0.6	10
Total dioxin-furans	ng/dscm	2.1	4.9	30
Total TE (89 EPA)	ng/dscm	0.05	0.13	NA
Arsenic	μg/dscm	0.2	0.2	10
Cadmium	μg/dscm	<detection limit	0.3	40
Chromium	μg/dscm	4.8	5.6	120
Lead	μg/dscm	3.6	30.9	490
Mercury	μg/dscm	15.8	2.9	80
Nickel	μg/dscm	3.1	3.1	100

All concentrations are at 7% O₂

NA-Not applicable

(1) NO_x values are without SNCR system in operation

Table 3. Comparison of Continuously Monitored Pollutants to the Emission Permit Limits.

Pollutants		Unit A/B Average	Emission Limit
SO ₂	ppm	0.9	30 ppm @ 7% O ₂ -24 hr. block average
CO	ppm	3.85	100 ppm @ 7% O ₂ -4 hr. block average
NO _x	ppm	80.25	130 ppm @ 7% O ₂ -24 hr. block average
THC	ppm	1.55	10 ppm @ 7% O ₂ - 24 hr. block average
Opacity	%	2.50	10% over a 6 min. block average

Table 4. Start-up Plan and Operations and Maintenance Manual Table of Contents

Volume	Description	Volume	Description
1	Introduction Description of Manual Manual Revision Requests Matrix of Vendors Manuals List of Enclosed Drawings Test/Turnover Program Plant Black Start Procedure Plant Cooling/Circulating Water System Plant Compressed Air System Demineralized Water System Scrubber, Lime & Activated Carbon Systems Bag House Plant Control System	4	Continuous Emissions Monitoring Procedures Remedial/Corrective Action Plan NO _x Abatement/Optimization Plan Ash Management Plan
2	Feedwater System Boiler/Steam Generator Combustion Air and Flue Gas No _x Control/UREA Injection System Steam Turbine and Condenser Plant Electrical System	5	Contingency Plan Inspection Plan Waste Management Plan Record Keeping Community Relations Plan Facility Staffing Plan IEPA Notification Procedure Fugitive Particulate Control Program
3	Waste/Raw/Potable Water Plant Fire Water System Bottom and Fly Ash Handling Systems Refuse Receiving and Processing RDF Fuel Feed Blowdown System Main Steam System Sampling Natural Gas System and Burners	6	Safety Program Manual
4	Mercury Optimization Plan Emissions Test Plan	7	Safety Program Manual
		8	Preventive Maintenance & Spare Pts.
		9	Training Program Manual
		10	Permit Overview & Compliance Summ.
		11	Hazard and Operability Study
		12	Engineering Flow Diagrams (4261-1-50-1 to 4261-1-50-203)
		13	Engineering Flow Diagrams (4261-1-50-204 to 4261-1-50-510)
		14	Electrical Power One-Line Diagrams (4261-1-73-1 to 4261-1-73-18)
		15	Electrical Power One-Line Diagrams (4261-1-73-19 to 4261-1-73-37)
		16	Electrical Power One-Line Diagrams (4261-1-73-38 to 4261-1-73-59)
		17	Site Preparation Plan Drawings (4261-1-51-100 and 4261-1-41-3 to 4261-1-41-22)

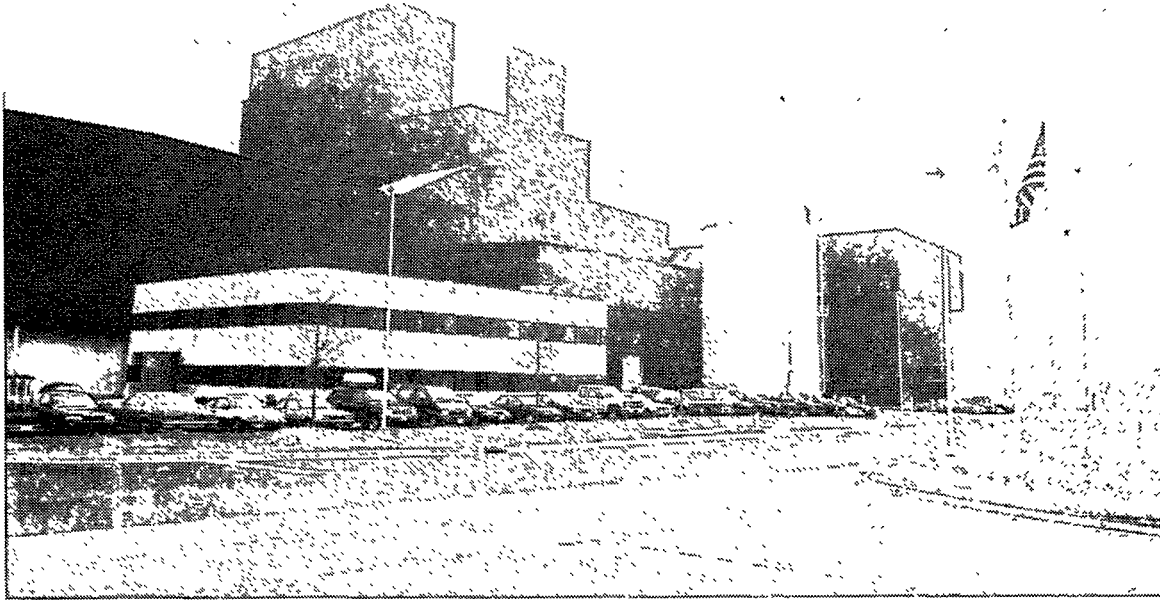


Figure 1. Photograph of the Robbins Resource Recovery Facility.

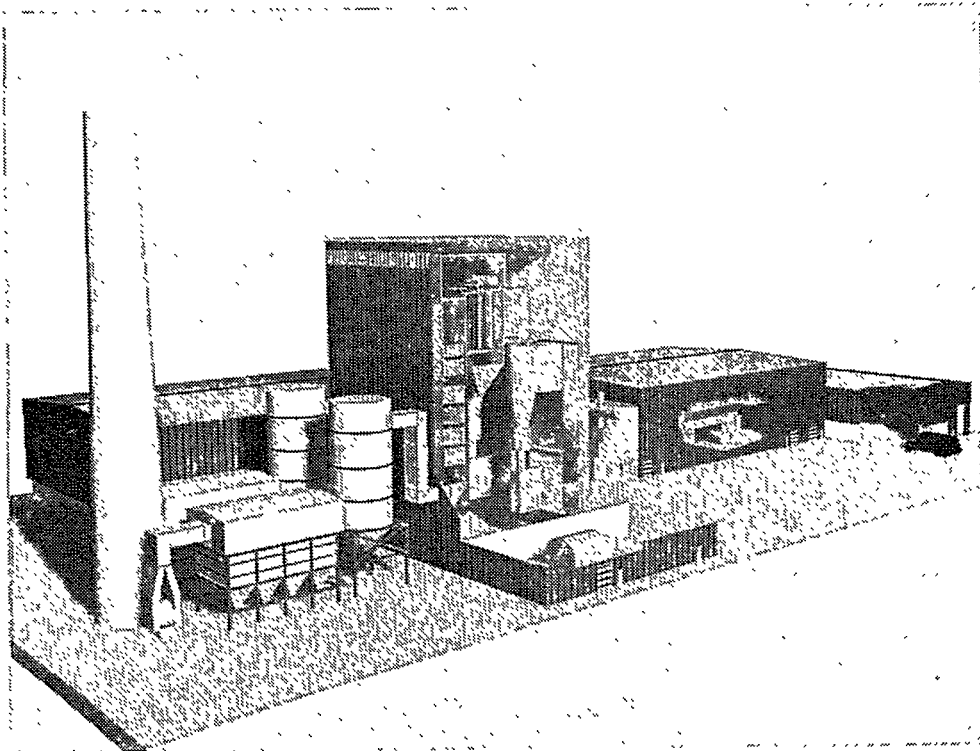


Figure 2. Computer Model of the Robbins Resource Recovery Facility.

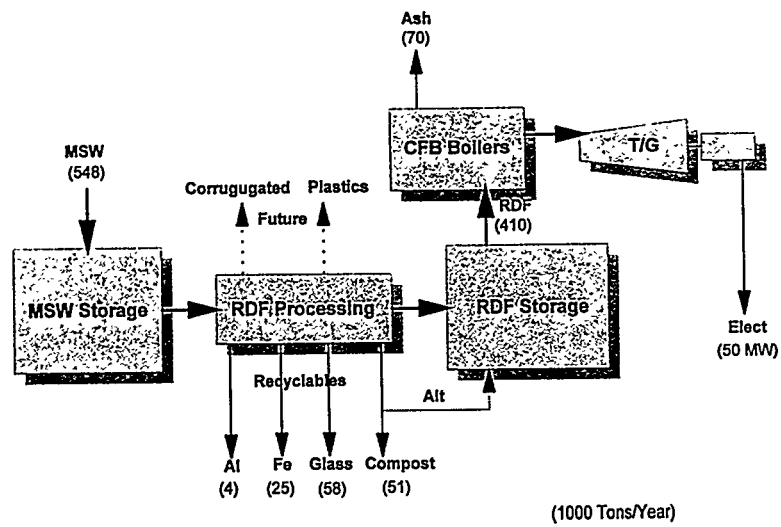


Figure 3. Robbins Process Flow Diagram

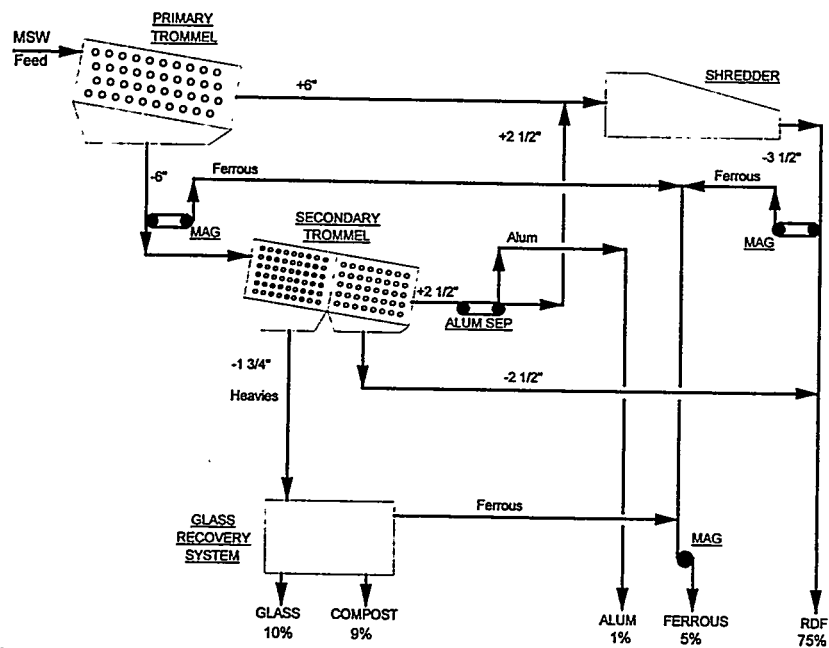


Figure 4. Robbins Fuel Preparation System

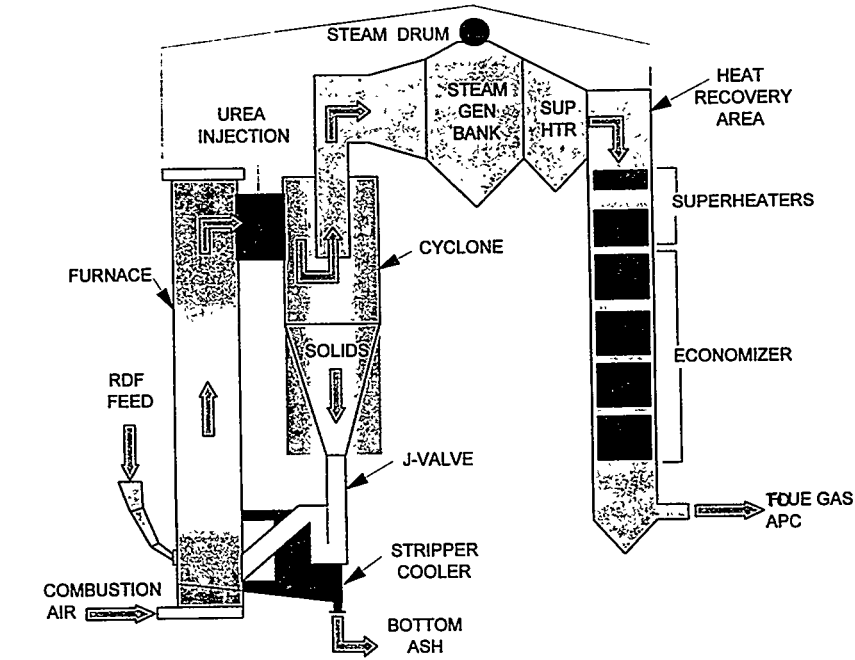


Figure 5. Robbins CFB Boiler

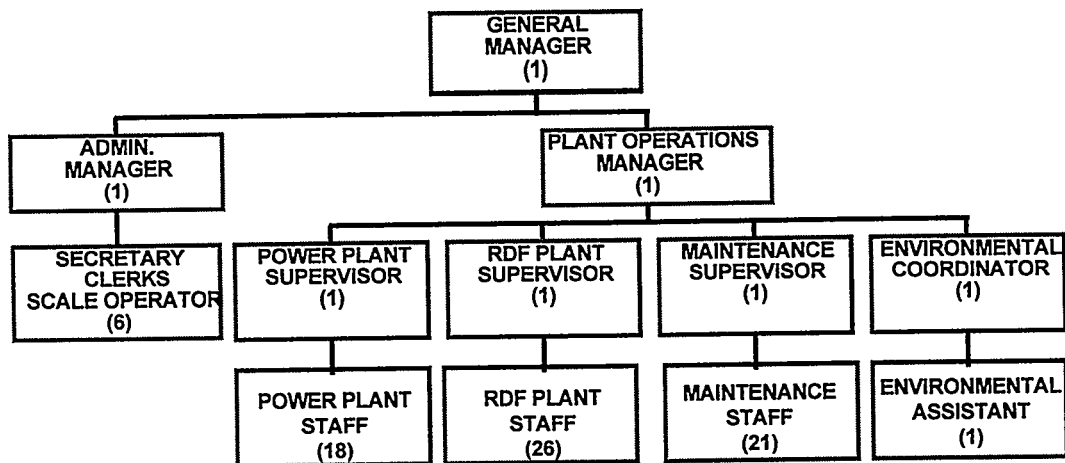


FIGURE 6. ROBBINS ORGANIZATION CHART

TECHNICAL SESSION III

Emissions Control

Mercury Emissions - Trends and Control Effectiveness

John G. Waffenschmidt
Director, Environmental Affairs
American Ref-Fuel Company
333 Earle Ovington Blvd., Suite 302
Uniondale, NY 11553

Stephen P. Goff
Manager, Environmental Technology
American Ref-Fuel Company
6127 Vista Terrace
Orefield, PA 18069

INTRODUCTION

Emissions of mercury from municipal waste combustors has been an item of interest in the 1990's. Standards have been established by the USEPA¹ (MACT Standard) and by state regulatory agencies such as the New Jersey Department of Environmental Protection². As the owner and operator of facilities that combust over 3.5 million tons per year of municipal waste, American Ref-Fuel has been very active in following the trends in waste mercury content, promoting the recycling of mercury containing wastes, and understanding and applying technologies to minimize mercury emissions from waste combustors.

Mercury emissions from waste combustors is determined by the mercury content of the waste stream, combustion efficiency, and the efficiency of the air pollution control equipment at removing mercury. In this paper we review some encouraging trends in waste mercury levels, and discuss the performance of several different combustor/air pollution control configurations for controlling mercury emissions.

CONCERN ABOUT MERCURY IN WASTE

Concern for mercury in the environment was highlighted in Clean Water Action's 1990 report termed Mercury Rising³. The principal argument in the report was that MSW incinerators emit mercury to the atmosphere and that mercury then enters the food chain, thereby increasing the potential health effects due to biomagnification. In this vein, another study⁴ found increased levels of mercury in sphagnum moss near a Waste-to-Energy facility. Other studies⁵ have placed modern atmospheric deposition rates and sedimentation rates at 3-4 times historical rates, with fresh water lake accumulation being proportional to catchment surface area.

In response to these and other studies, the United States Environmental Protection Agency commissioned a characterization study⁶ on mercury containing wastes for the period 1990 to 2000, and the New Jersey Department of Environmental Protection established a Task Force on Mercury Emissions. The NJDEP Task Force report² and USEPA study⁶ both listed batteries as the principal mercury-containing waste source today. The USEPA study concluded that mercury in waste peaked in 1986 (estimated at 770 tons) and would continue on a downward trend to the year 2000 (to an estimated 173 tons), based primarily on the removal of mercury from alkaline batteries and the elimination of mercury-based biocides in paints, for an overall reduction of over 70%. While we are on a definitive downward trend in mercury use, there will be individual product increases, such as mercury-containing fluorescent bulbs and mercury switches. New product applications, like sneakers with mercury switch activated lights, may also alter the dynamics of the decline.

American Ref-Fuel has seen the results of these mercury reduction efforts at its facility in Essex County, New Jersey. Figure 1 presents the change in uncontrolled mercury levels in the flue gas exiting the boilers, prior to the air pollution control equipment, from 1990 to 1996. In 1990 and 1991, the uncontrolled mercury averaged about 600 $\mu\text{g}/\text{dscm}$, and ranged from about 300 to over 1100 $\mu\text{g}/\text{dscm}$. In 1996, the uncontrolled mercury had dropped significantly, averaging about 200 $\mu\text{g}/\text{dscm}$, and ranging from about 100 to 300 $\mu\text{g}/\text{dscm}$. (Note that all mercury concentrations presented throughout the paper are at 7% O_2 .) While Ref-Fuel had developed and implemented a battery recycling program in Essex

County over this time period, the primary cause for this dramatic decrease is believed to be due to decreased mercury entering the waste stream, particularly from batteries. Battery manufacturers have sought to reduce the mercury content in batteries due to public pressure and legislative initiatives like New Jersey's. This downward trend in uncontrolled mercury levels has also been seen in data from other American Ref-Fuel facilities, although the trend is less pronounced and the database is less extensive.

MERCURY CONTROL IN MODERN WASTE-TO-ENERGY SYSTEMS

American Ref-Fuel operates five large municipal waste combustors in the United States employing a number of different combustion and air pollution control technologies. Reviewing the mercury emissions from these facilities illustrates the importance of both the combustor design and the type of air pollution control equipment, in determining the mercury control performance.

Ref-Fuel's first three facilities employ Deutsch Babcock's center-flow combustor design (see Figure 2) and operate with approximately 90% excess air. The air pollution control technologies, however, differ in each facility, as follows:

Essex, NJ	-	SDA / ESP
Hempstead, NY	-	SDA / Reverse-Air FF (low air/cloth ratio)
SE Connecticut	-	SDA / Pulse-Jet FF (high air/cloth ratio)

The average mercury emission and control performance of each of these facilities is presented in Figure 3. While these are commercial facilities, and do not operate identically, they do employ the same furnace design and boiler configuration, and operate with similar combustion conditions and SDA temperatures, which are thought to be the most important operating parameters affecting mercury control. The difference in mercury control between the facilities is believed to be primarily due to the different air pollution control technologies, which is consistent with the current industry knowledge. The SDA/ESP at Essex yields the worst performance, with mercury emissions averaging greater than 200 $\mu\text{g}/\text{dscm}$, and mercury reduction across the air pollution control equipment of about 65%. (This facility recently installed a supplemental mercury control system which will be discussed below.) The reverse-air fabric filter (RA-FF) at Hempstead achieves the best performance, with mercury emissions of about 30 $\mu\text{g}/\text{dscm}$, and reductions of about 95%. This performance rivals that of carbon enhanced systems, and easily meets MACT standards of 80 $\mu\text{g}/\text{dscm}$ emission or 85% reduction. This superior mercury control performance is believed to be due to a combination of the large fabric filter, and the quantity and nature of the residual carbon on the fly ash. SE Connecticut, with the smaller pulse-jet fabric filter (PJ-FF), also performs well with mercury emissions of about 60 $\mu\text{g}/\text{dscm}$, and reductions in excess of 80%, but is inferior to the larger reverse-air system at Hempstead.

American Ref-Fuel's SEMASS facility, in Rochester, Massachusetts, provides another comparison of the SDA/FF vs. SDA/ESP for mercury control. The SEMASS facility contains three units, all with the shred-and-burn technology developed by Energy Answers Corporation. Two of the units have SDA/ESP air pollution control systems, while the third unit, which was constructed more recently, has an SDA/FF system. While mercury reduction data is not available for all three units, a comparison of the mercury

emission levels again shows SDA/FF systems to be superior to SDA/ESP systems. The unit with the SDA/FF averages mercury emissions of about 20 $\mu\text{g}/\text{dscm}$, while the SDA/ESP units averages about 75 $\mu\text{g}/\text{dscm}$.

American Ref-Fuel's facility at Niagara was recently retrofitted with a new combustor, boiler, and air pollution control system. The combustor is Deutsch Babcock's new parallel-flow design (see Figure 4), which operates with just 60% excess air, and is designed for increased turbulence in the combustion zone relative to the center-flow design. The higher combustion temperature resulting from the reduced excess air, coupled with the improved mixing, result in improved combustion efficiency and lower residual carbon on the fly ash exiting the boiler. The new air pollution control system at Niagara is a SDA/reverse-air fabric filter, with a low air/cloth ratio, similar to that at Hempstead. The strategy in using this design was to seek to achieve the superior emissions control, including mercury, that was demonstrated at Hempstead.

The actual mercury control performance for the retrofitted Niagara facility, however, has turned out to be quite poor. The average mercury emissions and control performance for this new facility is presented in Figure 5, and compared to that of Hempstead. The average mercury reduction across the SDA/RA-FF at Niagara averaged just 35%, and the mercury emissions averaged about 170 $\mu\text{g}/\text{dscm}$. This is considerably worse than the 95% reduction, and 30 $\mu\text{g}/\text{dscm}$ emission achieved at Hempstead. The reason for this poor mercury control performance is believed to be due to the reduced, and possibly altered carbon content (due to the higher combustion temperature) of the fly ash at Niagara. Although based on a very limited database, analysis of the carbon content of Niagara fly ash shows it to be about 25% less than that of Hempstead. This alone, however, does not seem significant enough to explain the large difference in mercury control between Niagara and Hempstead. The chemical form of the mercury in the flue gas is also known to affect its adsorption potential on the carbon containing fly ash⁷. The different furnace and boiler configuration at Niagara may alter the speciation of mercury containing compounds in the flue gas entering the SDA/RA-FF, affecting its propensity for removal. However, no data has been collected to support this theory. The new Niagara facility is currently undergoing an evaluation for the addition of a supplemental mercury removal system to reduce the mercury emissions to less than MACT standards.

SUPPLEMENTAL MERCURY CONTROL TECHNOLOGY

While several technologies have been developed and tested to improve the removal of mercury in the primary air pollution control equipment, the injection of powdered activated carbon provides the best fit with the SDA/FF and SDA/ESP systems commonly used in the United States, achieving high mercury reduction at an affordable cost of approximately \$1 per ton of MSW. Activated carbon injection has been identified as the Best Available Control Technology by the USEPA, and has been repeatedly demonstrated in tests and commercial applications to easily meet the MACT standards of 80 $\mu\text{g}/\text{dscm}$ or 85% reduction. American Ref-Fuel has followed the development and commercialization of activated carbon injection for mercury control, has tested the effectiveness of various methods of carbon injection in their facilities, and has recently installed a commercial system in their Essex County facility.

In the early 1990's, American Ref-Fuel tested two methods of activated carbon injection at its Essex facility. In the first method, the activated carbon was injected "wet", by adding it to the lime slurry being sprayed into the SDA units. The second method injected the carbon "dry", by adding it in powdered form to the flue gas exiting the boiler, upstream of the SDA units. At about the same time, similar tests were being conducted by the USEPA at the Stanislaus County, California facility⁸, which employs an SDA/FF system, and at the Camden County, New Jersey facility⁹, which uses an SDA/ESP system similar to Essex. The results of these tests provide an interesting comparison of "wet" versus "dry" carbon injection in these different air pollution control systems.

Figure 6 presents mercury reduction data from the three tests for "wet" carbon injection. In the SDA/FF system at Stanislaus, mercury reductions ranging from about 83 to 97% were achieved at carbon injection rates between 60 and 100 mg/dscm. Essex and Camden, with similar SDA/ESP systems, yielded similar mercury reduction performance, but as expected, were inferior to the Stanislaus SDA/FF performance. Essex and Camden achieved only 70 to 80% mercury reduction at carbon injection rates of 80 to 90 mg/dscm.

Figure 7 presents mercury reduction results from the three systems for "dry" carbon injection. Although the data is very scattered at low carbon injection rates, at carbon rates above 50 mg/dscm the SDA/FF system again showed superior performance, with mercury reductions ranging from 88 to 98%. The SDA/ESP system at Essex was only able to achieve 78 to 89% mercury reduction at higher carbon rates of about 90 mg/dscm.

A comparison of the "wet" and "dry" injection results at Stanislaus (Figures 6 and 7, respectively), shows little difference in the mercury reduction performance with their SDA/FF system, as was concluded from the study⁸. However, this was not the case in the SDA/ESP systems at Essex and Camden. Figure 8 presents the "wet" and "dry" carbon injection results for both Essex and Camden. "Dry" carbon injection achieved significantly better mercury reduction performance in these SDA/ESP systems, reaching reductions of about 95% at carbon rates above 200 mg/dscm. While this carbon injection rate is significantly higher than that needed in the Stanislaus SDA/FF system, it does demonstrate that high mercury reductions can be achieved in SDA/ESP systems with "dry" carbon injection. "Wet" carbon injection at Essex and Camden was limited to between 80 and 90% mercury reduction, even at carbon rates above 200 mg/dscm, leaving some doubt as to whether "wet" injection in a SDA/ESP system can consistently meet the MACT standard of 85% mercury reduction. Some industry sources have reported that "wet" injection of carbon with enhancers may perform similarly to "dry" injection systems. If proven true, this may change the relative performance of "dry" vs. "wet" in SDA/ESP systems.

The results of these analyses formed the basis of American Ref-Fuel's evaluation to find the best carbon injection method for a permanent system to be installed at Essex last year. The system installed is a "dry" carbon injection system designed by Norit Americas, Inc. The system is designed to pneumatically convey and inject the activated carbon directly into the side wall of the SDA unit. The system has been in operation since January 1996, and performance to date has been very good, allowing the carbon injection rate to be optimized to maximize both mercury reduction and carbon utilization. The system has achieved 90 to 95% mercury reduction, and emissions of less than 15 µg/dscm, at carbon injection rates of about 75 mg/dscm¹⁰.

SUMMARY AND CONCLUSIONS

The available data suggest that facilities equipped with dry injection activated carbon systems, as part of an SDA/FF or SDA/ESP can easily achieve the MACT standards of 85% mercury reduction or 80 $\mu\text{g}/\text{dscm}$ mercury emission. While a number of factors influence the emissions of mercury from a waste-to-energy facility, reverse-air fabric filters appear to have slightly better mercury removal performance when compared to pulse-jet fabric filters, and both types of fabric filters are superior to ESP equipped facilities. The relative performance of the Hempstead and Niagara facilities suggests the importance of the combustor configuration, in conjunction with the air pollution control equipment, for determining mercury control. Improved combustor designs with higher combustion temperatures and better mixing, yield higher combustion efficiency and lower residual carbon on the fly ash, which negatively impacts mercury control in the downstream fabric filter. The mercury control in these more modern designs can easily be recovered, however, by adding a dry injection activated carbon system. Ultimately, facility designers may find a combustor/air pollution control configuration that achieves good combustion and minimal mercury emissions, without requiring the addition of activated carbon. Combustion efficiency and residual carbon quantities alone do not appear to explain the differences between Niagara and Hempstead; other factors related to carbon or mercury speciation may explain more with regard to removal dynamics.

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FIGURE 1
Downward Trend in Uncontrolled Mercury at Essex County

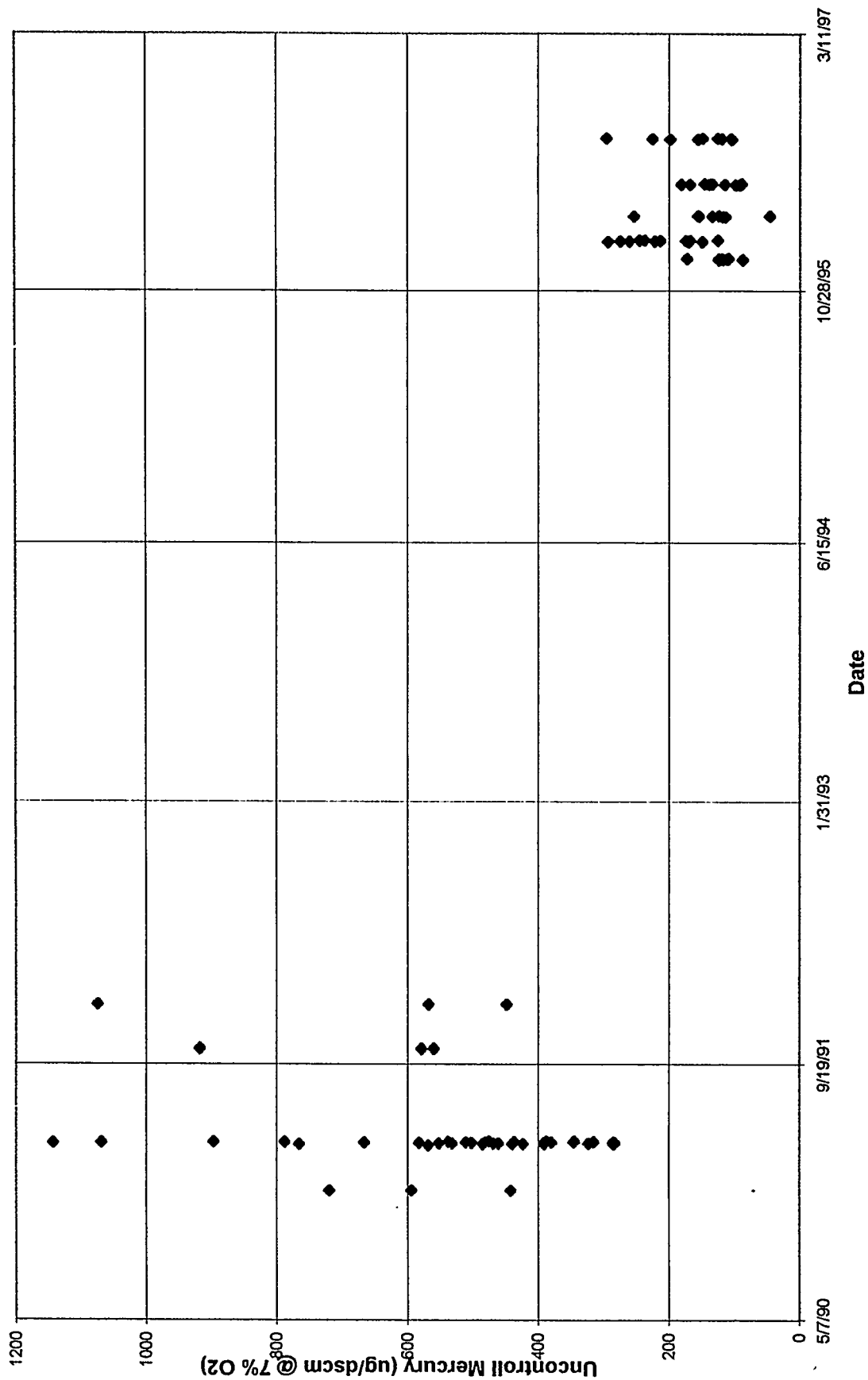


Figure 2
Center-Flow Combustor Design

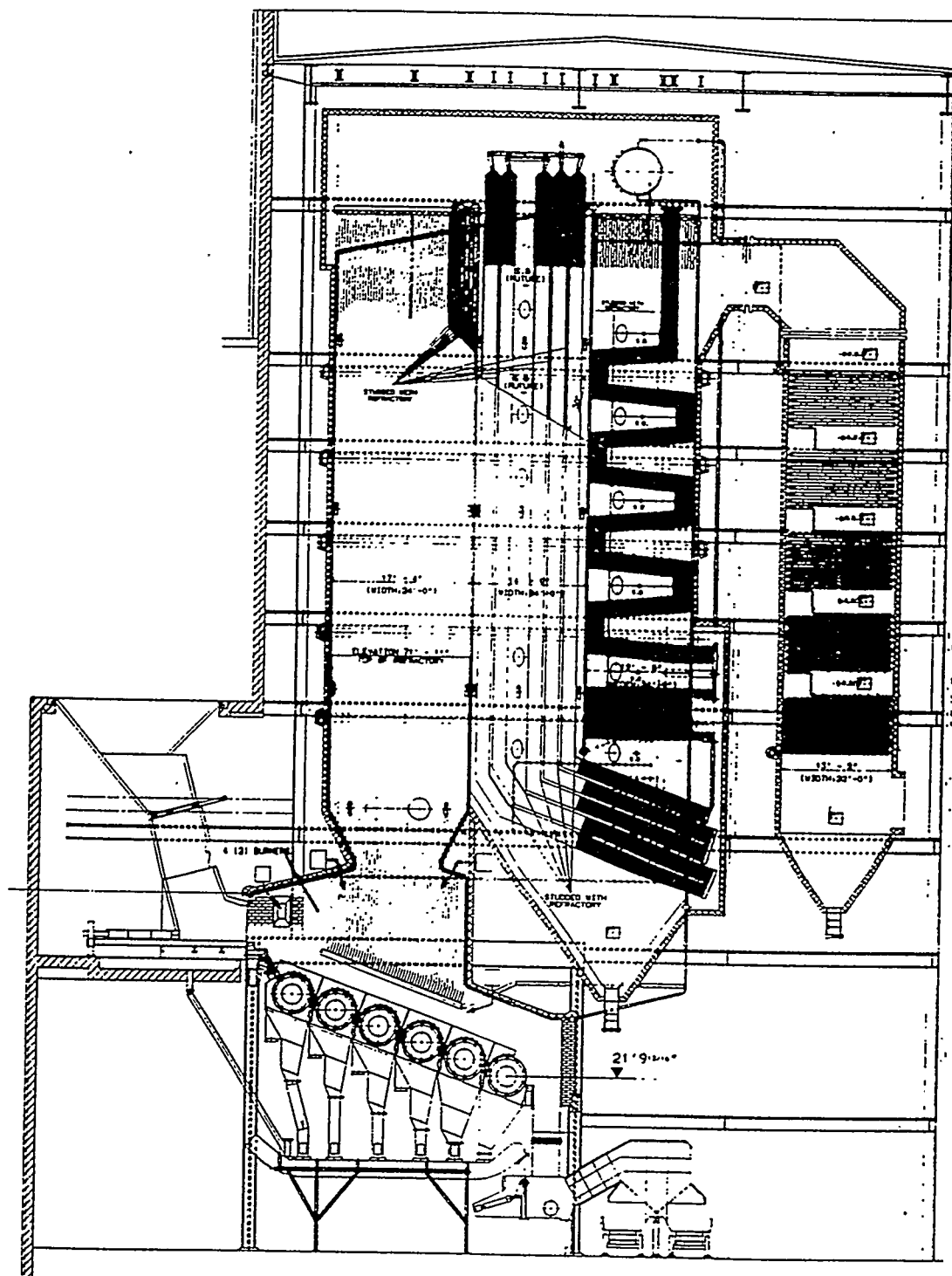


FIGURE 3
Comparison of Air Pollution Control Technology

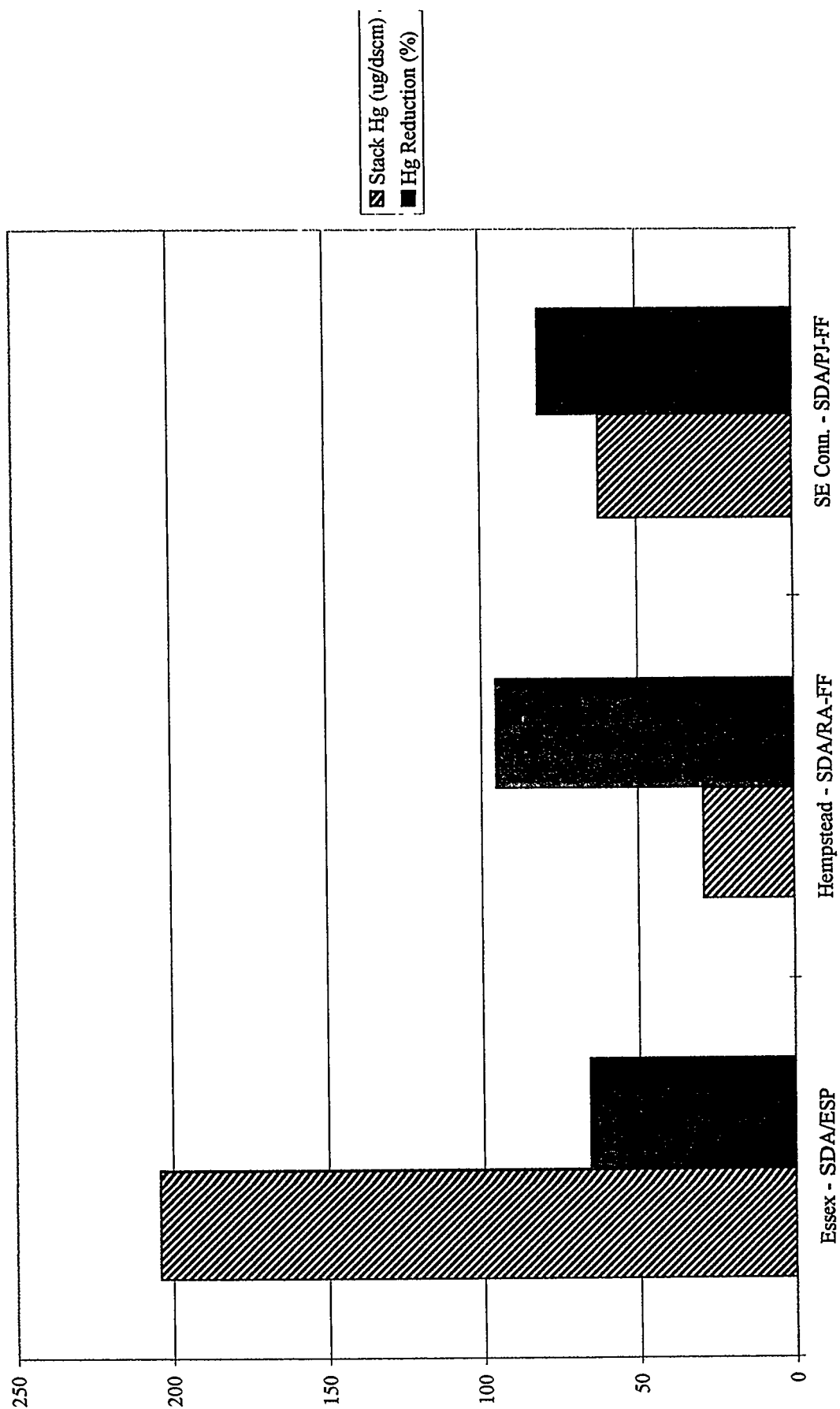


Figure 4
Parallel-Flow Combustor Design

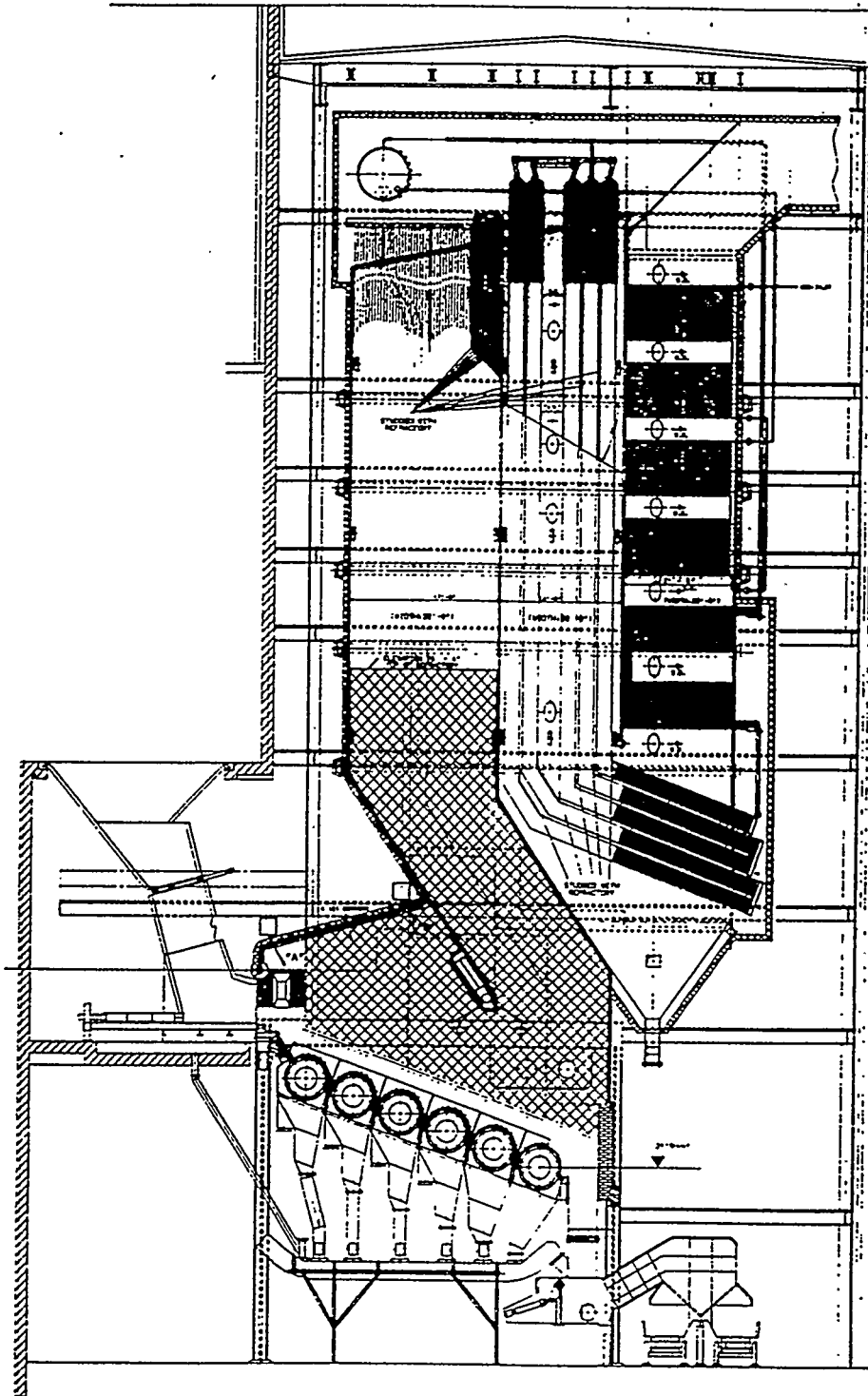


FIGURE 5
Comparison of Combustor Technology

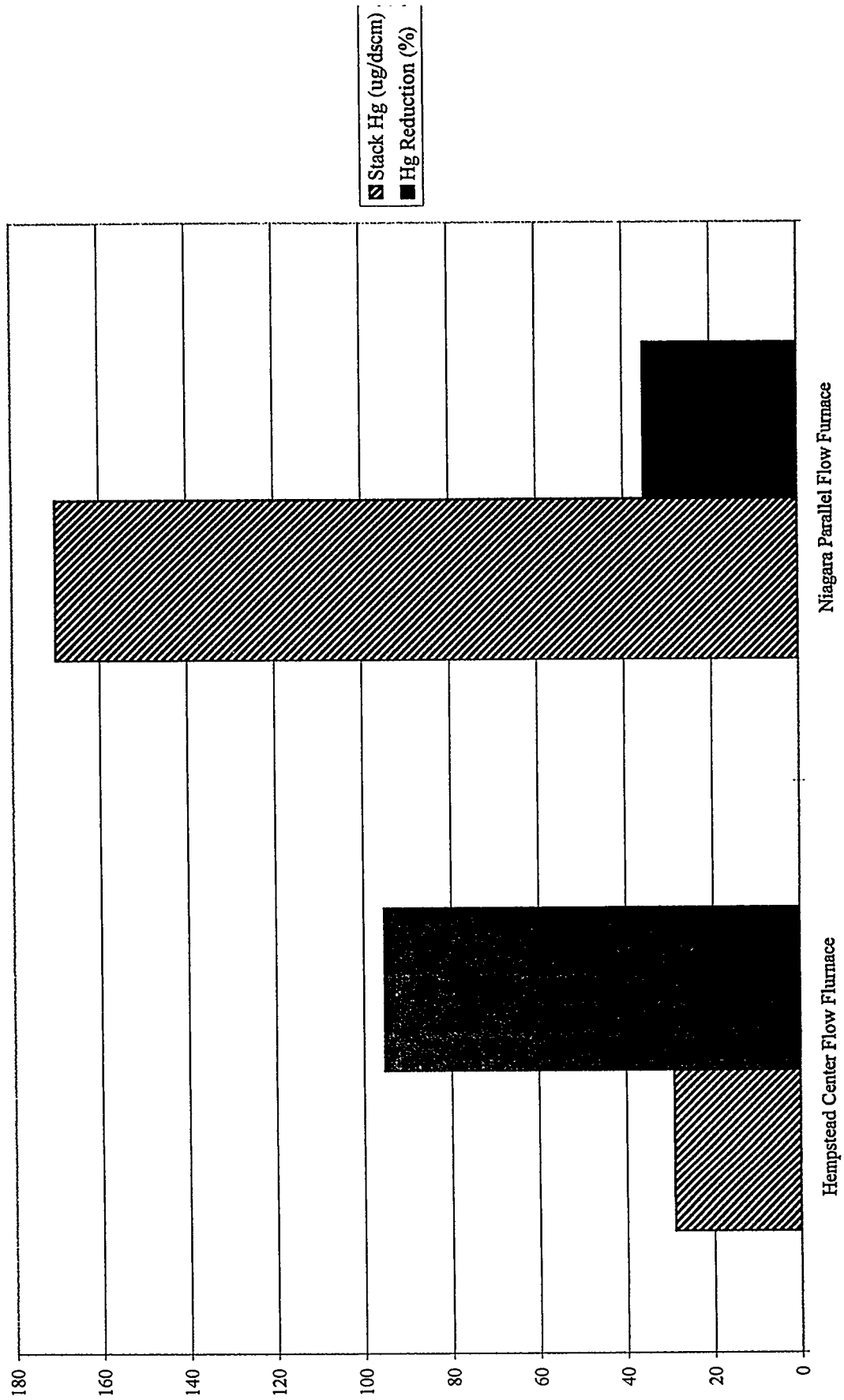


Figure 6
"Wet" Activated Carbon Injection Performance Data

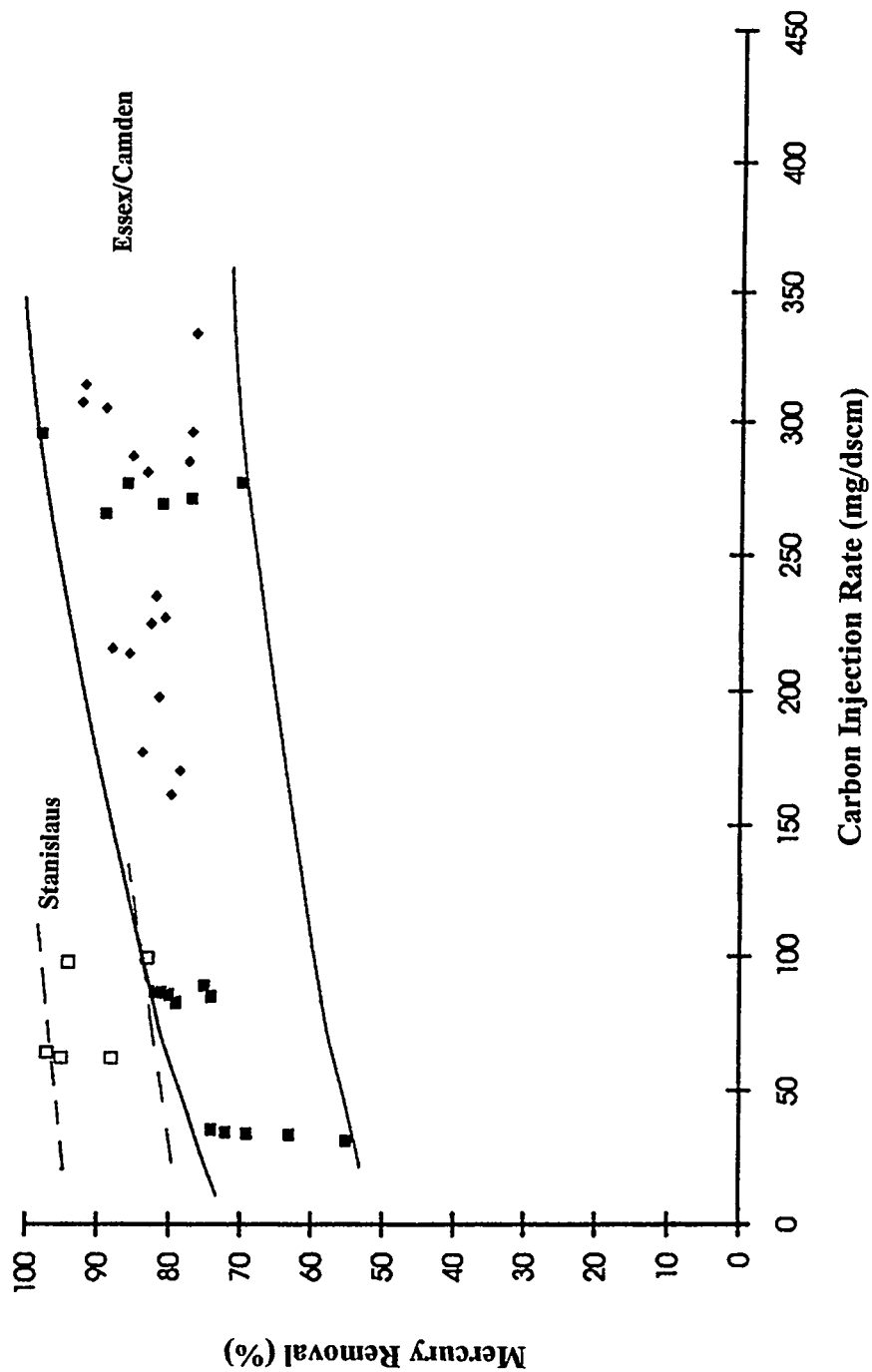


Figure 7
"Dry" Activated Carbon Injection Performance Data

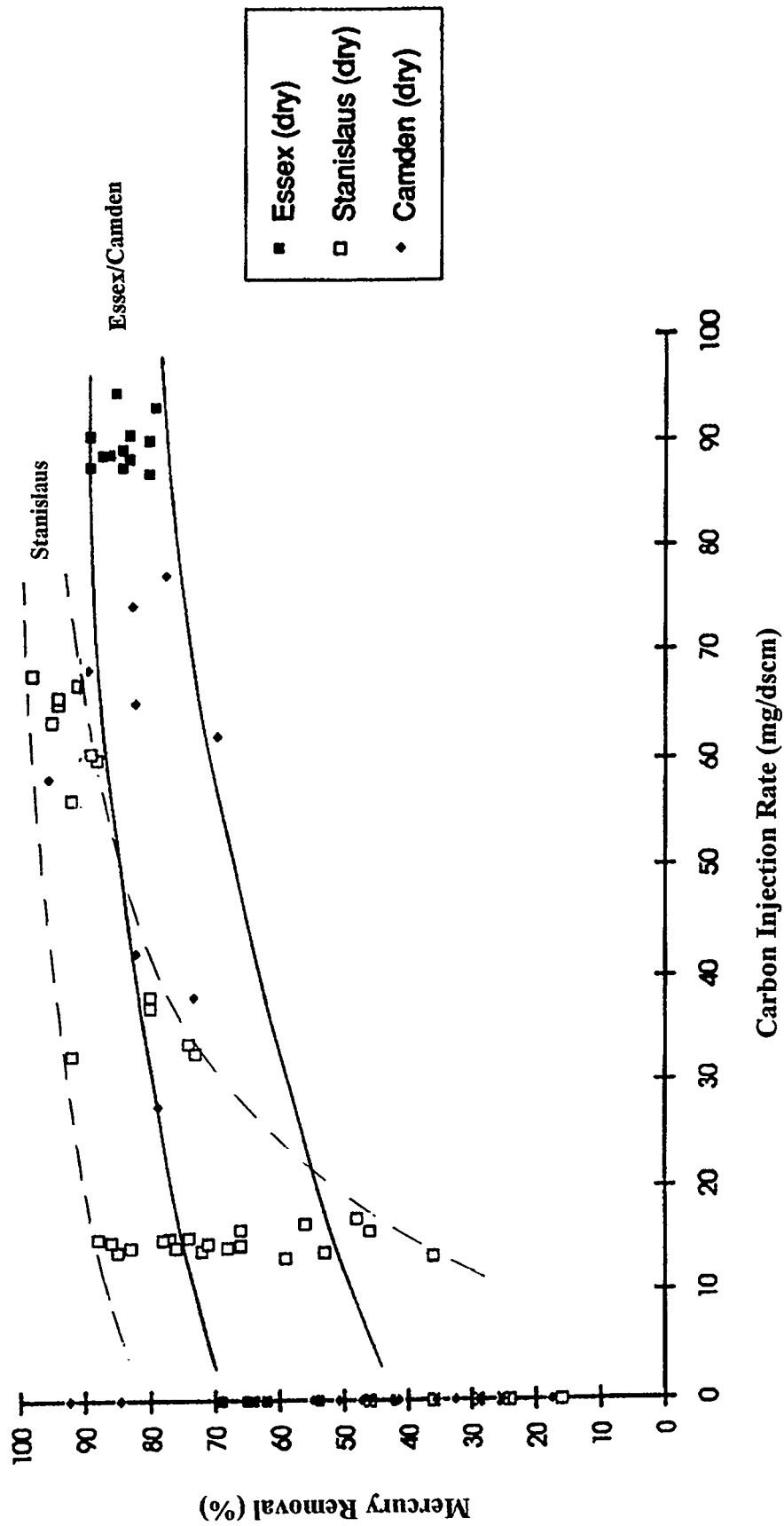
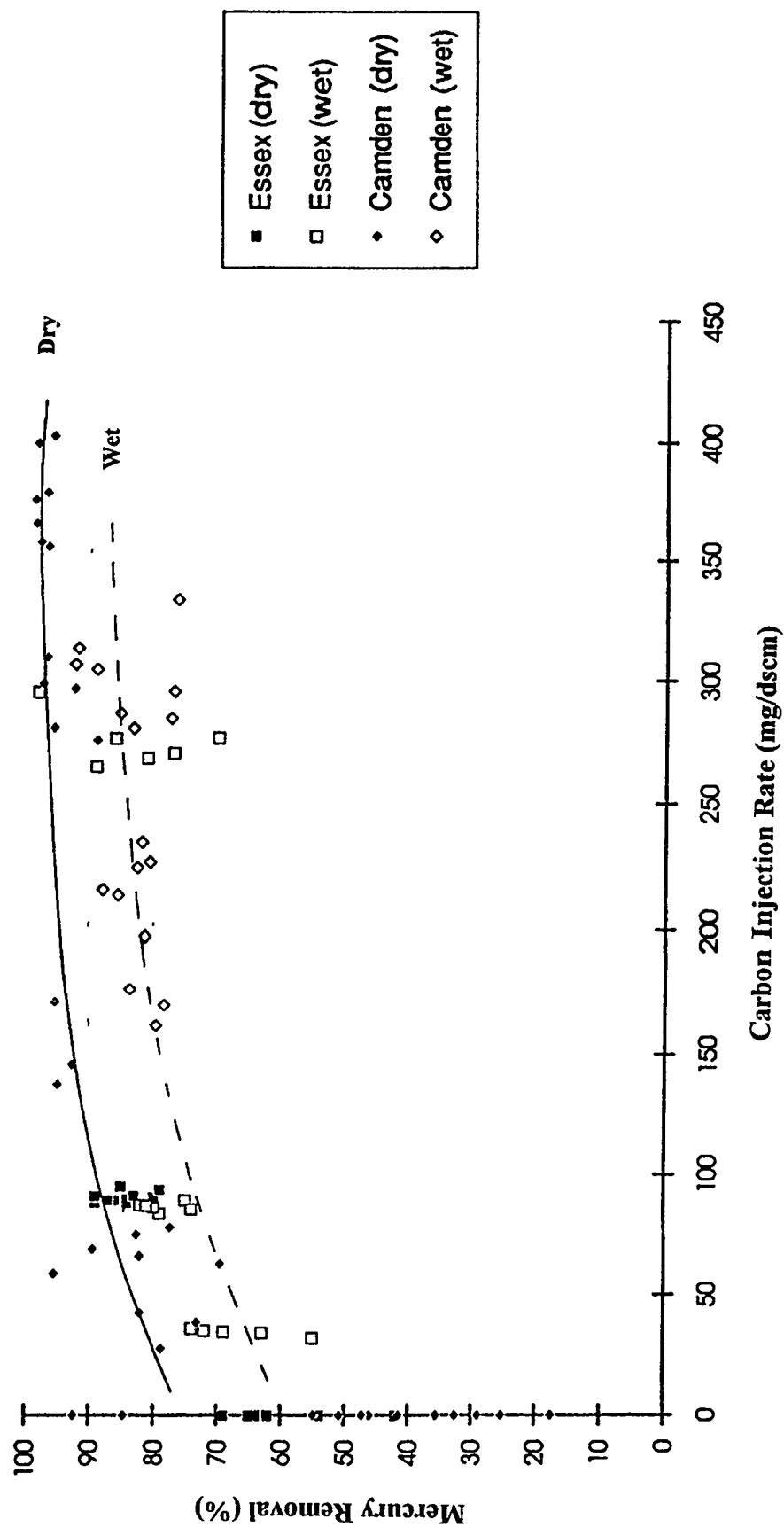


Figure 8
Comparison of "Dry" and "Wet" Carbon Injection for SDA/ESP Systems



Environmental Performance of the Robbins Resource Recovery Facility

Michael J. Cooper
Foster Wheeler Environmental Corporation
Perryville Corporate Park
Clinton, NJ 08809-4000

John F. Van Woy
Robbins Resource Recovery
FW Illinois Inc.
13400 S. Kedzie Ave.
Robbins, IL 60472

INTRODUCTION

For many years there has been incremental improvement in the environmental performance of Municipal Waste Combustor (MWCs) facilities. These improvements were obtained by additional control hardware and additional chemical additives being applied to traditional grate combustion systems. This paper presents early environmental results from a new and different combustion system for MSW, the Circulating Fluidized Bed (CFB) boiler. These results indicate a significant improvement in the environmental performance of waste to energy facilities.

DESCRIPTION OF FACILITY

The Robbins Resource Recovery Facility located in southern Cook County, Illinois, went commercial in January, 1997. It is designed to recover material for recycling and produce energy in the form of electricity from 1,600 tons per day (TPD) of municipal solid waste. The plant consists of two materials-recovery and fuel-preparation processing lines, two Refuse Derived Fuel (RDF)-fired CFB combustion systems, two state-of-the-art air pollution control systems, and a single turbine generator designed to produce more than 50,000 kW (gross) of electric power. The Robbins facility is a 24 hour-per-day, 365 day per year operation. The annual throughput of municipal solid waste (MSW) will be approximately 500,000 tons, assuming an 85% capacity factor.

This facility incorporates a combination of proven waste-conversion technologies in an innovative manner to exploit their inherent advantages, and the overall design builds on the industry's current experience.

Materials-Recovery and Fuel-Preparation System

Two processing lines, each designed to process 85 tons per hour of MSW, operate at a nominal throughput of 64 tons per hour, 16 hours per day, five-and-one-half days per week.

Trucks deliver the waste to the MSW tipping building, where plant personnel direct the dumping onto the concrete tipping floor and inspect the waste for unacceptable and unprocessable material. Front-end loaders are used to separate unprocessable items, such as large appliances, and push the waste onto the in-feed conveyors. The MSW is conveyed past a picking station located ahead of the primary trommel, where personnel inspect the waste stream and remove additional unprocessable waste. The MSW tipping building is capable of storing 3,000 tons of MSW, or nearly two days of system feed requirements.

The fuel preparation system is shown schematically in Figure 1.

The primary trommel opens trash bags, breaks glass, and separates any material under six inches in size. The fraction of MSW not removed by the primary trommel is shredded using a horizontal hammermill to a particle size of 3.5 inches or less, and sent to RDF storage after passing a magnet for ferrous recovery.

Material removed by the primary trommel is conveyed first past a magnet for ferrous recovery then to a two-stage secondary trommel screen for separation into three streams:

- Glass and organics (yard and food wastes); (19% of waste stream)
- An aluminum-rich fraction (1%); and,
- A fuel fraction of burnable material (75%).

The glass-recovery system yields organic-free glass product (10% of waste stream) and a compostible organic material (9%). The glass product is sold for use as concrete aggregate and the compostible material is processed off-site into compost for use as a soil conditioner. Each processing line incorporates several overhead belt magnets strategically located and designed for the recovery of 90% of the ferrous metals, or approximately 5% of the total MSW throughput. RDF produced is conveyed to the RDF-storage building where an almost three-day (3,500 tons) intermediate storage capacity is provided. Direct-feed conveyors or front-end loaders transfer RDF to the CFB boiler feed system.

CFB Boilers

Each of the two CFB combustors is designed to burn 600 tons per day of RDF with a higher heating value (hhv) of 6,170 Btu/lb (3482 Kcal/kg) and produce 229,000 pounds per hour of superheated steam at 830° F and 900 psig. The furnace system is capable of handling fuel with hhv range of 4500-7000 Btu/lb (10,460-16,320 KJ/kg).

In each boiler, the RDF is fed through four feeders located on the front wall of the furnace. The top-supported furnace walls are water-cooled, welded tube-and-fin construction.

Following each furnace is a single high-efficiency cyclone completely cooled with saturated steam from the drum. The cyclone is constructed of Monowall™, a welded tube and fin construction. The cyclone separates entrained solids including unburned carbon from the flue gas and returns them to the furnace, providing excellent carbon burn-out. A cross-section of the boiler and associated air pollution control equipment is shown in Figure 2.

Downstream of the cyclone is a vestibule that encloses the steam-generating boiler bank and the pendant finishing superheater. The heat-recovery area (HRA) is the final segment of the steam generator. It encloses the primary superheater and economizer. All tubes in the HRA are designed on a large clear spacing with a low inter-tube velocity to minimize any accumulation of sticky ash deposits. Flue gas leaving the economizer passes through the air pollution control system prior to discharge to the exhaust stack.

The use of CFB-combustion technology provides the Robbins project with several conceptual advantages over conventional grate-type combustors and contributes to the high energy conversion and low pollutant emissions achieved by the facility. CFB combustors do not burn the solid waste on a grate or hearth as in conventional municipal waste combustors (MWCs). Rather, the waste is burned in a hot, fluid suspension of material, entrained in a substantial upward flow of gas. This fluid suspension, the "fluidized bed," consists of the RDF mixed with intensely hot particles (1600°F) of an inert bed material (a mixture of screened bed ash and sand).

Because of the inherent differences in the combustion process of conventional grate-type combustors and CFB combustors, several important advantages are realized with the use of CFB technology. These advantages include high combustion efficiency, low combustion temperature, reduced NO_x formation, stable combustion, and clean stack emissions.

High Combustion Efficiency. The CFB's turbulent mixture of hot inert bed particles, fuel, and air results in excellent combination of the three T's of combustion: time, temperature, and turbulence.

Vigorous mixing of RDF with air, uniform combustion temperature within the entire furnace, and long residence time of the gases in the furnace contribute to high combustion efficiency.

The CFB's combustion capability is further enhanced by a highly efficient cyclone, which removes elutriated ash along with any unburned carbon from the flue gas. This ash, which normally would drop out into hoppers or be caught in the baghouse in a conventional combustor, is returned to the furnace for further carbon utilization.

Loss on ignition (LOI) testing show less than 1% carbon in the ash, giving 99% plus combustion efficiency, exceeding that of conventional solid-waste combustors, where only 97%-98% is achieved.

Low Combustion Temperatures. The CFB combustor typically operates in the range of 1525°-1675°F (829°-913°C). Besides reducing the potential for ash slagging and tube fouling, these relatively low temperatures reduce high temperature chlorine corrosion.

Reduced NO_x Production. The low furnace temperature of the CFB combustor produces lower nitrogen oxide (NO_x) emissions than conventional high-temperature combustion. In addition, the introduction of combustion air in stages (different elevations) suppresses the generation of NO_x even further. NO_x emissions average under 100 ppmv in the CFB as compared with 200 to 350 parts per million volume (ppmv) typically achieved with grate combustors.

Stable Combustion. The CFB combustion process allows a large thermal mass to circulate between the furnace and cyclone. More material resides in the furnace at any given time than would be possible in a similar-sized grate type unit. A tremendous amount of heat is absorbed and retained by this large mass of inert particles. This gives the furnace a thermal inertia, maintaining a stable temperature throughout the furnace.

The intimate mixing of fuel and air due to the extreme turbulence greatly reduces the potential for hot spots or a localized reducing atmosphere. Thus, CFB technology is particularly able to effectively combust RDF that may vary dramatically in composition and heating value.

Dioxin Emissions. The highly turbulent mixing and prolonged gas-residence time in the CFB combustor provides for nearly complete destruction of dioxin precursors even at the lower combustion temperature.

AIR POLLUTION CONTROL

Air emissions are controlled by the efficient combustion characteristics of the CFB boilers, a selective non-catalytic reduction (SNCR) system, and a semi-dry fluegas scrubber/baghouse system.

Due to the highly efficient combustion characteristics of the CFB technology at relatively low combustion temperatures (1500°-1700°F), together with staged combustion, NO_x emissions are extremely low.

Acid gas and particulates are controlled by a combination semi-dry scrubber/fabric filter. The spray dryer reactor is a parallel downward flow type that utilizes multiple two-fluid nozzles for atomization of the lime and activated carbon slurry.

The fabric filter baghouse is a pulsejet with eight modules. Net/net (two modules out of service) air to cloth ratio is 4 to 1.

A continuous emissions monitoring system is used to control and record flue-gas opacity, sulfur dioxide, carbon dioxide, carbon monoxide, volatile organic compounds, and nitrogen oxide, ensuring compliance with applicable environmental standards. Tables 1 and 2 are daily summaries of the hourly averages from the CEM system for each unit for one day during the acceptance testing.

HISTORY OF PERMIT REQUIREMENTS

Although the original permit to construct (PSD) was issued by the Illinois Environmental Protection Agency (IEPA) in June 1990, construction was not begun until 1994. The units are therefore regulated by the 1990 USEPA new source performance standards. A court order settling a procedural dispute in 1992 added Powdered Activated Carbon injection and a 80% mercury removal rate (below the previous requirement). An ambient monitoring program designed to show the effect of the facility on ambient pollutant levels was also instituted.

As a result of USEPA regulatory action in 1995, new federal requirements were added. Although the 1995 Emission Guidelines (40CFR60, subpart Cb) have been vacated by court order, the facility has submitted an application for an operating permit which contains those requirements.

Finally, in order to comply with a 1991 IEPA regulation concerning MWC metals, limits were placed on three additional metals: arsenic, nickel and chromium.

In the subsequent section, the emission test results are compared to the permit requirements. Since there are duplicative requirements for some pollutants, the permit requirements are a compilation of the above requirements and are the most stringent of the requirements.

RESULTS OF TESTING

Compliance test results are compared to the regulatory limits in Table 3. While overall comparisons are favorable, a few results stand out. First, the CO concentration is extremely low, and has been continuously confirmed in this range by the CEM system. This is directly attributable to CFB combustion, as can the continuously low NO_x emissions. This NO_x result presented in Table 3 is without the urea injection system in operation, and again shows the low NO_x potential of this firing method. The beneficial effects of the fuel processing system are evident in the low levels of heavy metals emission. The Mercury emissions data is with Powdered Activated Carbon being injected.

The CFB combustion process provides for increased fuel flexibility. This is shown in Table 4, which provides the air emission test results from burning an MSW mixture of 50% residential waste and 50% wood waste.

Although new construction activity for WTE plants is low in the U.S., European bidding opportunities are actually increasing. Table 5 presents the results in Table 3, converted to usual European convention. This Table also presents results from additional testing performed to begin a database on various other pollutants, which are a concern in Europe. Test results are compared to the required guarantees for a recent European request for proposals.

POLLUTANT LOADINGS INTO THE APC

The most interesting aspect of the system performance is the contribution of CFB technology to the reductions in pollutant levels. Table 6 shows CFB outlet emissions for selected pollutants. As previously discussed, the NO_x emission level shows the effect of limiting thermal NO_x production during combustion and the staging of combustion air. Mercury levels reflect fuel processing, which eliminates practically all batteries and electrical components. The SO₂ emission is particularly notable. Emissions average a few ppm until the ash bed builds up, when SO₂ emissions drop near to zero. Keep in mind that this is a sand bed, not limestone as is usual with CFBs. (Limestone is usually added to the CFB bed material in order to capture sulfur. Because of the level of chlorine in the MSW, which is not captured at bed temperature, a traditional semi-dry scrubber is used for acid gas control.) As a matter of fact, SO₂ emissions on natural gas firing are higher than waste firing. This is thought to be the result of refinery gas (with low levels of H₂S) being blended into the natural gas pipeline. Absorption of the sulfur by the bed material also has an effect on the ash, as discussed below.

RESULTS OF ASH TESTING

Robbins is unusual in the U.S., in that fly and bottom ash are not combined prior to disposal, but are handled separately. Also, due to the CFB combustion process, the ratio of bottom to fly ash is roughly the reverse of grate firing (recent testing shows 80% flyash, 20% bottom ash leaving the facility.)

Bottom ash is moved through the furnace area to an outlet location by a combination of an angled bed plate and the use of directional nozzles. Directional nozzles deliver the fluidizing combustion air, but in such a manner as to move the heavy bed material towards the discharge point. After cooling, the ash is screened and returned to the sand silo for bed make-up.

Fly ash is picked up from various boiler, scrubber and fabric filter hoppers and moved by drag conveyors to one of the fly ash storage silos. This ash is wetted during gravity loading into trucks, or can be transported dry if desired.

Table 7 provides results from TCLP testing of the bottom ash and flyash/scrubber residue. The excellent results are probably a combination of two factors. First, lower overall metals in the fuel, compared to mass burn, because of the fuel processing. Second, it appears that the conditions are right in the circulating fluid bed to form mineral combinations.

Because the ash in the bed is absorbing the sulfur, chemical reactions occur which appear to be binding metals in various sulfite and sulfate combinations. Future research includes looking for potential additives to improve the characteristics of the ash, increasing its market value.

CONCLUSIONS

The environmental benefits of using CFB technology are fully realized at the Robbins facility. One quarter of the waste stream is recycled. Air emissions to the atmosphere are very low, both for criteria pollutants and for those considered a health risk. Electrical power is produced which replaces the use of coal at the local utility, reducing overall air emissions.

The CFB ash stream has the physical and chemical properties which can be utilized by industry. This not only reduces disposal costs, but reduces impact on the environment caused by the ash transportation and disposal.

This fully integrated facility has the potential for a 100% reduction in waste.

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Table 1. CEM daily log, Unit A Robbins Resource Recovery Facility.
Robbins, Ill. Unit A
Daily Summary Report-Stack

Date	Time	No _x ppm	SO ₂ ppm	CO ppm	THc ppm	SO ₂ Remove%
01/16/1997	00:59	60	0	0	0	1.000
01/16/1997	01:59	64	0	1	0	1.000
01/16/1997	02:59	62	0	5	0	1.000
01/16/1997	03:59	56	0	6	0	1.000
01/16/1997	04:59	74	0	2	0	1.000
01/16/1997	05:59	76	0	4	0	1.000
01/16/1997	06:59	75	0	3	0	1.000
01/16/1997	07:59	65	3	1	0	0.785
01/16/1997	08:59	77	3	8	0	0.575
01/16/1997	09:59	73	0	1	0	1.000
01/16/1997	10:59	73	0	2	0	1.000
01/16/1997	11:59	66	0	1	0	1.000
01/16/1997	12:59	67	0	2	0	1.000
01/16/1997	13:59	72	0	3	0	1.000
01/16/1997	14:59	77	0	1	0	0.983
01/16/1997	15:59	61	0	1	0	1.000
01/16/1997	16:59	64	0	1	0	1.000
01/16/1997	17:59	83	0	12	0	0.862
01/16/1997	18:59	97	0	6	0	0.954
01/16/1997	19:59	91	0	35	0	0.916
01/16/1997	20:59	76	0	1	0	1.000
01/16/1997	21:59	77	0	5	0	1.000
01/16/1997	22:59	74	0	0	0	1.000
01/16/1997	23:59	74	0	0	0	1.000
AVERAGE		72	0	4	0	0.961

• Corrected to 7%O₂

Table 2. CEM daily log, Unit B Robbins Resource Recovery Facility.
Robbins, Ill. Unit B
Daily Summary Report-Stack

Date	Time	No _x ppm	SO ₂ ppm	CO ppm	THc ppm	SO ₂ Remove%
01/16/1997	00:59	74	0	6	0	1.000
01/16/1997	01:59	81	0	6	0	0.968
01/16/1997	02:59	75	0	7	0	0.996
01/16/1997	03:59	78	0	8	0	0.973
01/16/1997	04:59	86	0	10	0	0.947
01/16/1997	05:59	83	0	10	0	0.946
01/16/1997	06:59	86	3	8	0	0.836
01/16/1997	07:59	73	0	5	0	0.964
01/16/1997	08:59	79	1	4	0	0.882
01/16/1997	09:59	82	0	7	0	0.959
01/16/1997	10:59	77	0	4	0	0.977
01/16/1997	11:59	82	0	6	0	1.000
01/16/1997	12:59	76	0	3	0	0.979
01/16/1997	13:59	77	0	3	0	0.968
01/16/1997	14:59	89	0	5	0	0.894
01/16/1997	15:59	89	0	6	0	0.707
01/16/1997	16:59	89	0	5	0	0.647
01/16/1997	17:59	92	0		0	0.872
01/16/1997	18:59	91	0	8	0	0.612
01/16/1997	19:59	97	0	6	0	0.992
01/16/1997	20:59	93	0	4	0	0.986
01/16/1997	21:59	89	0	2	0	0.981
01/16/1997	22:59	98	0	6	0	0.994
01/16/1997	23:59	90	0	4	0	0.994
AVERAGE		84	0	6	0	0.920

• Corrected to 7%O₂

Table 3. Comparison of Compliance Stack Test Results to the Emission Permit Limits.

Burning 100% RDF				
Pollutants	Units	Unit A	Unit B	Permit Limit
Particulate	gr/dscf	0.0015	0.0056	0.01
SO ₂	ppm	1.0	0.5	30
HCl	ppm	4.6	6.2	25
CO	ppm	4.4	2.2	100
NO _x (1)	ppm	73.1	90.4	130
VOC	ppm	1.5	0.6	10
Total dioxin-furans	ng/dscm	2.1	4.9	30
Total TE (89 EPA)	ng/dscm	0.05	0.13	NA
Arsenic	μg/dscm	0.2	0.2	10
Cadmium	μg/dscm	<detection limit (0.01)	0.3	40
Chromium	μg/dscm	4.8	5.6	120
Lead	μg/dscm	3.6	30.9	490
Mercury	μg/dscm	15.8	2.9	80
Nickel	μg/dscm	3.1	3.1	100

- All concentration are at 7%O₂, dry.
- NA = Not Applicable
- (1) NO_x values are without SNCR system in operation.
- Average of 3 test runs
- 3-hr. test runs for all pollutants, except 4-hr. for PCDD/F

Table 4. Comparison of Compliance Stack Test Results to Emission Permit Limits.

Burning 50% Residential Waste and 50% Wood			
Pollutants	Units	Unit B	Permit Limit
Particulate	gr/dscf	.0047	0.01
SO ₂	ppm	0.6	30
HCl	ppm	2.4	25
CO	ppm	1.9	100
NO _x (1)	ppm	82.5	130
VOC	ppm	0.9	10
Total dioxin-furans	ng/dscm	2.1	30
Total TE (89 EPA)	ng/dscm	0.053	NA
Arsenic	μg/dscm	0.3	10
Cadmium	μg/dscm	0.1	40
Chromium	μg/dscm	5.9	120
Lead	μg/dscm	22.1	490
Mercury	μg/dscm	0.5	80
Nickel	μg/dscm	3.1	100

- All concentration are at 7%O₂, dry.
- NA = Not Applicable
- (1) NO_x values are without SNCR system in operation.
- Average of 3 test runs
- All test runs 3-hr., except 4-hr. for PCDD/F

Table 5. Robbins RRF's Compliance Stack Test Results vs. European Air Emission Requirements.

Pollutants	Unit A	Unit B	Recent European Requirement
Total Particulates	2.62	9.76	15 (hourly)
Hydrochloric Acid	5.34	7.2	10 (daily av.)
Sulfur Dioxide	1.89	1.02	50 (daily av.)
Carbon Monoxide	3.92	1.96	50 (daily av.)
Volatile Organic substance, given as total carbon (THC)	0.07	0.3	5 (daily av.)
Nitrogen Oxide	107	132	200 (daily av.)
Ammonia	<1.9	<1.9	10 (daily av.)
Hydrogen Fluoride	<.06	<.06	1 (daily av.)
Cadmium + Thallium	.001	.002	0.05
Mercury (Hg)	0.01	.002	0.05
Pb + Cr + Cu + Mn + Ni + As + Cd + Hg	.08	.06	2
* Dioxins and Furans (ITE)	.039	.10	0.10
Polynuclear Aromatic Hydrocarbon (PAHs)	.0007	.0008	0.05
Chlorophenol	<.0006	<.0006	.001
Hydrogen Cyanide (HCN)	<.004	<.004	0.50
Chlorobenzene	<.00005	<.00005	.001

- All concentration are mg/Nm³ at 11% O₂ except noted otherwise.
- *ng/NM³ at 7% O₂
- Average of 3 test runs
- All tests 3-hr. duration, except 4-hr. for PCDD/F
- Ammonia detection limit with CEM

Table 6. Emission at the CFB Boiler Outlet

Pollutant	Units	Unit A	Unit B
CO	ppm	4.4	2.2
NO _x	ppm	73.1	90.4
SO ₂	ppm	6.6	1.7
HCL	ppm	357.5	351.2
Mercury	μg/dscm	60.7	141

- All concentrations corrected to 7% O₂.
- Average of 3 test runs

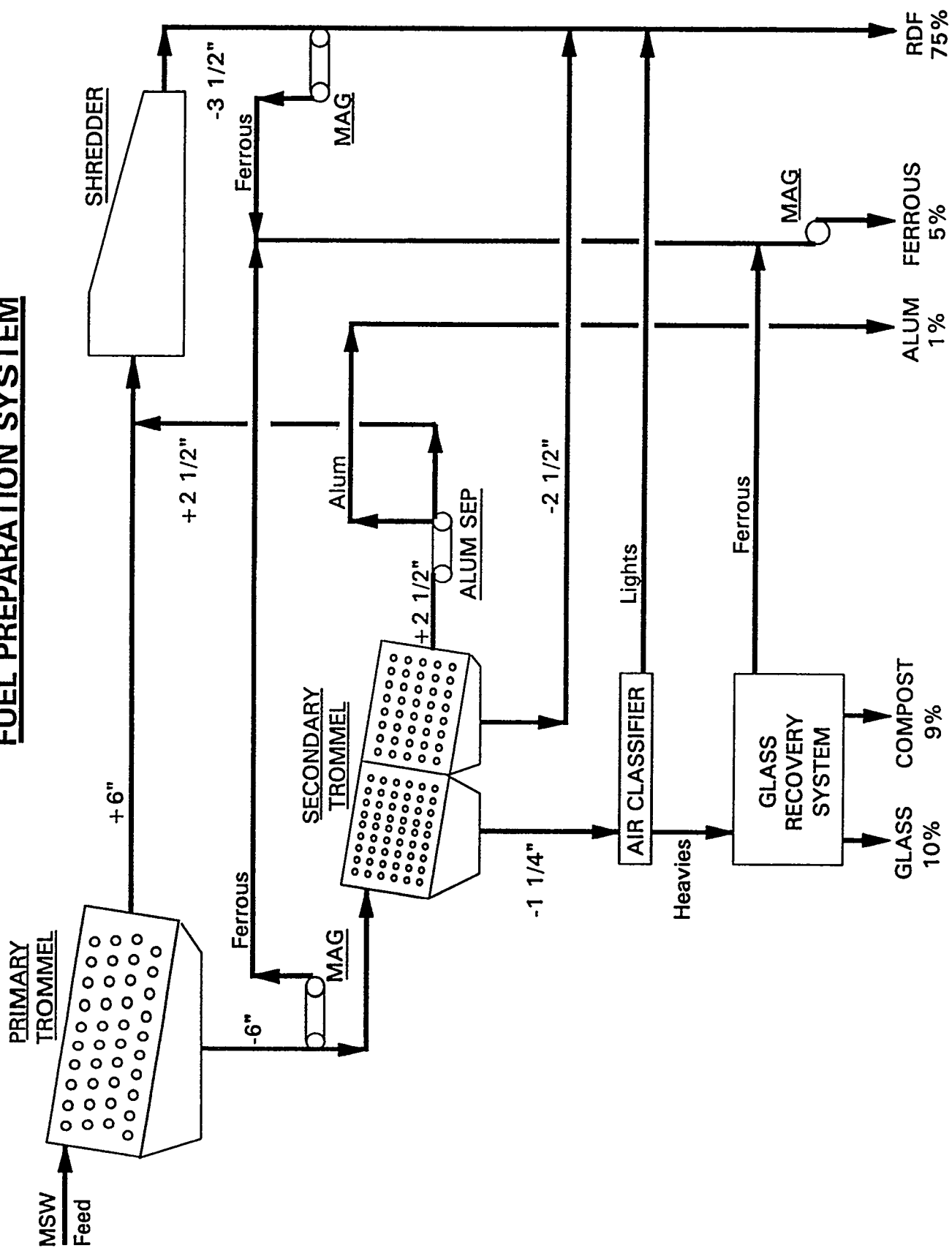
Table 7. Summary of Ash Analytical Results.

Flyash Performance Test Samples				
Parameter	Regulatory Limit	Sample 1	Sample 2	Sample 3
TCLP arsenic	5	<0.05	<0.05	<0.05
TCLP barium	100	<5	<5	<5
TCLP cadmium	1	0.2	<0.05	<0.05
TCLP chromium	5	<0.5	<0.5	<0.5
TCLP lead	5	<0.5	<0.5	<0.5
TCLP mercury	0.2	<0.05	<0.05	<0.05
TCLP selenium	1	<0.05	<0.05	<0.05
TCLP silver	5	<0.5	<0.5	<0.5
Putrescibles	NA	<0.01%	<0.01%	<0.01%

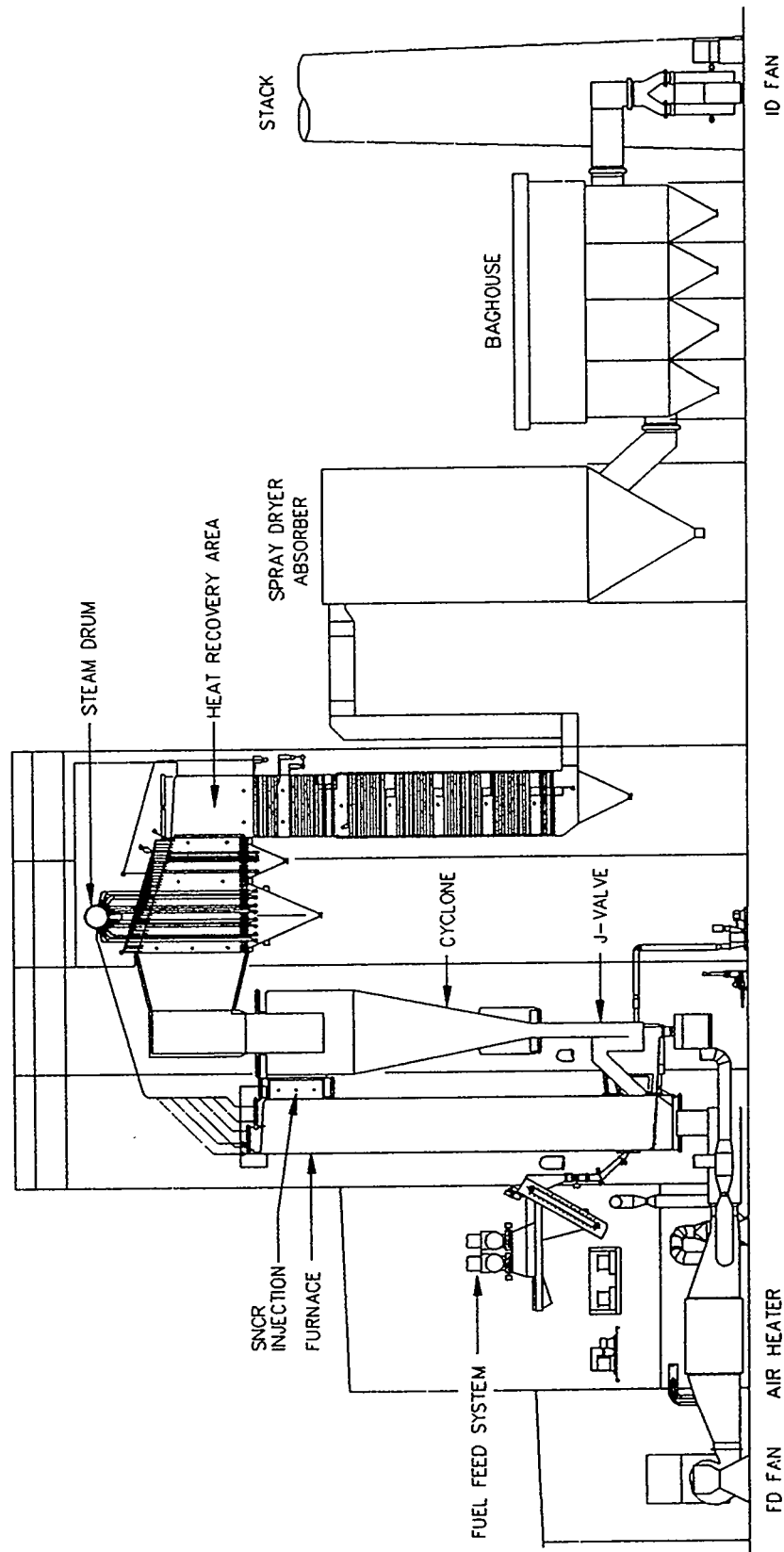
Bottom Ash Performance Test Samples.				
Parameter	Regulatory Limit	Sample 1	Sample 2	Sample 3
TCLP arsenic	5	<0.05	<0.05	<0.05
TCLP barium	100	<5	<5	<5
TCLP cadmium	1	0.05	<0.05	<0.05
TCLP chromium	5	<0.5	<0.5	<0.5
TCLP lead	5	<0.5	<0.5	<0.5
TCLP mercury	0.2	<0.05	<0.05	<0.05
TCLP selenium	1	<0.05	<0.05	<0.05
TCLP silver	5	<0.5	<0.5	<0.5
Putrescibles	NA	<0.01%	<0.01%	<0.01%

- TCLP metals concentrations are in PPM.
- NA = Not Applicable
- Putrescible not detected at indicated concentration

ROBBINS RESOURCE RECOVERY FACILITY **FUEL PREPARATION SYSTEM**



FW-CFB BOILER BURNING RDF



1/8/84

New Mercury Control Technology for the Ft. Dix Waste-to-Energy Plant

Sid Nelson Jr.
Sorbent Technologies Corporation
1664 E. Highland Rd.
Twinsburg, OH 44087

Jon Miller
Sorbent Technologies Corporation
1664 E. Highland Rd.
Twinsburg, OH 44087

INTRODUCTION

Mercury emissions from waste-to-energy plants, municipal solid waste incinerators, and other industrial processes have come under increased regulatory scrutiny. National Emission Guidelines were recently promulgated for municipal incinerators eventually requiring either 85% mercury removal or compliance with an $80 \mu\text{g}/\text{Nm}^3$ emission standard.¹

The ability of air pollution control equipment to remove mercury from a gas stream has been found to be largely a function of the particular mercury species present, their concentrations, and the gas temperature. Mercury chloride (HgCl_2) tends to be found in incinerator flue gases and this species may be well-removed by activated carbon injection,² wet scrubbing,³ or even hydrated-lime injection at low temperatures.⁴ When the gas streams are relatively small, as with incinerators, fixed beds of mercury sorbents are also feasible. Beds of granular activated carbon have long been used to remove mercury vapors from small gas volumes in chloro-alkali plants and from other industrial processes.⁵ The co-absorption of water and SO_2 , leading to bed-soaking and corrosive sulfuric acid production, however, can limit this method of control. And activated carbon beds can spontaneously combust. However, very thick carbon beds have been applied in Europe in recent years on incinerator streams for the adsorption of mercury and other toxic species.⁶

Finer activated carbons can also be injected into the gas stream and removed in a particulate removal device.^{6,7} Activated carbons can do a good job capturing high concentrations of mercury chloride, particularly when injected at relatively low temperatures. However, once the carbons are injected, they are lost; they become mixed in with large masses of acid gas sorbents and/or fly ash, which goes to disposal. Any sorbed mercury is not recovered.

The elemental form of mercury, unfortunately, has proven to be much more difficult to control. Elemental mercury is not soluble in water, and even iodine-impregnated activated carbons⁸ and lime at extremely-high injection rates⁴ may do little to remove it at temperatures above 300 F.

The operators of some incinerators need to be concerned about elemental mercury capture. While the mercury in most incinerator streams is predominantly HgCl_2 , this is not always the case. Prior compliance measurements from the Ft. Dix municipal waste-to-energy plant in New Jersey, for example, indicate a high degree of elemental mercury.⁹ And some sites, like that at Ft. Dix, do not have a cool-side baghouse for activated carbon injection. Moreover, to meet the new 85% mercury removal requirements, some sites will have to remove a significant amount of elemental mercury. For example, if 90% of the mercury in a gas is in the form of HgCl_2 and activated carbon injection removes 90% of that, the 81% net removal is less than the 85% minimum.

After promising early experiments, the U.S. EPA and Air Force awarded Sorbent Technologies Corporation contracts to develop and demonstrate granular elemental mercury sorbents for incinerator use. The target was a recoverable-mercury sorbent that would last for from six-months to two years on a concentrated incinerator stream in a thin, simple, panel-bed arrangement. Two sorbent materials have been developed in this effort: a low-temperature version from which the mercury can be recovered, and a high-temperature version for upstream applications. This paper describes some of the work that has been done on these sorbents. Sorbent Technologies is scheduled to demonstrate the new mercury sorbent technology at the Fort Dix incinerator later in 1997.

PANEL-BED SORBENT PELLETS

Laboratory Screening

A laboratory test stand was constructed to evaluate the elemental mercury capture performance of various sorbent chemistries and a large number of screening runs were conducted. While the majority of treatments gave little evidence of any mercury sorption, two chemical combinations showed excellent potential.

The test stand used in the screening program included bottled gases, mass flow controllers, a constant-temperature oil bath, laboratory oven, mercury analyzers, and a computer data acquisition system. Elemental mercury was introduced into the simulation gas from permeation tubes. These tubes emit highly-constant elemental mercury vapor at rates strictly dependent on their temperature. A certified permeation tube, traceable to NIST standards, was used to calibrate the analyzer. During testing, the permeation tubes were placed inside a glass container that was maintained at a constant temperature using a constant-temperature oil bath. The permeation rate of mercury was varied by using multiple permeation tubes or by changing the temperature of the bath.

To test the various materials, a small fixed-bed of the candidate sorbent material was held in a custom-fabricated glass chamber which was heated in a laboratory oven to the simulation temperature. To prevent the absorption of mercury by the test apparatus, all components exposed to the mercury-laden gas stream were constructed of Teflon or glass and heated. The mercury-laden gas was pre-heated in an inert, glass-bead-loaded preheater before it entered the sorbent bed.

A data acquisition system allowed long-term, unattended system operation. The elemental mercury measurements were made using a Jerome 431-X gold-film mercury analyzer, manufactured by Arizona Instruments, and/or a Jupiter cold vapor atomic adsorption (CVAA) analyzer. The Jerome analyzer uses a gold-film sensor to measure elemental mercury vapor. The gold-film sensor is inherently stable, selective to elemental mercury, and has a detection range from 0 to 999 $\mu\text{g}/\text{Nm}^3$. The sensor is periodically regenerated. The Jupiter CVAA instrument has a dual-beam design that decreases zero-drift and improves the way in which the sample gas is refreshed in the sample cell. By altering the feed line configuration, this CVAA instrument is capable of providing continuous elemental mercury measurement with no interference from acidic gases, such as SO_2 .

Low-Temperature Sorbents

After screening many potential chemistries, a good low-temperature elemental mercury sorbent was found. We call this material low-temperature "Mercsorbent." The new material can be pelletized for low-pressure-drop application in panel-beds and shows good potential for long-term mercury capture at temperatures from about 130 F to 220 F. Importantly, once the Mercsorbent is saturated, the captured mercury is easily recovered with simple thermal treatment.

The new sorbent's potential for long-term elemental mercury-capture is suggested in Figure 1. With a mercury inlet concentration of 150 $\mu\text{g}/\text{Nm}^3$, a space velocity of 2400 hr^{-1} , and a 7.6-cm deep sorbent bed, a removal rate of over 95% was obtained with no diminution in performance in a 70-hour run. The ultimate capacity of the sorbents has not yet been determined.

Mercury Desorption Tests

Effectively sorbing the mercury from the exhaust gas is not enough; it must be assured that it no longer threatens human health or the environment. Consequently, leachability and thermal desorption tests were conducted to explore the safety and mercury recovery potential of the new sorbent. Saturated sorbent containing approximately 0.12 wt% of mercury from a long-term utilization test run was used in these studies.

If a waste material like the saturated sorbents is easily leachable, heightened precautions are necessary in its storage and transport, and disposal can be expensive. Two 5-gram samples of the partially-saturated sorbent, containing approximately 6.000 mg of mercury, were sent to an independent testing laboratory, Electro-Analytical Laboratories of Mentor, Ohio, for standard Toxic Characteristic Leaching Procedure (TCLP) extraction analysis. Two identical samples were subjected to an 18-hour extraction with a 20:1 solution-to-solids ratio using an acetic acid solution with a pH of 2.9. The detection limit of the process was 0.010 mg Hg/liter. The first sample had a TCLP extraction test result of 0.082 mg Hg/liter; the second sample had a result of 0.080 mg Hg/liter. The TCLP mercury leachate level to qualify as hazardous wastes is 0.200 mg Hg/liter. Thus, these saturated sorbent samples would not be classified as a hazardous waste.

It is not ultimately helpful to remove mercury from the gas phase if it is simply transferred to another medium. Mercury captured by activated carbon injection, for example, becomes mixed in with other fly ash that is ultimately sent out for land disposal. The mercury is not recovered, but left to become a potential groundwater pollutant. The sorbents examined in this research, however, present the possibility of mercury recovery.

A growing secondary source of mercury supply is its recovery from mercury-containing wastes, which are roasted in retort furnaces to recycle their mercury. Today there are five secondary mercury recovery facilities around the country, supplying about half of the U.S. needs for mercury by retorting mercury wastes and condensing out and purifying the mercury for sale.¹⁰ Nine U.S. gold smelting and refining operations, which supply about 60 tons of by-product mercury per year, could also be used for this purpose.

Experiments were performed to examine the new sorbent's thermal recovery potential. A 0.50 g sample of partially-saturated sorbent, with a known quantity of sorbed mercury, was heated under a flowing gas stream and the elemental mercury content of the off-gas was continuously measured. In order to accurately measure the mercury, a low desorption temperature of 450 F and was selected. Integrating under the desorption curve revealed that after six hours fully 85% of the mercury had evolved from the sorbent.

Mercury recovery retort furnaces and ore roasters operate at a temperature of about 1100 F. A desorption test was carried out at this temperature also. Under these conditions, however, the mercury desorbed from the materials so quickly and in such quantities that the initial exit mercury concentration was far over the upper detection limit of the analyzer, even with 80:1 dilution sampling. The mercury concentration of the off-gas rapidly dropped to zero after a period of two minutes, indicated a very fast desorption process at this temperature. Thus, the mercury captured by the new sorbents should be desorbed very quickly and completely by the furnaces of mercury recovery facilities.

High-Temperature Sorbents

A second elemental mercury sorption chemistry was also discovered which operates at higher temperatures, from 220 F to over 450 F. This composition can also be easily pelletized into granular, low-pressure-drop, panel-bed sorbents. However, while this sorbent material is capable of operating under more extreme conditions, unlike the low-temperature version, its mercury is not thermally recoverable.

At higher temperatures, elemental mercury is difficult to capture. For example, the performance of an activated carbon at higher temperatures is plotted in Figure 2. One gram of a granular activated carbon (Calgon CPG; 12x40 mesh) was tested over the range of 280 F to 400 F with gas containing 40 $\mu\text{g}/\text{Nm}^3$ mercury. The test was run with air also spiked with SO_2 and moisture. Measurements were simultaneously taken on both the Jupiter and Jerome instruments.

With dry air, 1.0 g of this carbon in a 2.5 cm bed was capable of sorbing about 45% of the mercury at 400 F. However, when 0.06 lb-of-moisture-per-pound-of-dry-air was added to the gas stream, the mercury removal level dropped to zero. Apparently with carbon, water molecules compete for the same sites as the mercury. After the gas temperature was lowered to 300 F, a small amount of mercury sorption began to occur, perhaps to 10% removal. At high temperatures, this carbon does not appear to be a good candidate for elemental mercury capture.

In contrast, a run with a 3.8 cm bed of the new high-temperature Mercsorbent pellets is shown in Figure 3. Here the gas flow and face velocity were the same as the previous test, but the mercury concentration was twice as high. This gas was spiked with 200 ppm each of SO_2 and HCl. For over 65 hours at 230 F, the Mercsorbent removed over 95% of the elemental mercury in the gas stream. When the temperature was raised to 300 F for the last three hours of the experiment, the removal rate increased to nearly 100%.

These Mercsorbents can work well at even higher temperatures. Figure 4 contains a plot of a short-term test of a 2.5 cm bed of pelletized sorbent as a function of temperature. The data from this test indicate the potential for 90+% elemental mercury removal up to 700 F.

Bench-Scale Testing

Based on the earlier laboratory runs, sorption testing of the low-temperature sorbents was then scaled up to a large 150 m^3/hr (90 acfm) simulation system. This bench-scale system included a propane burner, elemental mercury spiking system, dilution air intake for temperature control, 24 m of ducting, an orifice plate for flow measurement, three heated sample lines for gas analysis at various points, and a variable speed ID fan. The spiking system was capable of adding 50 $\mu\text{g}/\text{Nm}^3$ of elemental mercury to the hot gas stream.

A thin filter of the new sorbent was inserted into the end of the ducting. Sitting in a drum, the conically-shaped, flat filter was 1 m high, 0.5 m at its maximum diameter, and 7.5 cm thick. It held 15 kg of the new sorbent. See Figure 5. At a gas flow rate of 150 m³/hr, with a space velocity of 2700 hr⁻¹, the pressure drop across the filter was only 0.5 cm of water column. When operated in multi-hour tests, the sorbents removed from 80% to 100% of the mercury passing through them, depending on the operating conditions.

POWER PLANT SLIP-STREAM TESTING

The low-temperature Mercsorbents were also tested in the field on actual flue gas from the Ohio Edison Company's R.E. Burger station near Shadyside, Ohio. A test rig was constructed that drew off a slipstream of the plant flue gas after the electrostatic precipitator and divided it between six small test beds. Approximately 550 lpm of gas with approximately 3.5 µg/Nm³ of elemental mercury was drawn through each of the sorbent test beds, 13-cm in diameter and 15-cm deep, for nine days. A blower returned the gas to the ductwork.

Each sampling train consisted of a particulate pre-filter, ice bath, two acid-gas filters in series, two gold-coil dosimeters, a mass flow controller, and a pump operating at 90 cc/min. The acid-gas filters were to eliminate any hydrogen sulfide or other acidic gases. The gold-film dosimeters are made to sorb very low concentrations of elemental mercury, concentrating it for more accurate measurement. Two dosimeters in series were used to insure that all of the elemental mercury was collected. They are designed not to sorb any mercury chloride that may be in the gas. After 90 minutes, the dosimeters were removed and analyzed using the Jerome instrument. The elemental mercury concentrations of the gas is the mass of mercury collected divided by the total gas volume sampled. To save time, three sampling lines, with a total of six dosimeters, were run simultaneously.

The mercury content of gas from power plants is about two orders of magnitude lower than that of waste incinerators and some measurement difficulties were experienced. An interferant gas appeared to affect our measurements at these levels. By using a plain vermiculite dummy bed, however, a method was developed to correct the readings. Using the dummy-bed correction, the elemental mercury removal rates measured after nine days varied from between about 75% and 97%, similar to what was seen in the laboratory. These numbers are approximate because the mercury sampling at the power plant was episodic and the inlet mercury would be expected to vary over the nine days.

To do a mass balance, a sample from one of the Burger beds was thermally desorbed at a low temperature of 400 F. A plot of the results appears in Figure 6. Integrating under this curve provides a value for the amount of mercury sorbed. The consistent mercury removal efficiencies for this sorbent observed in a laboratory test, field slipstream test, and calculated based on the desorption test, are shown in Figure 7. Combining the desorption result with measurements of mercury in the Burger plant gas stream suggests an average mercury removal rate of about 80 to 90% for the new sorbent under the actual flue gas conditions.

FABRIC FILTER BAGS

Research is also underway to examine other possible ways of applying the Mercsorbent chemistries to flue-gas applications. For example, many municipal waste incinerators have spray dryers and fabric filters in their air pollution control trains. At these facilities an additional strategy is available. First, activated carbon injection would remove the majority of the oxidized mercury species, such as mercury chloride. Then, the large surface area in the baghouse would be exploited by treating the fabrics with the mercury-reactive substances to create a polishing filter for elemental mercury.

Low-Temperature Fabrics

Initial laboratory tests of the mercury-sorbing baghouse fabrics have been promising. So far, the treatments have been successfully applied to samples of commercial baghouse fabrics of acrylic, polyester, and Ryton, and to both felts and weaves.

In one example, a 5.4-cm diameter polyester fabric filter sample was treated with the new low-temperature chemistry and dried. A simulated flue gas at 1 lpm, spiked with elemental mercury to about $170 \mu\text{g}/\text{Nm}^3$, was then passed through the fabric. The gas temperature was held at 160 F, a temperature representative of spray dryer baghouses.

Over 95% mercury removal was achieved for nearly 24 hours under these conditions. This sample was then further saturated at higher gas flow rates for 108 more hours, in 5 additional tests examining changes in various conditions. Although still not saturated and removing most of the mercury passing through it, the testing was stopped with the sample having sorbed 4.1 mg of mercury, or almost 2 g Hg/m^2 of fabric. A photograph of the fabric, with its captured mercury coating very evident, appears in Figure 8. Like the low-temperature Mercsorbent pellets, the baghouse application allows for simple recovery of the sorbed mercury. When the fabric filter bags have met their useful life, the mercury-laden fabrics could be shipped to a mercury recovery facility.

When operating on a pulse-jet baghouse, the mercury-laden stream would pass through the fabric at a high rate. To examine such conditions, a treated fabric was tested at a very high air-to-cloth ratio of 8 ft/min. The results of this run appears in Figure 9. The elemental mercury concentration into the fabric was $150 \mu\text{g}/\text{Nm}^3$ and the gas temperature was 160 F. Even at this high gas-flow rate, mercury removal averaged about 90% in this 50 hour test.

High-Temperature Fabrics

The high-temperature sorbent composition can also be applied to baghouse fabrics. In the next example, a high-temperature Teflon® baghouse fabric (Pyro-Tex®) was treated with the high-temperature Mercsorbent. The fabric was then tested in the laboratory test stand with a $200 \mu\text{g}/\text{Nm}^3$ mercury simulation gas at 375 F and an air-to-cloth ratio of 4.0 ft/min. The performance of this material leveled off at about 70% elemental mercury removal at about 40 hours. See Figure 10.

Of course, much more development and testing of this concept is required, with much longer run times, lower concentration mercury streams, and frequent bag pulsing. Disposal of the mercury-containing bags must also be addressed. However, the sorption capacities of the samples has been high and no breakthroughs have yet been achieved. The concept deserves further work.

FUTURE PLANS

Laboratory and bench-scale testing and optimization of the sorbents at Sorbent Technologies Corporation is an ongoing activity.

Like many incinerator facilities around the country, the refuse incinerator at Fort Dix in New Jersey has a mercury emission problem. Prior compliance sampling at this unit suggests that a significant amount of its mercury is in the elemental form. While it complies with other emission regulations, this Army incinerator has been unable to meet its operating permit mercury limit (0.00093 lb/hr) or the new statewide mercury standards (65 $\mu\text{g/dscm}$ now and 28 $\mu\text{g/dscm}$ later) on a regular basis. The facility has been fined by the State of New Jersey for its mercury emissions. Sorbent Technologies Corp. is scheduled to demonstrate the new recoverable-mercury sorbent technology at this Fort Dix incinerator in later 1997.

ACKNOWLEDGEMENTS

This work was largely funded by the U.S. Air Force, through their Armstrong Laboratory, and the U.S. Environmental Protection Agency. The authors would like to thank Dr. Joseph Wander and Lt. Tammy Abbett of the Environics Division of the Air Force Civil Engineering Support Agency and Donald Carey of the U.S. EPA for their support and advice. They would also like to thank Frank Nolan of the U.S. Army Environmental Division and Scott Spurlock of United Cogenerators for access to the Ft. Dix waste incinerator.

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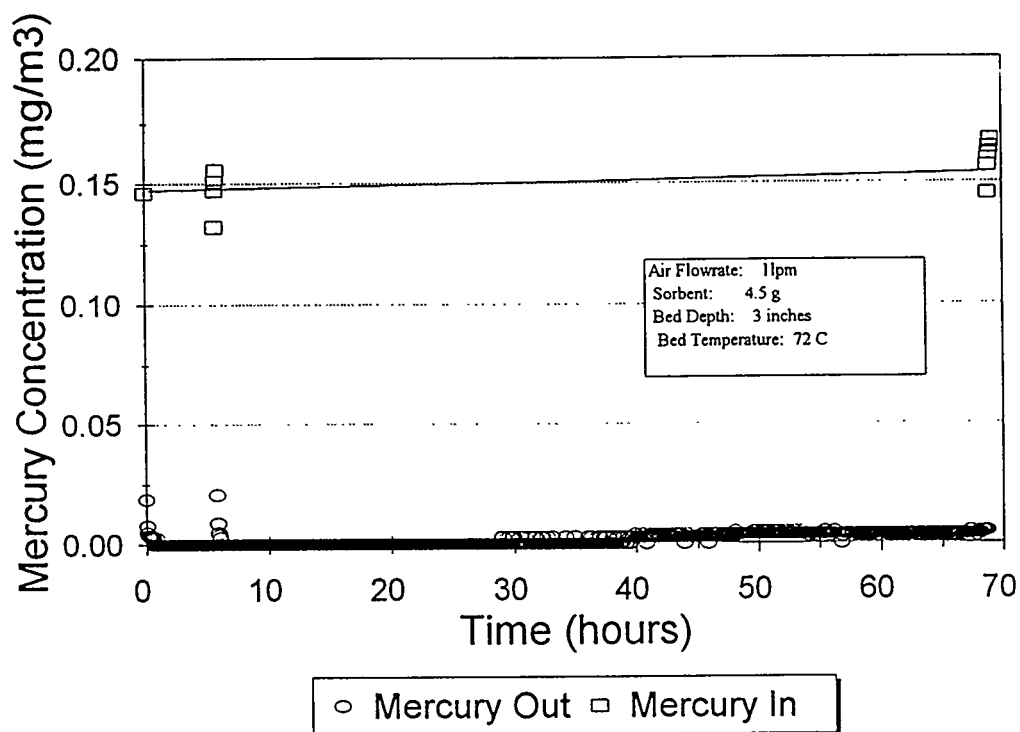


Figure 1. Elemental mercury removal of low-temperature Mercsorbent.

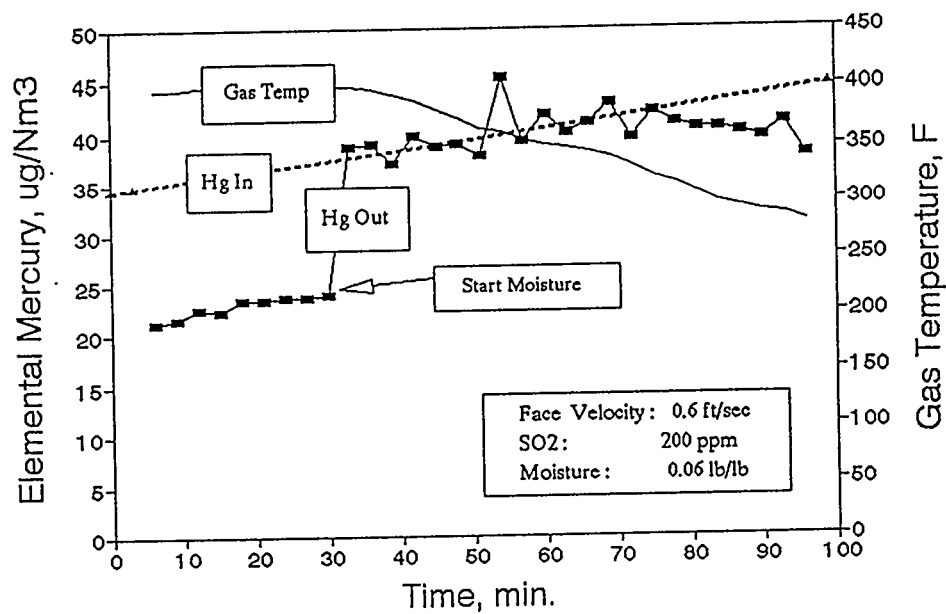


Figure 2. Elemental mercury removal of an activated carbon at high temperatures.

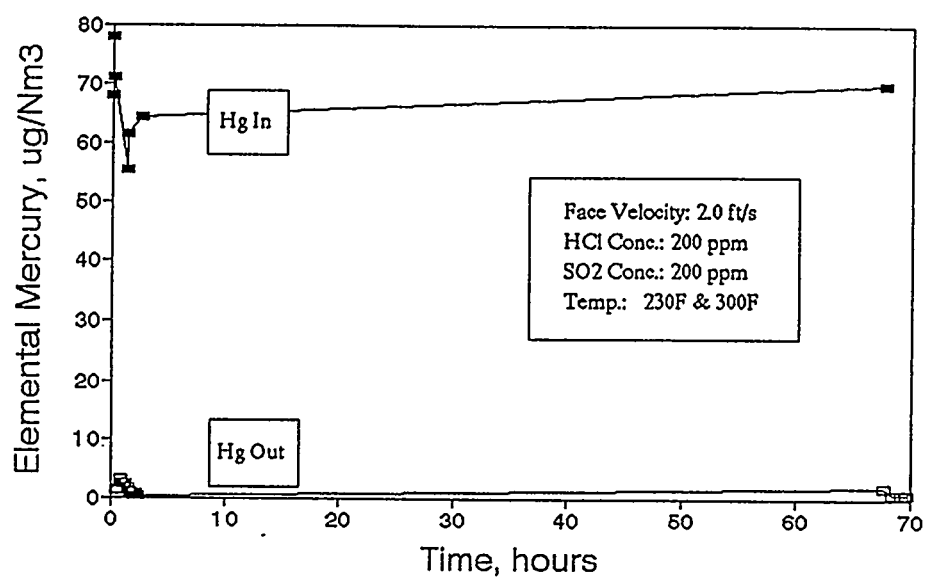


Figure 3. Elemental mercury removal of high-temperature Mercsorbent.

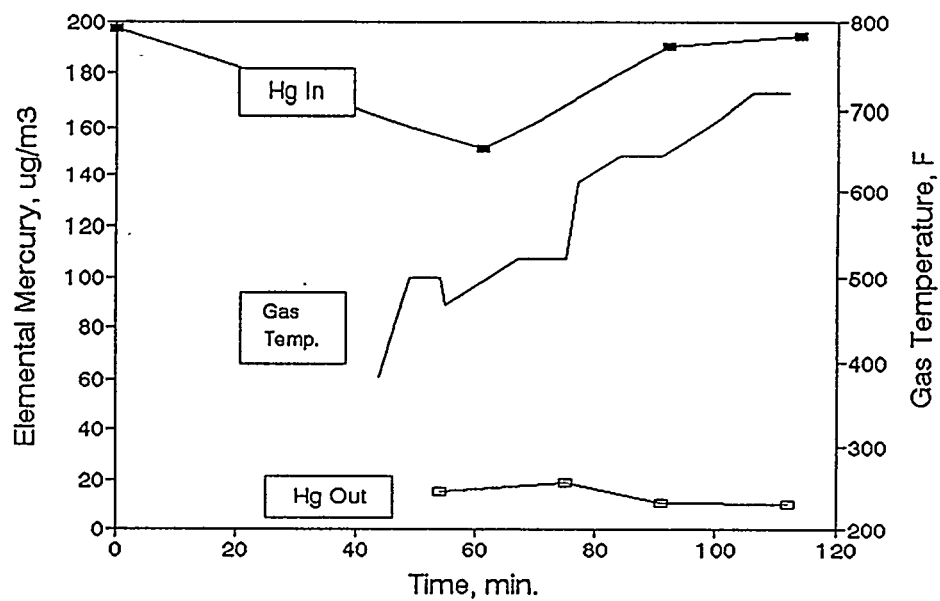


Figure 4. High-temperature range of Mercsorbent.

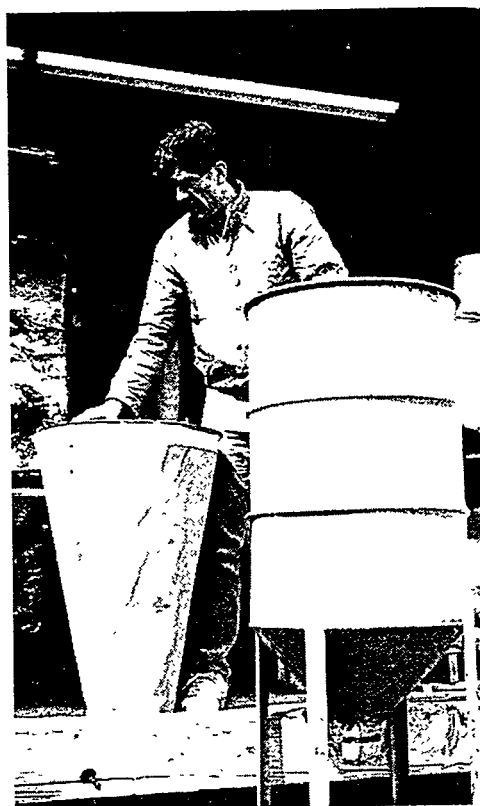


Figure 5. Small conical panel-bed filter of mercury sorbents.

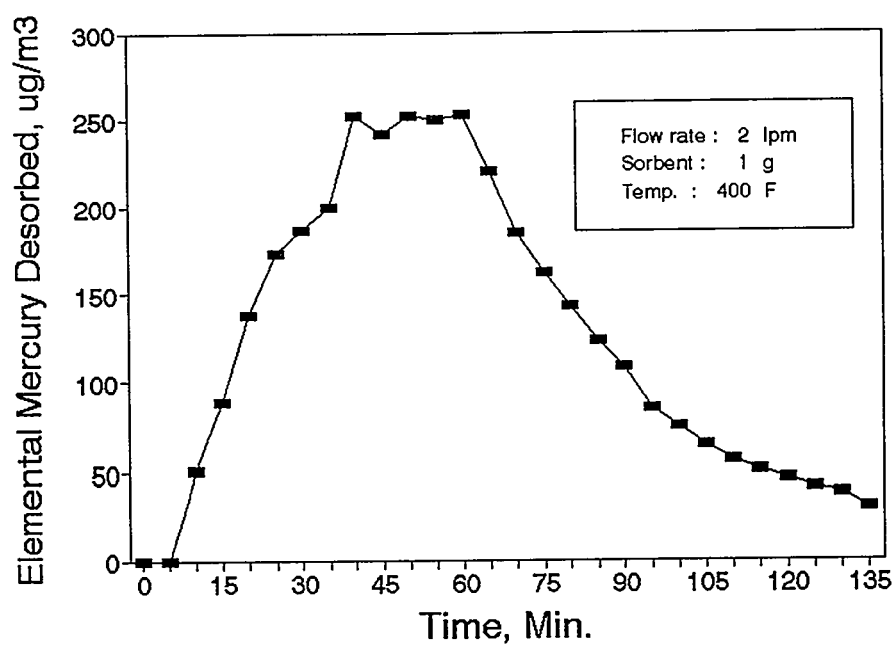


Figure 6. Desorption of elemental mercury from the Burger station Mercsorbent.

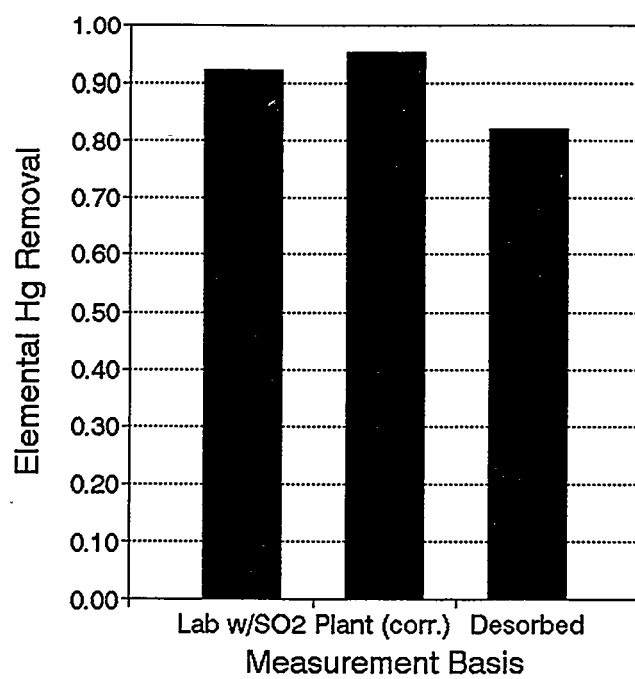


Figure 7. Low-temperature performance of Burger plant Mercsorbents.

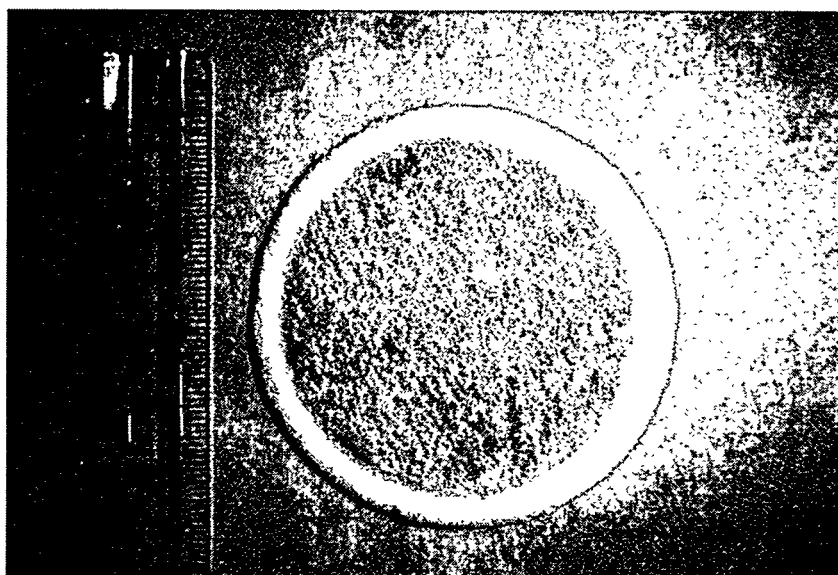


Figure 8. Mercury captured on a low-temperature Mercsorbent baghouse fabric.

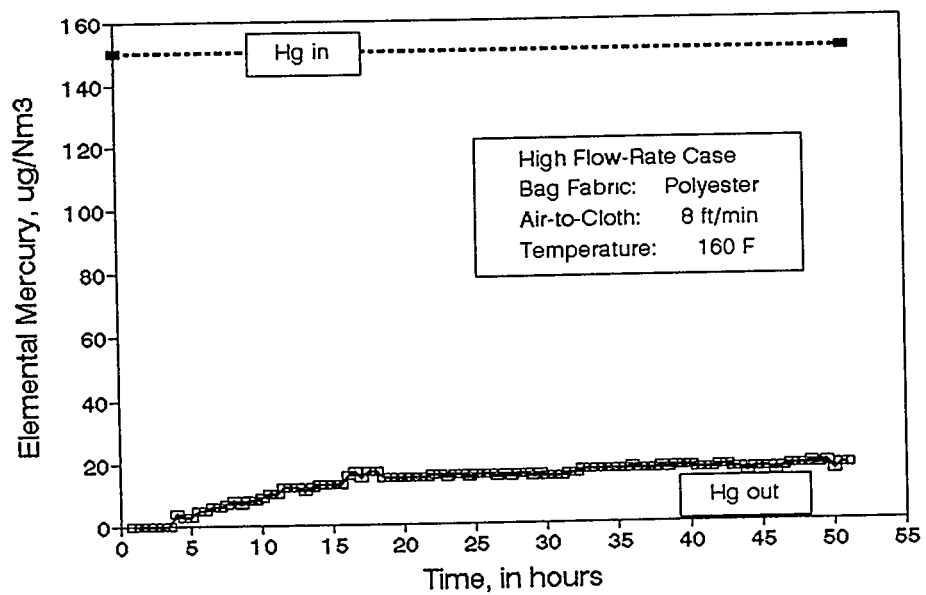


Figure 9. Results of a low-temperature Mercsorbent baghouse fabric test.

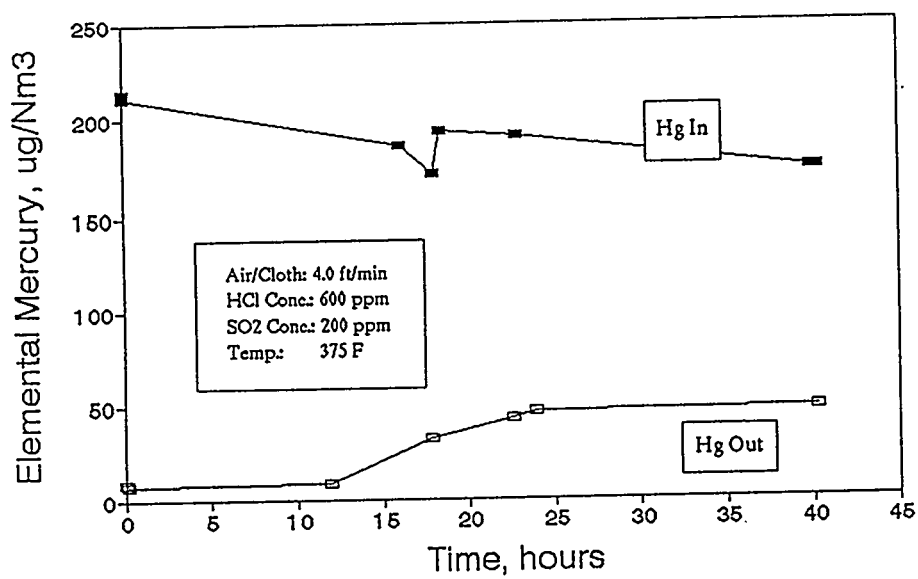


Figure 10. Results of a high-temperature Mercsorbent baghouse fabric test.

Is There a Meaningful Relationship Between Chlorine Feed and Non-Dioxin Stack Emissions?

H. Gregor Rigo
Rigo & Rigo Associates, Inc.
1 Berea Commons, Suite 211
Berea, Ohio 44017

R. Stephen Champlin
Vitco, Inc.
900 E. Wabash Avenue
Nappanee, Indiana 46550

INTRODUCTION

The American Society of Mechanical Engineers' Center for Research and Technology Development (ASME/CRTD) published an extensive analysis and tabulation of available dioxin and chlorine in late 1995¹. The preponderance of that data produced no meaningful relationship between dioxin stack emissions and chlorine feed across a broad range of commercial waste combustor types. In the Preamble to the April 1996 proposed Hazardous Waste Combustor Rule, EPA acknowledged that changes in chlorine feed have little effect on dioxin emissions², but the text goes on to speculate that reducing chlorine input is still a good idea because fewer metals and chlorinated organics might be emitted.

Given that the conventional wisdom — reducing chlorine input to full scale facilities will reduce dioxin emissions — proved groundless when the available data were examined in a consistent manner, what does the available data tell us about the relationship between chlorine feed rate and municipal waste combustor (MWC) stack emissions in general? Product substitution and waste component diversion programs are expensive and economically disruptive at current levels. So, the likelihood of achieving any benefit needs to be determined before public policy changes are made. If there is no significant relationship between chlorine feed rate and stack emissions, then efforts to reduce chlorine feed are unlikely to reduce the trace levels of contaminants that leave state-of-the-art MWCs. Interventions to reduce chlorine feed rate would simply cause society to squander its scarce resources chasing ghosts.

APPROACH

The ASME/CRTD analysis used a segment of a much larger emissions database that contains emitted concentrations for a host of non-dioxin pollutants. These data can be subjected to the same analysis used in the ASME/CRTD report to determine if there is a meaningful relationship between chlorine input and MWC stack emissions.

Database Characteristics

All database entries are from the most reliable information available. Whenever possible, emitted concentrations are calculated directly from analytic laboratory reports and field data sheets to avoid intermediate transcription, rounding and interpretation problems. The databased values are brought to USEPA standard reference conditions (dry, 20°C, 1 atmosphere, 7% O₂) and compared to reported concentrations as a quality assurance check. In addition, the database is routinely screened for outliers — unusually large or small results. Potentially aberrant results are checked and corrected whenever possible. Remaining outliers are flagged so that their effect on subsequent data analysis can be determined.

Metals, volatile and semivolatile organics and criteria pollutant concentrations are covered to varying degrees in the database. The metals include those in the Clean Air Act Sections 112 and 129 lists along with additional environmentally sensitive metals listed in 40 CFR 266, the Boiler and Industrial Furnace Rule, and the European Union standards. Trace organics include much of the Section 112 Organic Hazardous Air Pollutants (HAPs) list along with data on other trace organics collected as part of broad-scope emissions assessments and research programs.

Below Analytic Laboratory Detection Limits Results

Much of the trace organics data are below analytic laboratory detection limits (ADL). Traditional analytic laboratory practice involves establishing the detection limit for their instruments. An instrument response that is less than 2.5 to 3 times the noise (variability) established by repeatedly analyzing samples without the pollutant present is not distinguishable from a sample with the pollutant absent. Analytic laboratories report these values as below detection limits (BDL). Some labs go a step further

following ASTM³ practice and identify results between the ADL and a value 3.33 times higher as tentative since the variability is too large to provide reasonable assurance that the measured value is within 30 percent of the true value. When the ADL is converted into an equivalent emitted concentration using standard data reduction procedures, it is called the analytic laboratory detection limit equivalent concentration or ADLE.

When two below ADLE results are compared, source characteristics are not involved. Rather the comparison is between the low level quantitation capabilities of the instruments and laboratories involved. Such results must be excluded from the statistical data analysis since they provide no useful information on the relationship between MWC stack emissions and chlorine. Below ADLE results are excluded so that relationships are neither caused nor hidden by laboratory detection limit differences and random chance.

A fully correct analysis should also exclude data that are below the Reference Method Practical Quantitation Limit (RMPQL). The ADL inherently considers only analytic laboratory procedures and instrument responses. Emitted concentrations, on the other hand, have a whole host of additional sources of variability — for example, spatial differences within the stack, velocity pressure and flue gas molecular weight determination errors, residual sampling train contamination, recovery losses, matrix differences, sample volume and diluent measurement errors, laboratory concentration procedure and sample clean-up errors, etc. — in addition to the instrument limitations considered by the ADL. These sources of variability raise the concentration that can be accurately quantified.

EPA Method 301⁴ describes the practical quantitation limit (PQL) as “the lowest level above which quantitative results may be obtained with an acceptable degree of confidence.” A reasonable degree of confidence is defined in Method 301 as 99 percent of replicated results being within 30 percent of the average value. The PQL is determined by analyzing paired test results obtained by operating, recovering and analyzing two or more simultaneous sampling trains. The “lower limit of the test method” is, by definition, equal to the PQL.

Results that are between the ADLE and the PQL are too variable to provide any meaningful information. They are so noisy that any relationships uncovered between the ADLE and the PQL are as likely to be attributed to data noise (random chance) as they are to the phenomena being investigated. Unfortunately, EPA has not determined the PQL for Methods 23, 26 and 29. Consequently, all results above the ADLE have been treated as valid numbers in this analysis.

Analysis of dual and quad train testing sponsored in part by the ASME Research Committee on Municipal and Industrial Waste indicates that the median PQL to ADLE ratios are 10, 3,000 and 120 for Methods 23 (dioxins, chlorobenzenes, PAHs and other semivolatile compounds); 26 (HCl, Cl₂, HF and HBr); and 29 (Section 112, BIF and EU) results respectively. The controlled metals data are probably sufficiently accurate for this analysis; the uncontrolled HCl and trace Organic HAPs analyzed may be sufficiently noisy that really firm conclusions are not possible.

Chlorine Input

Determining the chlorine concentration of a particular batch of MSW burned during a test run is virtually impossible. Previous analysis of MWC data shows, however, that there is a strong correlation between chlorine feed measurements and uncontrolled flue gas HCl concentrations. The starting amount of chlorine available of participation in organic chlorination reactions and formation of metal chlorides is the amount released from the MSW (not bound up with the bottom ash). Also, the uncontrolled HCl concentration is usually large compared to the amount of chlorine that is associated with uncontrolled MWC fly ash. Consequently, uncontrolled HCl is used as a proxy for chlorine feed rate.

Statistical Techniques

The techniques used in the ASME/CRTD study to investigate the relationship between dioxin feed rate and dioxin stack emissions can be applied to these as well. Those analyses included: Spearman Rank-Order and Partial Correlation Analysis, Analysis of Variance (ANOVA) and Factor Analysis to find whatever relationship might exist between chlorine input and stack dioxin concentrations.

The major parametric studies which required ANOVA techniques to sort out confounding effects do not generally include metal or other trace organics emissions. Instead, partial correlation techniques were employed to sort out the effect of readily discernible differences like the type of air pollution control device (APCD) and designed interventions (e.g., purposely running the afterburner at low temperature for research purposes), from whatever effect chlorine feed might have on non-dioxin pollutant emissions. Factor Analyses were not performed due to the sparse nature of the data. To be reliable, Factor Analysis requires that all the parameters being investigated be complete. When there are significant data gaps, the analysis can still be mathematically performed, but the interaction terms are not fully characterized and the results can be misleading.

Spearman Rank-Order Correlation techniques were used to perform most of the analyses. Here, rank orders rather than absolute values of data sets are compared. This method has the advantage of not requiring precise knowledge of the underlying data distribution. Regardless of whether the data are normally, lognormally or otherwise distributed, the rank order of each data point remains the same. Sidestepping the distribution type question simplifies the analysis without losing any ability to uncover a relationship if one exists. Whenever Spearman Rank-Order Correlations could not be performed, the natural logarithms of the data were used, since it is well known that emissions data are usually lognormally distributed.

Statistically significant correlations are ones whose significance level are less than 5 percent. This is a way of saying that we are 95 percent confident that the correlation is significant. Since this is an exploratory data analysis, we have to be aware that one in 20 comparisons will be “significant” due to chance alone. To avoid the problem of finding false positive results while minimizing the chance of declaring there is no relationship when one is really present, we used the False Discovery Rate (FDR) procedure⁵. This is a refinement of Bonferroni which scales the significance level from $\alpha = 0.05$ found in most EPA regulations by the total number of comparisons (n) to be made and the rank order (i) of the significance level determined for a specific comparison:

$$\alpha^* = i\alpha/n \quad (1)$$

The FDR criteria effectively increases the required level of significance as the number of less significant comparisons already made increases. The advantage compared to other techniques that use a single threshold value is an increased potential for finding meaningful relationships that could otherwise be lost using a more conservative screening criteria while still avoiding the problem of finding a large number of false positives.

Just because a relationship is statistically significant does not mean that it is practically significant. The amount of change seen in one variable as a result of a change in the other is explained by the square of the correlation coefficient. As a result, with large data sets, statistically significant relationships can explain practically inconsequential portions of the total observed response.

For each statistically significant relationship, a scattergram was produced and a loess line — a localized regression fit through the nearest 25 percent of the data on each side of an uncontrolled HCl concentration — was added to determine if a threshold is apparent. A loess line that is flat at one end

followed by rapid rising is evidence of a threshold effect. When the loess line flattens out again, this is an indication that different mechanisms are at work. A continuing straight line indicates the relationship is valid over the data range. Separate loess lines were fit through data from facilities equipped with high efficiency particulate control devices and those that were not to separate that effect in the plots.

RESULTS

The 28 databased HAPs and pollutants found in other country's regulations with enough simultaneous uncontrolled HCl and emitted concentration data to support analysis are tabulated in Table 1. The number of paired data points and the strength of the relationship (squared partial correlation coefficient) with uncontrolled HCl as a chlorine feed surrogate are included along with available melting and boiling temperatures for metal chlorides.

Scatterplots contrasting Section 112 HAP and uncontrolled HCl emissions are provided for all pollutants displaying a statistically significant relationship.

Metal Emissions

Figures 1 through 7 are scatterplots for analyzable Section 112 and 129 metal emissions versus uncontrolled HCl concentrations that show a statistically significant relationship. In each plot, data collected at facilities equipped with high efficiency particulate control devices (fabric filters and large electrostatic precipitators) are plotted as solid points. The balance of the data, principally from low efficiency electrostatic precipitators, are plotted using open symbols. While some plots show roughly an order of magnitude difference between these two data sets, the majority of the results are interleaved. This indicates that either the volatilization and condensation mechanism often ascribed to chlorine is not applicable to commercial scale systems or state-of-the-art air pollution control devices are efficient enough that this mechanism becomes essentially irrelevant.

The lack of applicability of the volatilization mechanism to MWCs is illustrated by the metal chloride boiling point data in Table 1. For metals showing a statistically significant relationship with uncontrolled HCl, after controlling for known confounding factors, the metal chlorides boil between 130 and >1,600°C while those that show no such relationship have metal chloride boiling points between 12 and 1,560 °C. There is no obvious relationship between increased releases and the metal chloride boiling point.

Most of the loess curves show either a hockey stick or a S-type pattern. Metal concentrations are initially flat, rising rapidly between 600-800 ppm_{dv} @ 7% O₂ uncontrolled HCl concentrations and then flatten again. This indicates that there is either a change in mechanism taking place or, alternatively, this effect could be a data artifact. A data artifact could be caused by distinct plant or test method differences above and below 600-800 ppm_{dv} @ 7% O₂.

Inspection of source descriptions and test reports indicates that design differences are probably not the cause, but the possibility cannot be ruled out. Interestingly, the majority of the higher uncontrolled HCl data tend to be from European MWCs. Thus, sampling method variations are a credible explanation. For the purposes of this paper, this possibility will be ignored.

Even though statistically significant relationships exist between chlorine and some metals, those relationships are not practically significant. For example, only 11 percent of the variability in cadmium concentrations, the most strongly related Section 129 HAP, is explained by changes in uncontrolled HCl concentration after design and location differences were accounted for in the partial correlation analysis. For lead, only 7 percent of the variability is accounted. Mercury is not statistically related to

uncontrolled HCl concentrations in this data set even though it is believed that mercury chloride is more readily captured than elemental mercury. These observations provide a strong indication that other mechanisms predominate.

Turning to the other Section 112 metals, antimony and selenium are the most strongly related. Here around 50 percent of the variability is explained by changes in uncontrolled HCl concentrations. The other Section 112 metals exhibiting statistically significant relationships also have practically insignificant relationships.

Trace Organic HAPs

Figures 7 and 8 display the simultaneous data for Section 112 trace organic HAPs that are statistically significantly related to uncontrolled HCl concentrations. The strongest relationship is for 1,4 dichlorobenzene, and that relationship is negative. That is, increasing uncontrolled HCl concentrations is associated with reduced 1,4 dichlorobenzene concentrations. This entire relationship could be nonsense since 1,4 dichlorobenzene is a contaminant in the North American supply of dichloromethane used in the laboratory extraction and clean-up technique.

Total chlorobenzenes, as a surrogate for the Section 112 HAP monochlorobenzene, on the other hand, are statistically significantly related to uncontrolled HCl concentrations after accounting for confounding effects. As a practical matter, however, they are found at environmentally insignificant stack concentrations and only 24 percent of the variability in this pollutant is explained by changes in uncontrolled HCl. Interestingly, 2,3,7,8 TCDD shows neither a statistically significant (significance level 0.2 for a statistical confidence level of 80 percent) nor a practically significant relationship (5 percent of the variance is explained after controlling for confounding factors) to uncontrolled HCl. So, while total chlorobenzenes are sometimes used as surrogates for dioxin emissions, they probably should not be.

CONCLUSION

The same techniques that found no statistically significant relationship between dioxin and chlorine in combustor stack emissions have found a transition in emitted concentrations when uncontrolled chlorine concentrations are around 600 ppm_{dv} @ 7% O₂. On either side of this bound, there is no significant relationship. Since there is no theoretical reason to expect a step-type threshold effect, these conclusions may be a data artifact caused by differences in European (much of the high uncontrolled HCl concentration data) and North American (much of the low uncontrolled HCl concentration data). In any case, the metals showing a statistically significant relationship that is also practically meaningful are not environmentally significant. So, interventions to reduce MSW's chlorine content for the purpose of reducing metal emissions are unlikely to improve the environment. The same finding is reached for trace organic HAPs.

Analysis of the information in our database and review of the Regulatory Docket for the 1995 Emissions Guidelines indicates that current uncontrolled North American HCl concentrations are on the order of 550 ppm_{dv} @ 7% O₂. Consequently, it appears that little benefit would result from interventions to reduce the chlorine content of MSW, even if there were a meaningful chlorine—HAP link. No intervention for the purpose of reducing metal or trace organic HAPs emissions is indicated.

It must be realized, however, that the database employed in this analysis, as extensive as it is, only has a small amount of applicable data. Further work is needed to reach very strong conclusions. The available

information indicates that such an effort is unlikely to discover that significant reductions in metal emissions will be realized by reducing the level of chlorine in North American MSW. Nevertheless, such research is encouraged to minimize the chance that erroneous public perceptions rather than sound science will drive regulatory efforts.

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Table 1. Correlation results for uncontrolled HCl versus metals and HAPs.

Pollutant	n	significance (2-tail)	RDF significance criteria	result significant?	signed squared correlation coefficient	metal chloride melting point	metal chloride boiling point
Silver	36	0.0028	0.013	yes	25%	455	1500
Aluminum	34	0.0000	0.005	yes	52%		177.8
Arsenic	52	0.0124	0.021	yes	13%	-8.5	130.2
Boron	37	0.0533	0.027	no	11%	-107.5	12.5
Barium	35	0.4391	0.043	no	-2%	963	1560
Beryllium	14	0.6528	0.046	no	-2%	405	520
Calcium	23	0.0000	0.007	yes	64%	752	>1600
Cadmium	65	0.0149	0.023	yes	11%	568	960
Cobalt	25	0.7109	0.048	no	1%	742	1049
Chromium	62	0.0031	0.014	yes	15%	824	
Copper	38	0.1109	0.032	no	8%	620	993
Iron	37	0.0000	0.002	yes	69%	674	
Mercury	101	0.0955	0.030	no	3%	276	302
Nickel	56	0.0099	0.020	yes	13%	1001	976
Lead	83	0.0222	0.025	yes	7%	501	950
Antimony	35	0.0000	0.004	yes	54%	283	602
Selenium	25	0.0004	0.011	yes	43%	305	288
Tin	26	0.0000	0.009	yes	54%	246	652
Zinc	93	0.1981	0.039	no	2%	283	732
Total Chlorobenzenes	35	0.0056	0.016	yes	24%		
1,2 Dichlorobenzene	12	0.1616	0.034	no	26%		
1,3 Dichlorobenzene	18	0.9718	0.050	no	0%		
1,4 Dichlorobenzene	17	0.0069	0.018	yes	-44%		
Total Hexachlorobenzene	33	0.5454	0.045	no	1%		
4 Methylphenol	11	0.1937	0.038	no	18%		
Napthalene	13	0.0694	0.029	no	32%		
Total Pentachlorophenol	33	0.2294	0.041	no	5%		
2,3,7,8 Tetrachlorodibenzo-p-dioxin	44	0.1899	0.036	no	-5%		

Figure 1. Relationship between antimony and uncontrolled HCl concentrations.

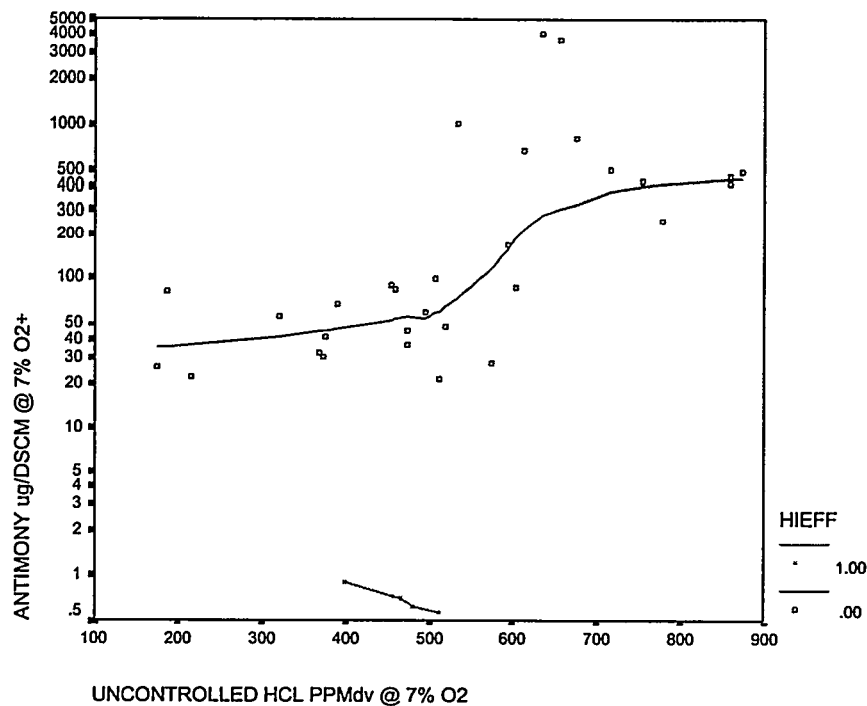


Figure 2. Relationship between selenium and uncontrolled HCl.

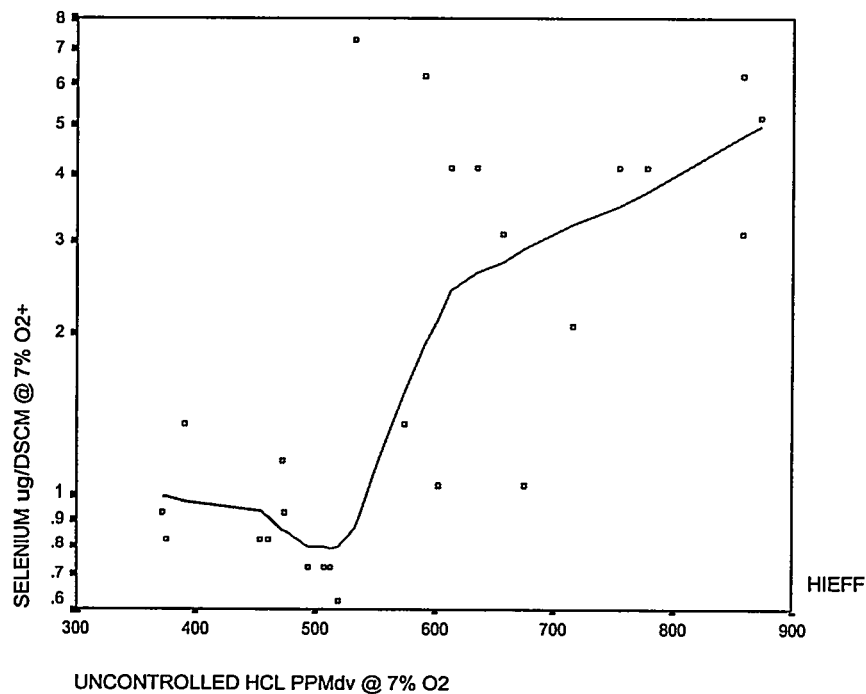


Figure 3. Relationship between chromium and uncontrolled HCl.

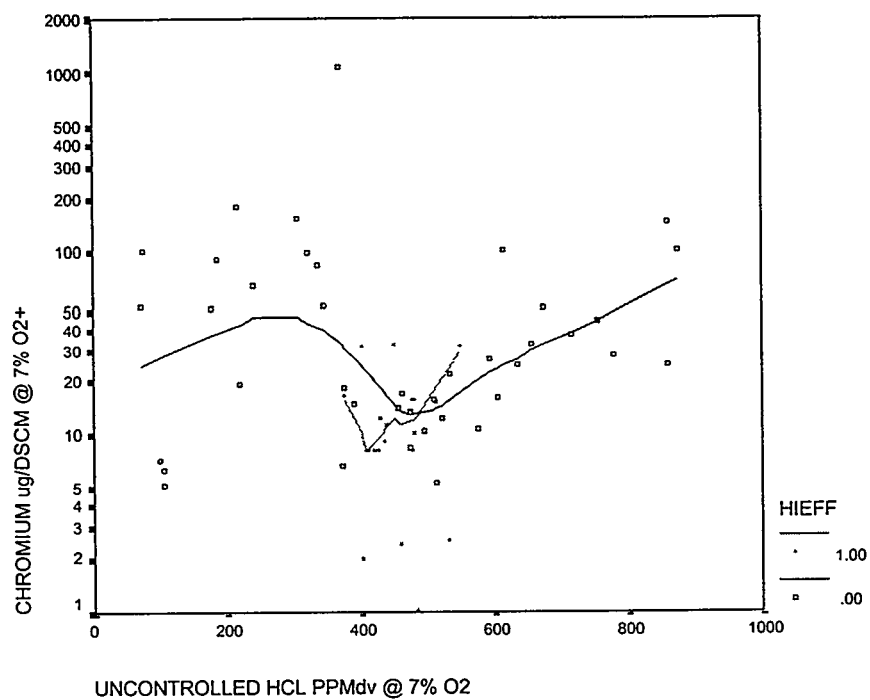


Figure 4. Relationship between arsenic and uncontrolled HCl.

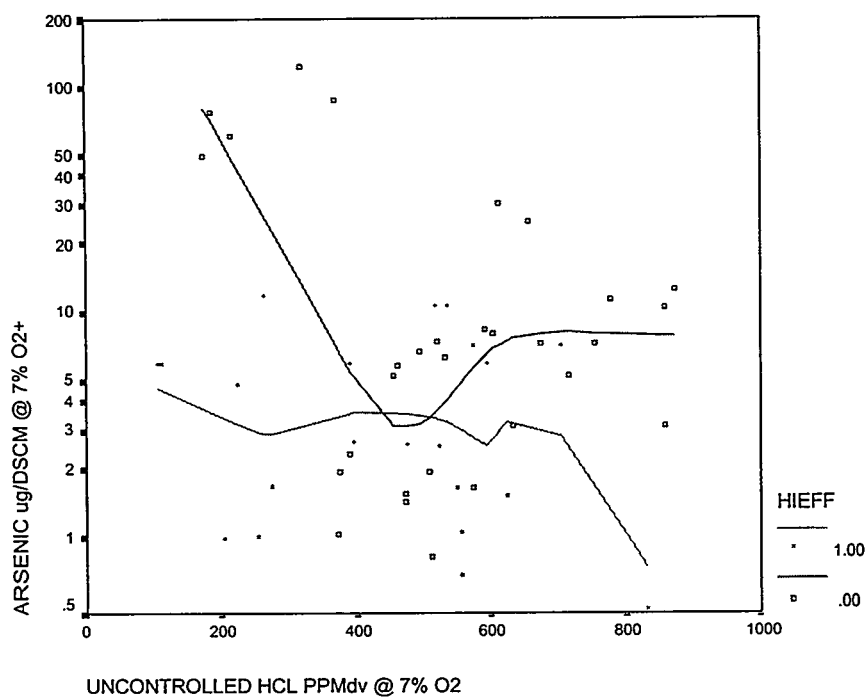


Figure 5. Relationship between nickel and uncontrolled HCl.

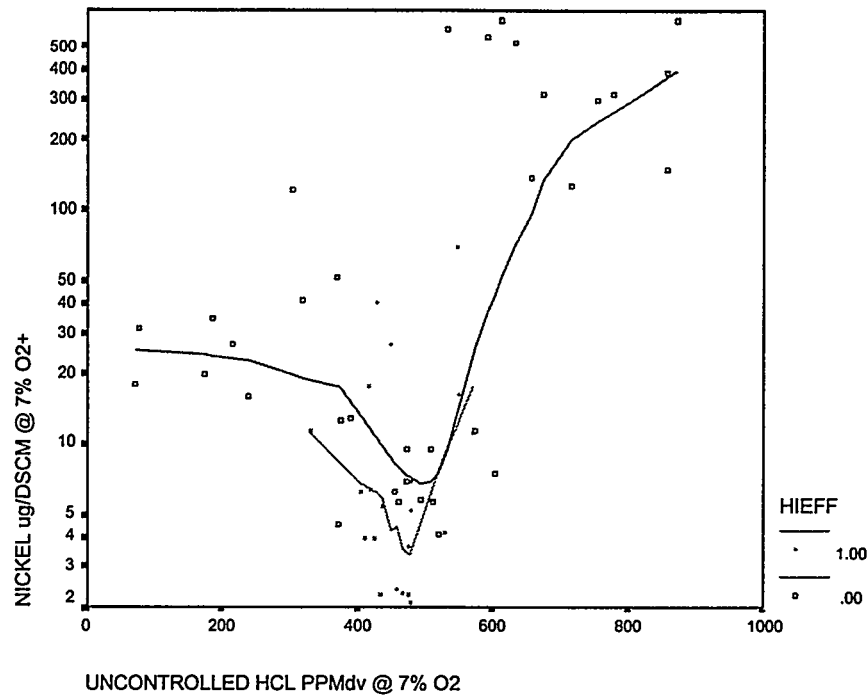


Figure 6. Relationship between cadmium and uncontrolled HCl.

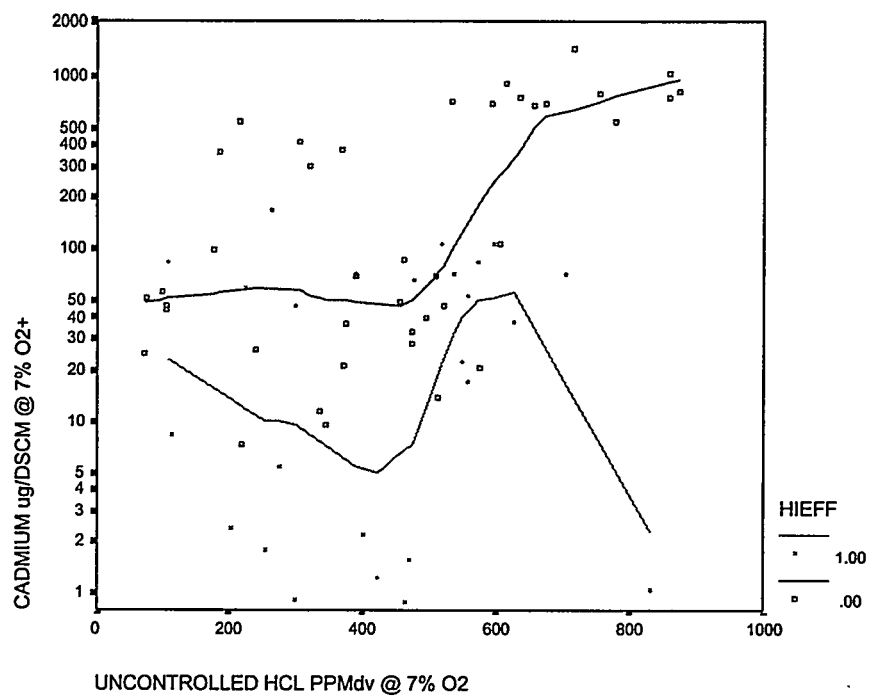


Figure 7. Relationship between lead and uncontrolled HCl.

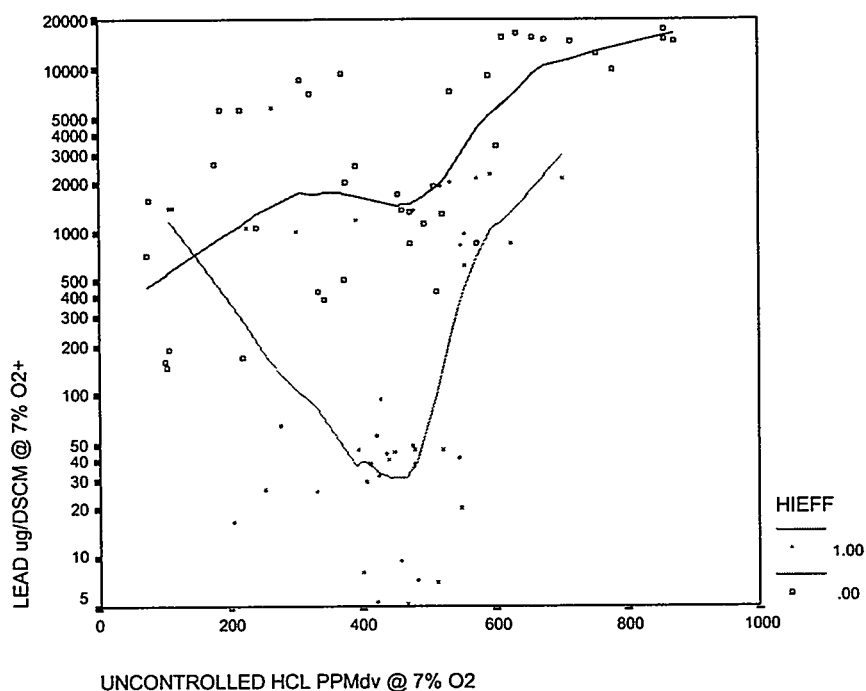


Figure 8. Relationship between total chlorobenzenes and uncontrolled HCl.

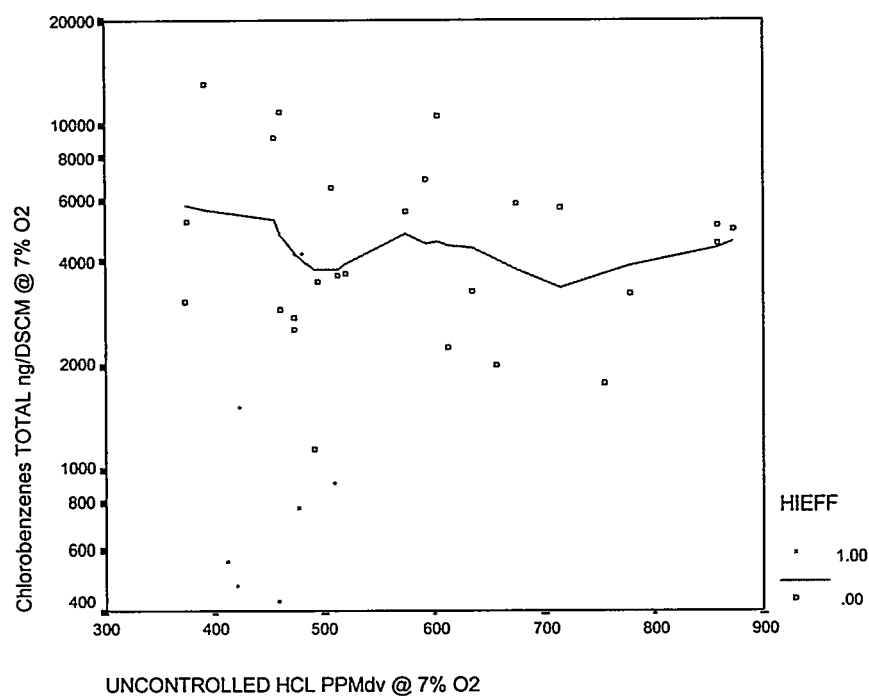
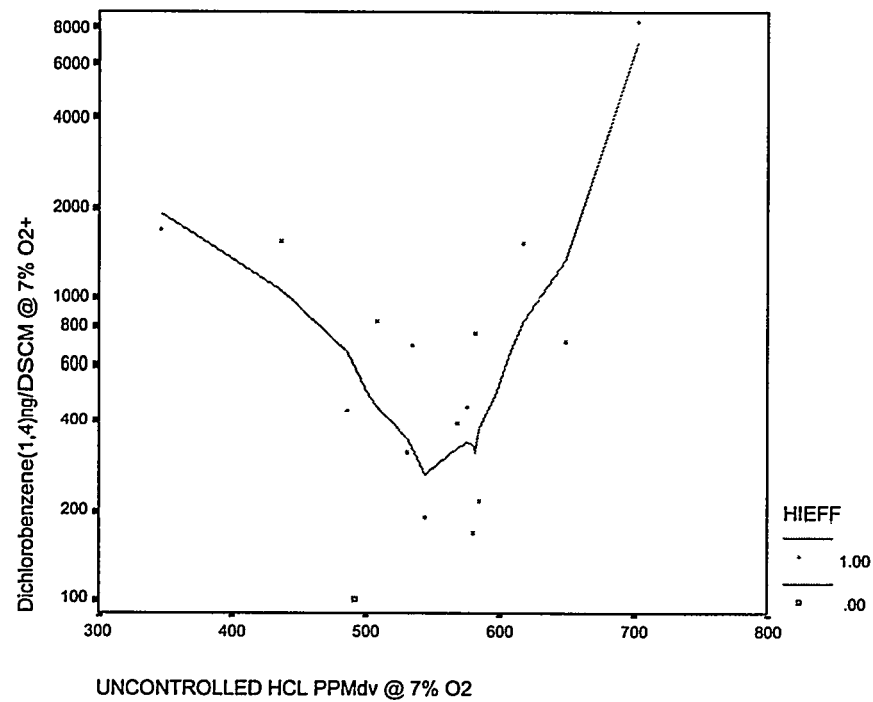


Figure 9. Relationship between 1,4 dichlorobenzene and uncontrolled HCl.



TECHNICAL SESSION III

Regulatory Issues

Acceptance of Waste-to-Energy as Part of an Integrated
Approach to Waste Management is Better for the Environment
and Could Reduce Community Waste Management Costs

Gerard A van Rijswijk
Association of Liquidpaperboard
Carton Manufacturers Inc
Level 7, 140 Arthur Street
North Sydney NSW 2060
Australia

INTRODUCTION

Many countries have set targets for reducing the quantity of waste that ends up in landfill. Early waste management strategies were often based on assumptions of an impending landfill shortage or a desire to reduce the environmental impact of landfill itself, although this can be most economically achieved through landfill design and engineering. In recent years the emphasis has shifted to the recovery of resources that were perceived to be wasted by landfilled materials and this has resulted in the setting up of thousands of kerbside recycling programs aimed at recovering paper and packaging, increasingly complemented by green or yard waste programs.

Since a recycling based approach has limitations, the concept of 'integrated waste management' emerged. To many this means using a variety of treatment options including material recycling, composting and waste-to-energy (wte) to handle waste and landfilling the left-overs. Unfortunately wte tends to be dropped out of the mix for a variety of reasons and communities make do with the remaining options. Also waste policy makers, even if committed to integrated waste management, often fail to integrate waste policy with other policies which aim to reduce our overall impact on the environment, those relating to greenhouse reduction, renewable energy, resource optimisation and, ultimately, sustainability. The latter implies reducing our impact on the environment in a manner which meets social and economic objectives as well as environmental ones.

The reason wte is left out of the equation is in many cases based on the perception that it is more polluting than other means of managing waste and that, rather than recovering resources, it destroys them.

Complicating the development of appropriate waste strategies is the concept of a 'waste hierarchy' which assigns a higher place to methods of handling waste which recover materials than those which recover energy.

This paper examines the benefit of addressing these perceptions and how the use of wte in a fully integrated waste strategy can help communities to meet resource recovery and environmental impact reduction objectives cost-effectively.

PUBLIC PERCEPTION AS POLICY DRIVER

Many who live in a highly urbanised environment would regard a weekend away in a rural retreat with evenings in front of an open fire as the ideal break. They would be happy to burn timber in the fireplace but would object to the burning of organic material or wood derivatives such as paper in a wte plant. They would happily burn several tankfuls of fuel getting there and back but would be concerned about the burning of petroleum derivatives such as plastics to recover the energy content. They would object to the pollution potential of a wte plant without realising that both the open fire and the automobile were more polluting and whilst they would understand that in both cases the

'destruction' of the resource derived an energy benefit they would be less likely to see the same benefit being derived from a wte facility. Physical, material based, recycling is so much easier to visualise.

Community, state and national policies are based on similar perceptions. For example the city of Seattle chose to exclude wte from its waste strategy on the basis of public opinion.

We should also remember that politicians too are members of the public and are likely to share the same perceptions. This point was made by researchers at the Energy Systems Division of Argonne Laboratory conducting a study for the US Department of Energy into the impact of mandated recycling rates on energy consumption. The Argonne study suggests:

"Congress specifically excluded combustion for energy recovery from counting towards the recovery goals, probably because combustion is viewed as a form of disposal and therefore is assumed to waste resources and have negative environmental impacts. However, cocombustion in coal fired plants or combustion in appropriately pollution controlled waste-to-energy plants is safe, avoids landfill costs. And can displace fossil fuels - in some cases more fossil fuels than by recycling. Therefore the objectives of the proposed legislation must be examined to see if they can most effectively be met by recycling at the mandated rates or by other methods of disposition."¹

This approach is interesting as the US government had previously adopted policies which encouraged the development of wte facilities.

German policy on packaging waste provides another example of how wte is seen as a less than optimum means of recovering resources. Although the German Packaging Ordinance sets high recovery and recycling targets for packaging and insists that all types of packaging are recovered it prohibits the use of wte as a recovery option, insisting on recovery methods not based on combustion. The measure has resulted in real problems for the plastics industry because the volume of material recovered far exceeds the reprocessing capacity and, in some cases, the available technology. This has led to a number of creative solutions including the use of plastic waste as a reducing agent in steel blast furnaces. This is not categorised as combustion because the oxygen comes from the iron ore and not the atmosphere.

The legislation is about to be changed to allow some use to be made of energy recovery under defined conditions relating to the proportion of the total energy recovered.

Germany's insistence on material recovery in preference to energy recovery has resulted in increased community costs with the cost of recovering plastics calculated at thousands of dollars a tonne.

France on the other hand allows both the recovery of materials and energy from waste and this has resulted in reduced community costs. The Netherlands government negotiated a 'Packaging Covenant' with industry which agreed to eliminate packaging waste from landfill by the year 2000 using a combination of approaches including wte. Although this objective was reached ahead of schedule it now appears that the covenant will need to be renegotiated to include minimum rates of recycling for each material type so that the Dutch scheme meets the requirements of the European Packaging and Packaging Waste Directive which insists that at least 15% of each material group is recovered through physical recycling means, although the directive itself recognises energy recovery as an equivalent means of resource recovery.

The debate in Europe is now centred on whether wte should be demoted in accordance with the 'waste hierarchy' with the result that the Directive will state a distinct preference for material recycling. Again it is felt by some that wte does less than a complete job of resource recovery.

RECYCLING AND RESOURCE RECOVERY

When householders put out an item for collection each week they see the whole item disappear and therefore it is easy to assume that in each case it is fully recovered. The high resource recovery assumption is further strengthened by pictures of bales and bales of recovered materials. So in the consumer's mind a glass bottle becomes a new glass bottle (never mind about the cap and the label) and an aluminium can becomes a new can - which needs a new lining as the old one wasn't recovered.

Recycling rates are reported on the basis of the volume of material collected rather than the amount recovered at the end of the process. It is not generally recognised that recycling is an industrial process which consumes further resources and generates wastes and impacts and that material losses occur during collection, sorting and processing. i.e. no material is 100% recyclable. Rarely is the reported waste saving discounted by the waste generated in the recycling process.

Several studies have looked at the comparative benefit of using secondary rather than virgin resources which is one way of judging the merit of recycling. A study for the US Department of Energy² into glass recycling concludes "the maximum energy saved is only about 13%" and recycling saves no energy if the glass has to travel more than 100 miles further than the distance to the landfill. The study concludes "Recycling of glass does not save much energy or valuable raw material and does not reduce air or water pollution significantly. The most important impacts are small reductions of waste sent to landfill...." (but of course glass is inert in landfill)

A similar conclusion was reached by the Tellus Packaging Study³ which aimed to put packaging policy on a scientific base. It suggested a 23% saving in overall impact for glass, ignoring all transport impacts which in the case of glass are significant. The manufacture of steel containers had an impact similar to that of glass on a volume

packed basis and this was not reduced by recycling it. Aluminium starts off with a higher per ounce packed impact but it is the only pack where impact is significantly reduced by recycling "cans made from recycled aluminium have impacts below 40% of the recycled glass level as do (unrecycled) aseptic packages (juice boxes) paperboard and HDPE juice containers"

The study also makes the point that the major portion of the environmental impact associated with packaging relates to its manufacture not its disposal with the environmental impact of disposal typically less than 1% of overall impact.

A similar theme is followed by T Kingsbury in a yet unpublished study⁴ comparing the benefits of source reduction with those of recycling. In his paper he lists energy savings by material type gleaned from a number of sources. Savings range from 75,000 Btu/pound for aluminium against a virgin material production energy of 97,500 Btu/pound down to 1000Btu/pound for glass whose virgin material production energy is 8,500 Btu/pound (Given the different pack weights for these materials it would be interesting to compare per pack savings) Plastic bottles come in at 22,000 Btu/pound saving, paperboard at 13,500 and steel cans at 5,500. Again transport impacts are excluded. In percentage terms the savings incurred range from 75% for aluminium down to 12% for glass. Plastic, paperboard and steel come in at 57%, 44% and 20% respectively.

There is no suggestion here that recycling leads to full recovery of resources whereas there is a tendency to criticise wte because not all of the energy in a material is recovered in a wte plant.

Kingsbury goes on to suggest that higher energy gains result from an emphasis on source reduction, reducing pack weight, a conclusion shared by the Tellus study.

WTE AND RECYCLING COMPARED

Several studies have compared the resource recovery potential of wte with that of recycling and have concluded that they are comparable for most combustible materials. The Argonne study into mandated recycling rates referred to above concluded that for kraft paper wte was comparable to recycling whilst a Swedish study⁵ suggests that for paper an optimised mix of recycling, where it is cost-efficient, and wte is the best solution since recycling can reduce the use of certain resources and wte can be used to conserve fossil fuel.

A collaborative study⁶ conducted in Germany recently comparing the mechanical recycling of plastics with a range of energy recovery based technologies showed that in the case of a plastic detergent bottle mechanical recycling was superior to energy recovery only when recycled plastic could be substituted for virgin plastic on a 1:1 basis (i.e. there was no reduction in function or efficiency through the use of recycled materials) In energy recovery terms, greenhouse benefit terms and renewable energy

terms the use of recovered plastic in, say, a blast furnace achieved 92-94% of the benefit of mechanical recycling. Given the high cost of recovery of plastic waste for recycling in Germany, a case could be made for sending it unsorted to a wte plant with other non-recyclable household waste.

LIMITS TO SUSTAINABLE RECYCLING

It would be easy to conclude that if recycling is good for the environment, more recycling would be even better. There is a tendency amongst waste policy makers to set and increase recycling targets on just that assumption.

Given the task of reviewing the European approach to recycling recently, the Institute for Prospective Technological Studies based in Seville, Spain reported back to the European Parliament as follows:

“Recycling is not always necessarily the preferable waste management solution since it is limited by the Second Law of Thermodynamics and obeys the law of diminishing returns. Other options such as prevention, reuse and recovery of energy can offer ecological or economic advantages over recycling according to the application area. In this light, the growth of the recycling industry is not a necessarily desirable policy target. The point is to perform recycling at its optimum rate both on an economic and environmental point of view. This optimum can vary widely according to material, location, available infrastructure, application, scientific and technological state of the art. etc.

The desirability for increasing recycling depends on its relative merits compared to the other waste management options in a given geographic area.”⁷

So what are the limits to sustainability for recycling? Obviously they vary by material and situation. Juha Kaila of Finland presented a paper on glass recycling⁸ to the ISWA workshop held as part of the R'97 Conference in Geneva in February of this year in which he suggests that if the impact of the collection vehicle is taken into account, fossil fuel use considerations would dictate a glass collection rate of between 40 and 60% and if the truck's emissions were to be the deciding factor a collection rate of between 10 and 30% was sustainable.

FRAGMENTATION OF THE WASTE STREAM

One of the consequences of the 'Integrated Waste Management' approach to waste is that it results in a multiplicity of waste streams - a stream for each 'solution'. This can result in the duplication or multiplication of waste collection systems putting more resources behind collection and sorting at increased community cost. Whereas in the old days one truck used to come past to pick up all the trash, now there can be two, three or even four separate fractions requiring collection.

Again Germany supplies an example of a trend. On top of its controversial approach to the recovery of packaging waste the German government has passed legislation to control the recovery of other materials. Called the Closed Substance Cycle and Waste Management Act it seeks to make all industry waste materials part of 'substance loops' with the producer taking the responsibility for the establishment of loops for products produced. The recovery of waste therefore becomes the responsibility of every original owner or producer of wastes or products that eventually become waste. Wte is , however, not excluded as a recovery option but restricted to materials with an inherent calorific value of 11MJ per Kg going through a plant that recovers a minimum of 75% of this energy.

The legislation targets certain industry sectors, e.g. electronics, white goods, automobiles, and will lead to the development of a multiplicity of waste streams as recovery options tend to be based on what the material recovered is (and who is notionally responsible for it) rather than what it is made of and therefore what resource recovery option best suits.

Further complicating the material recovery task is the ever increasing range and complexity of products, ones which defy disassembly. Some say products should be designed for recycling, but that too is debatable.

Dealing with the waste fraction already commonly targeted for recovery we see three continuing trends. The first is towards lighter packaging, the second is a greater variety of pack types and the third is the increased use of multi-material or multi-layer which although more efficient make mechanical recycling difficult, if not impossible. The packaging industry is doing its bit for the dematerialisation of consumption - doing more with less. Each of these trends will make recycling more expensive as a resource recovery option. To get an appreciation of the impact of these trends have a look at the packaging currently on supermarket shelves that is not being recycled. It is mostly efficient, lightweight packaging that, whilst not being recyclable can easily and safely be used as a source of energy.

THE NEED FOR RE-INTEGRATION

The tendency in recent years has been to find different things to do with different parts of the waste stream. Much of waste policy has been based on the landfill diversion imperative rather than any genuine consideration of the relative environmental merits of available alternatives or the need to base strategies on the reduction of overall environmental impact rather than the reduction of solid waste. In many cases the recovery of material resources has been pursued at the expense of energy and other resource use and the generation of a range of other impacts.

The result is a multiplicity of approaches and programs each coming at significant community cost. Again taking kerbside recycling as an example there have been a number of studies which have sought to allocate the collection cost to each of the

materials being collected. Whilst it is possible to get close to breaking even on some materials, especially in areas where landfill costs are high, plastic bottles, PET and HDPE are typically collected at a significant cost - studies show collection costs approaching \$1000 in excess of their market value. The cost of collecting and reprocessing the variety of lightweight packaging collected by the German DSD system is substantially higher. As these materials are a good source of energy it would make sense to allow them to go with the residual waste to a wte plant rather than to persist with their collection.

The disproportionately high recovery cost for some materials is largely the result of persisting with policies and strategies on prevailing perceptions rather than on substantive fact based analysis of what can be achieved in the way of impact reduction at optimum cost. The starting point of such an analysis should be the realisation that in many ways energy is the common denominator to the question of resource optimisation and impact reduction. A re-examination of options that focus on energy rather than material optimisation would show that wte has a role to play in both resource recovery and environmental impact reduction.

There is also a need to re-examine waste policy to try to bring together the divergent waste streams and treatment options as reducing their number can increase overall efficiency and cost-effectiveness.

Including wte in the range of treatment options allows the waste manager to recover resources in the form of energy from those materials currently not recyclable, materials for which there are no markets and materials which present a risk to community or worker health and wte can do so with a relatively low overall environmental impact.

If we were to take the concept of policy integration further and consider the need to take into account greenhouse issues, renewable energy, air and water impacts, inter-generational equity and sustainability in the development of a responsible waste management strategy, again wte would be the centrepiece or unifying theme.

The role of wte is recognised by many governments. It forms the focus of waste strategies for the Danish and Swiss government who have a 'here and now' approach to waste - solve the waste problem where it is generated and in the current generation. Singapore burns 85% of its waste in three modern wte plants which supplement the local coal fired power stations. Yes, Singapore does recycle paper, and aluminium for which it can find markets and has an impressive record in building and construction waste recycling.

Japan has close to 2000 plants each servicing a local community but has recently caught the recycling bug, passing legislation to increase the recovery of household recyclables. Japan's latest facility, due to come on stream this year, is part of the Tokyo Harbour Sub Centre, a new development built on reclaimed land in Tokyo Bay (an old landfill site) designed to house 60,000 people and accommodate a further 150,000 office workers

during the day. The waste generated by this community goes through underground pipes directly into the wte plant. This provides district heating, hot water and air conditioning to its host community and generates a portion of its electrical energy. Local use of the energy recovered optimises the environmental benefits.

We should continue to encourage the community to see waste as a resource but as a source of energy as well as secondary materials. A greater emphasis on energy recovery will result in opportunities to consolidate waste streams and reduce overall costs. The environment benefits from a more complete recovery of resources in a manner that has a relatively low impact and yield other benefits such as greenhouse gas reduction.

¹ Mandated Recycling Rates: Impacts on Energy Consumption and Municipal Solid Waste Volume Energy Systems Division Argonne National Laboratory, December 1993

² L.L. Gaines et al Energy Implications of Glass Container Recycling Energy Systems Division Argonne National Laboratory and National Renewable Energy Laboratory, March 1994

³ F. Ackerman et al CSG/Tellus Packaging Study for the Council of State Governments and the US EPA, Tellus Institute, May 1992

⁴ T Kingsbury Source Reduction in Recycling Terms Unpublished draft, Jan 1997

⁵ Environmental Impacts of Waste Paper Recycling International Institute for Applied Systems Analysis, Sweden

⁶ Life Cycle Analysis of Recycling and Recovery of Households Plastics Waste Packaging Materials, Fraunhofer Institute, Munchen, Technical University of Berlin and University Kaiserlautern

⁷ L Bontoux et al The Recycling Industry in the European Union: Impediments and Prospects Institute for Prospective Technological Studies, Seville, Spain, December 1996

⁸ J. Kiala Limits to Sustainable Recycling - A Case Study on Glass Recycling ISWA Workshop on Sustainability R'97, Geneva, February 1997

Economic Factors Influencing the Development of
Resource Recovery Facilities in the Continental U.S. and Overseas

Patrick F. Mahoney
Energy Answers Corporation
79 North Pearl Street
Albany, New York 12207

In the 1970's there was a confluence of economic and social influences which were responsible for creating the resource recovery industry: an industry which we are all here today, in some capacity, to discuss and hopefully to advance.

The waste-to-energy industry did not exist in the U.S. before 1975: so the industry just turned 20 years old. That is quite young for a major industry, making it still possible to have live industry veterans, who can also be historians and maybe even prophets of the future, at conferences such as this one.

It is my opinion that, as with most industries, the waste-to-energy/resource recovery industry is economically driven. It wasn't always so, but, with the ever-advancing global privatization of what were formerly municipal or public services, I believe we've seen the last of the publicly owned and/or subsidized projects. I also happen to think that the privatization movement is a very good thing. The free market brings with it accountability and responsibility, and minimizes political influence as a dominant factor in the determination and implementation of appropriate infrastructure solutions.

Before discussing economic influences, a bit of industry history is appropriate. A major environmental event, which many see as the starting point of our industry, thrust me into this delightfully and painfully complex business. It was Earth Day 1970. Though I am here today to discuss economic issues, I am an engineer, problem-solver and environmentalist first. If I were a pure capitalist, I would not be in this business and here today as an advocate of the resource recovery industry. The economics for success have not been good in this business for the past five years. I don't believe this industry is dead, but it has been in a deep coma for the past five years and economic indicators don't paint a bright picture for the next five years.

The first large-scale public participation in an environmentally focused activity occurred on Earth Day in April 1970 and it, among other things, spawned the environmental movement which has had such an influence on our industry (both positive and negative). It also created a public awareness of environmental issues including the manner in which society manages its wastes. This in turn was communicated to our Congress which, in its wisdom, produced the Resource Conservation and Recovery Act (RCRA) of 1976. This Act had a noble purpose stated as "to promote the protection of health and the environment and to conserve valuable material and energy resources". In other words, the conservation and recovery of resources became part of the law of the land.

In 1973, shortly after the first Earth Day, we experienced our first energy crisis brought on by what was then called the "Arab Oil Embargo". (See Figure 1) There were dramatic increases in oil and gas prices and the environmental community, with newly found power, sought to have renewable energy sources developed to replace our growing dependence on imported and limited supplies of fossil fuels. Congress again responded by passing the Public Utilities Regulatory Policy Act (PURPA) of 1978 which, among other things, would provide a reliable buyer for energy generated from independently produced power from renewable resources.

These two acts were intended to provide communities and private industry with both a ready and financeable market for energy generated from waste, and a national commitment to abandon landfilling as the primary method of waste disposal.

But, back to the history:

I choose 1975 as the date that the waste-to-energy industry began because that is the year that the Saugus, Massachusetts RESCO facility went on-line, accepting waste from Boston metropolitan area communities and supplying steam to General Electric. It was the first privately developed and financed facility to make money at generating energy from waste. It brought the Von Roll mass burn technology to the U.S., to work for the first time on U.S. waste materials. It did not have an easy start-up and did not initially generate electricity. However, after several significant modifications, the RESCO facility became a successful operation and is still operating, over 20 years later.

But, most importantly, RESCO was done privately, with no government subsidies, and included an air pollution control system which met or exceeded all standards in place at the time. The macro economics were good, but not great, and this facility should have been the beginning of elimination of the landfill approach in the U.S.

Certainly there were other energy-from-waste facilities constructed in North America prior to that time. (See Figure 2) They were, however, municipally sponsored projects which did not have to meet the test of the marketplace economics and thus must be considered subsidized or protected projects. The earliest of these is the Hamilton, Ontario Solid Waste Reduction Unit (SWARU) which went into service in 1969 and, after a number of retrofits, is still in service today. It was the first *prepared fuel* waste-to-energy system and the technological "grandfather" of the SEMASS facility. Despite its technological contribution, it was, and still is, publicly owned and that is why I use the free-market Saugus facility to mark the birth of the industry.

The Congress, obviously reacting to concern for the environment and intending to encourage the development of renewable energy sources, thought that the waste-to-energy/resource recovery approach was good national policy. (See Figure 3) But, the regulators apparently did not; and, as regulators can do, they slowed the process by regulating the waste-to-energy industry, if not to death, certainly into the comatose state where it now resides. I have previously stated that the resource recovery industry, along with other industries, is economically driven. Well, how then do regulators impact the industry? Simply by influencing the economics through regulation or de-regulation, as well as slowing any process they are involved in. Time is money when it comes to the development of these complex projects and, just as de-regulation drives the price of a product down, regulation or pending regulation drives the price up.

We cannot, however, lay the blame entirely at the door of the regulatory community.

If there is one thing that we overlooked as an industry that has hurt us more than anything, it is the lack of inclusion of landfills under the original Clean Air Act of 1970. Though we tend to blame the regulators and politically correct environmentalists for that, a large portion of the blame rests with our industry --- in particular, with the large parents of industry players who have a vested interest in protecting the economics of mega-landfills.

But, getting beyond blame, the regulatory community chose to impose incredibly tough air quality standards on waste-to-energy facilities while ignoring the severe environmental impacts (including air impacts) of landfills. They also ignored or postponed air quality upgrades to other energy generation facilities. So, what was intended by Congress as an economic incentive became a severe handicap to our industry. (See Figure 4) Waste-to-energy facilities are the most heavily regulated energy generation facilities in the U.S., while emissions are cleaner than coal, oil and even natural gas in some cases. The trucks bringing waste to the facilities are now a greater source of air pollution than the modern waste-to-energy facility stack gasses. In a feeble attempt to correct this obvious environmental error, the Clean Air Act Amendment of 1990 for the first time brings landfills under the Act but sets no firm standards. In addition, the MACT (Maximum Achievable Control Technology) standards were proposed (and adopted in December 1995) on an industry that represents a great solution, not part of the problem. At least in Europe where tight air quality standards are in place, they apply to all energy generating facilities, and landfills are recognized as the last resort in waste management and price controlled accordingly.

However, I am not advocating price controls or regulation; I am advocating de-regulation and open market solutions with a level playing field. The setting and enforcing of uniform environmental standards should be the only government function. Objective comparative environmental assessment is essential to that function. What are the environmental, social and economic impacts of the disposal alternative, the recycle/landfill alternative, and the resource recovery alternative? That is a legitimate question for government to ask and answer.

Let's look at two Energy Answers facilities for examples of the economics of private sector resource recovery systems. (See Figures 5 & 6) Both the SEMASS and Pittsfield facilities are located in Massachusetts and were built and operated privately, without public subsidy. SEMASS is a 3000 ton/day facility designed, developed, built and operated by EAC and now owned and operated by American Ref-Fuel. Pittsfield is a 240 ton/day modular system acquired and upgraded by EAC in 1993.

In both cases the private sector decision to invest and build was based on the projections that each facility could produce a return to investors of approximately 30%. The mix of expenses and revenues were, and remain, quite different: Pittsfield has a relatively low energy sales component, while SEMASS has somewhat lower tip fees and materials sales revenue. The project economics were a function of local economics, regional economics, technology choices and capital and O & M costs. (See Figure 7)

These projects have operated successfully for 8 and 15 years respectively and have provided a valuable community and environmental service in a tough regulatory environment (Massachusetts). So why can't these economics be duplicated now and what could we as an industry do to improve the project economics for future projects?

First, let's look at the factors influencing the economics and discuss them:

1. Energy prices
2. Waste disposal prices
3. Economics of the particular resource recovery system
 - size
 - local subsidies available
 - technology cost
 - local economics (tipping fees and energy prices)
 - interest rates
4. Regulatory community position and support/lack of support for resource recovery
5. Site selection
6. Public perception of resource recovery vs. landfill/recycle
7. Environmental issues and their appropriate management
 - air pollution control
 - ash management
 - community impacts; traffic, noise, odor
8. Politics

The first two factors are generally out of the direct control of our industry and are the two factors which most critically influence the economics of resource recovery systems. We will look at them a bit more closely since overly aggressive projections of these prices has led to the deteriorating economics of our industry which we have experienced.

First, let's look at energy projections. (See Figures 8 & 9) I chose gas as the fossil fuel to establish the base price for wholesale energy since a large number of gas-fired combustion turbine combined cycle power plants are being built by the non-utility generators both in the U.S. and abroad. Energy prices will in the near term, in effect, be set by the supply and price of natural gas. Supplies right now seem to be abundant but the projection of future pricing is left to each project developer to develop and defend. One warning: as the price of energy escalates, as it undoubtedly will someday, and waste-to-energy becomes more attractive, so may other energy sources such as photo voltaics, biomass and most importantly, coal. This should be factored in to moderate aggressive projections of escalating energy prices.

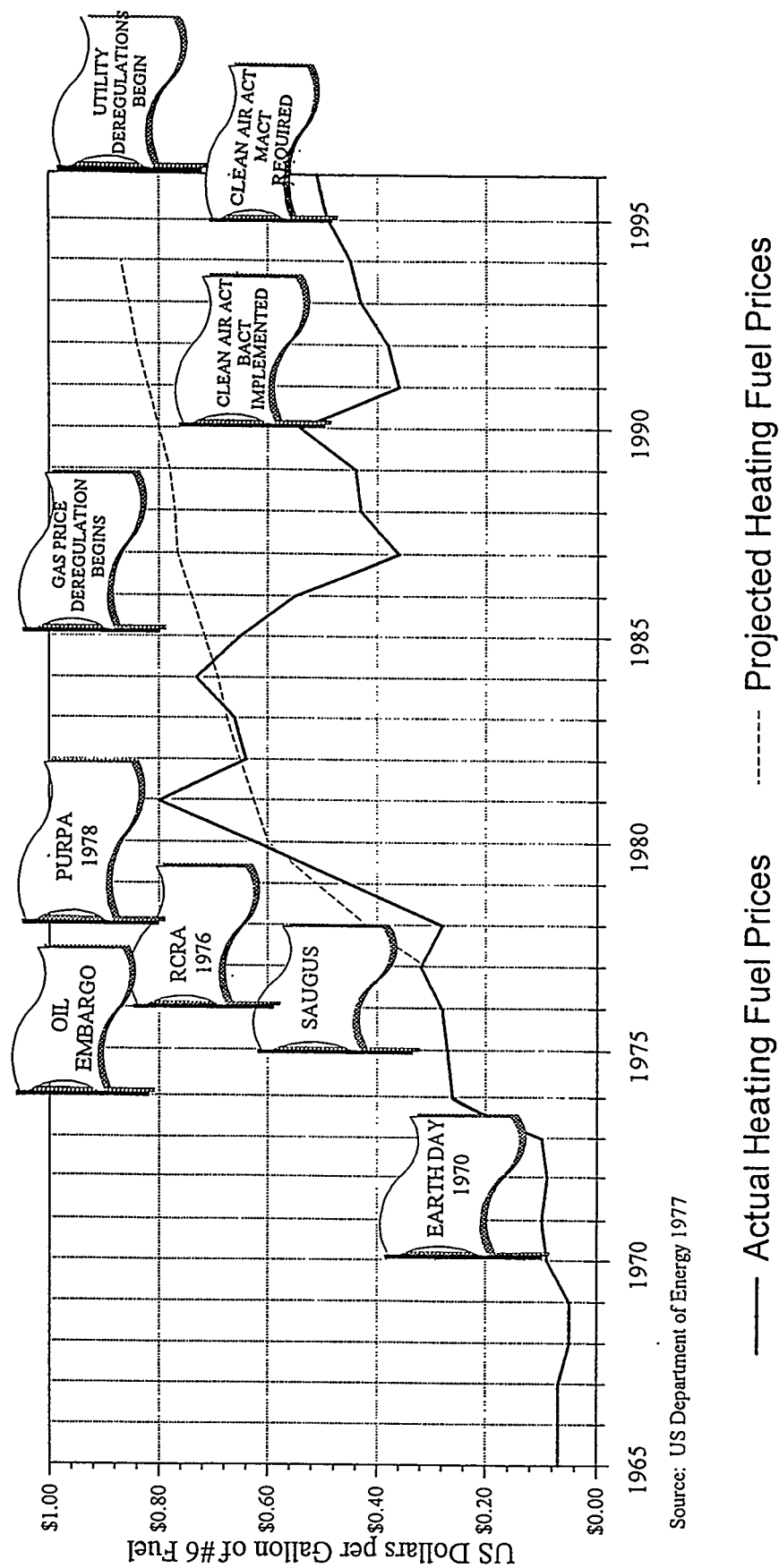
Then, we should discuss the past projections and future of tipping fees (See Figure 10) which in great part will be determined by the treatment of landfilling (and I think it would be appropriate to return to the old term “dump” when a landfill is not being used to productively restore a piece of scarred land). If the government in its wisdom chooses to impose uniform environmental standards and enforce them, then I think that tip fees will rise and therefore make resource recovery relatively more attractive economically. If not, I have seen compelling numbers which suggest that the U.S. has enough permitted landfill capacity to last through the next century, and the law of supply and demand being what it is, I would expect landfilling prices to remain quite low.

With these two factors essentially out of the control of our industry, it is then necessary to find the potential project locations where waste and energy prices are likely to be highest and to focus on the other factors in an attempt to bring facilities into a more competitive position compared with the disposal alternatives.

Therefore, the key to developing good resource recovery project economics in anticipation of competing with the dumping of resources in landfills (dumps) is to: select locations where energy and dumping costs are high; reduce capital and O & M costs through creative design and proper incentives; recover more materials and reduce residue disposal costs; increase energy efficiency; improve environmental performance; educate the public and regulators about the environmental benefits of a resource recovery approach; and don't attach your project to a political sponsor.

NO. 6 Heating Fuel Prices

1965-1996



Source: US Department of Energy 1977

Figure #1

Resource Recovery Facility Startups

1970-1996

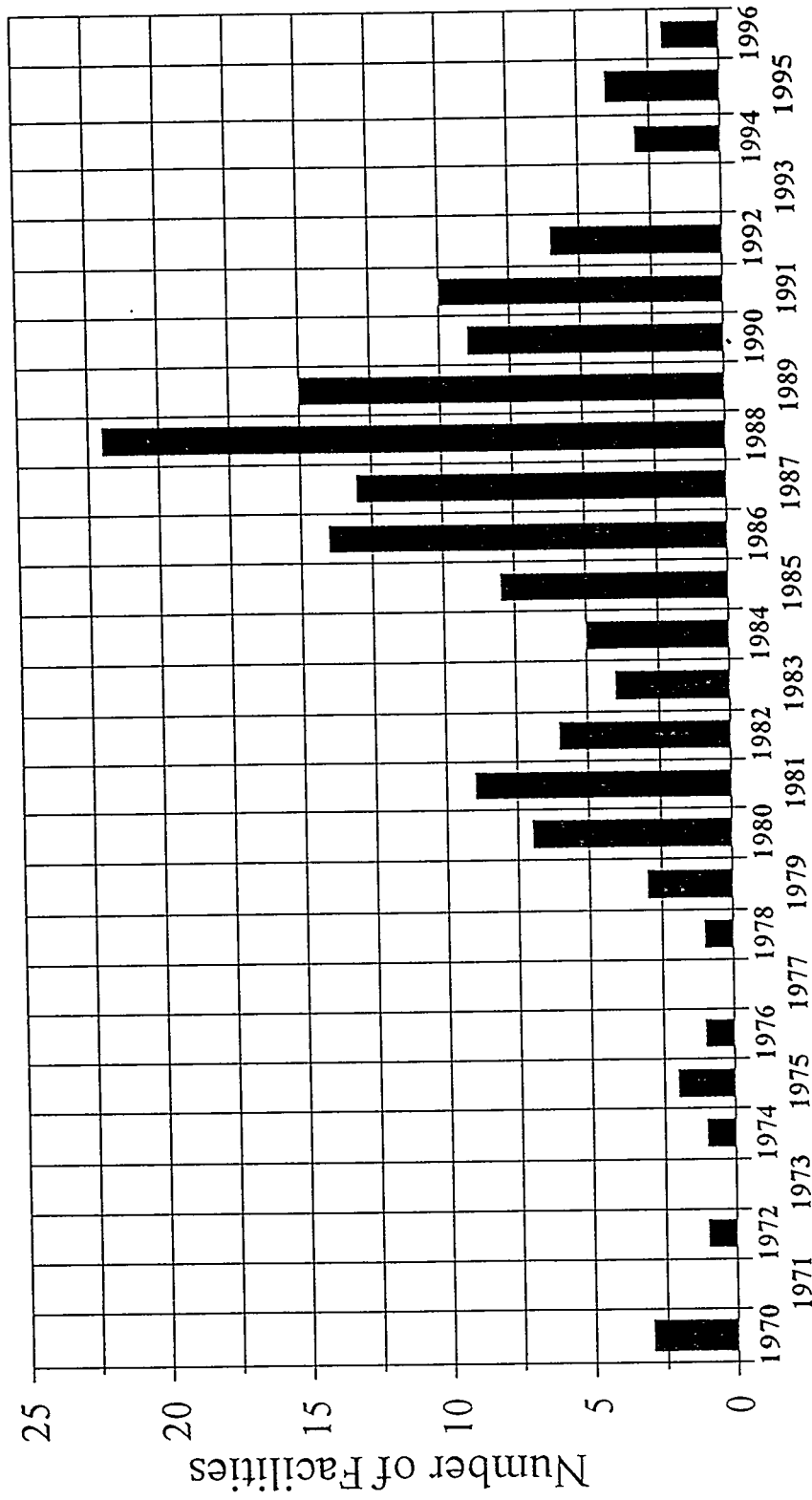


Figure #2

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RESOURCE CONSERVATION AND RECOVERY ACT (RCRA) 1976

Objectives:

Sec. 1003 The objectives of the Act are to promote the protection of health and the environment and to conserve valuable material and energy resources ...

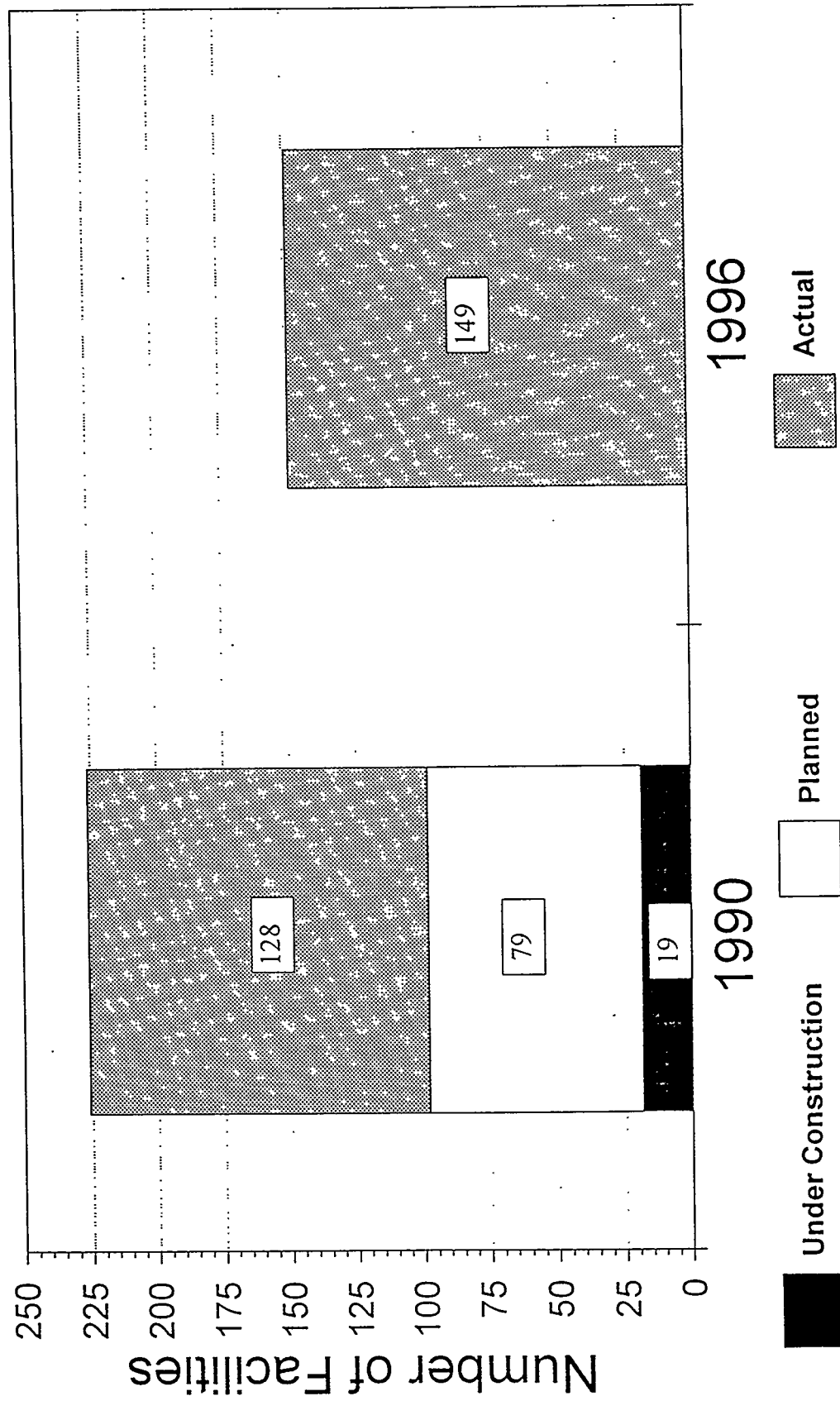
National Policy:

Sec. 4001 ... developing and encouraging methods for the disposal of solid waste which are environmentally sound and which maximizes the utilization of valuable resources including energy and materials which are recoverable from solid waste and to encourage resource conservation.

Figure #3

Resource Recovery Facilities

Projected versus Actual



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Figure #4

SEMASS Resource Recovery Facility

COST and REVENUE PROJECTIONS

1800 Tons Per Day (average daily throughput)

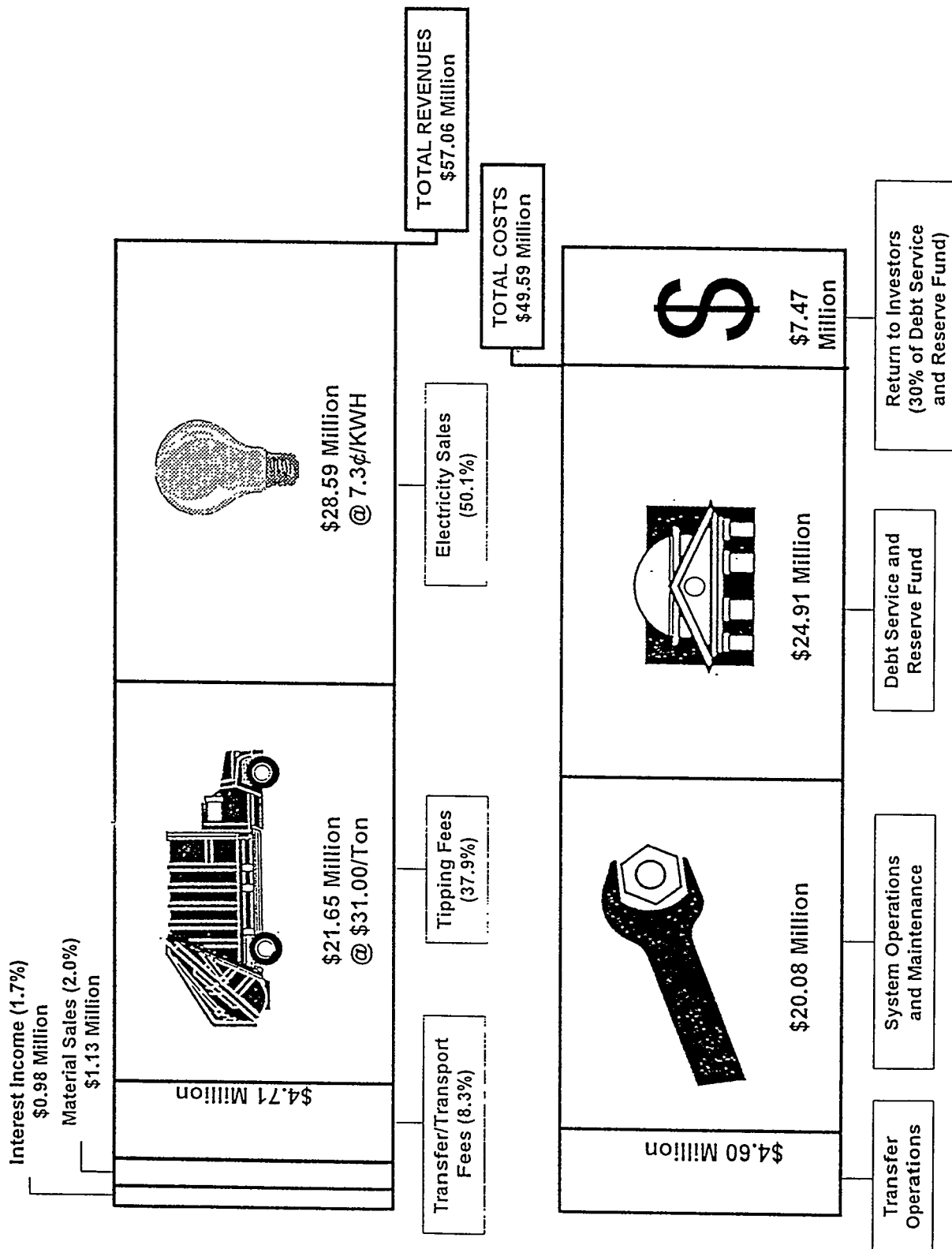
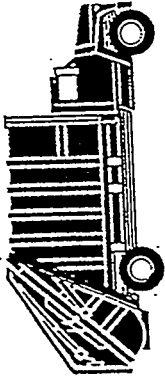


Figure #5

PITTSFIELD Resource Recovery Facility

COST and REVENUE PROJECTIONS

240 Tons Per Day (average daily throughput)

Interest Income	Steam Sales		Long-Term Contracted Waste Fees	Short-Term Contracted Waste Fees SPOT	Special Waste	Misc. Revenues

 Debt Service	 Operations and Maintenance Costs	 Return to Investors 30%
---	--	--



Figure #6

O & M Cost Components

- Operator's Fee
- Host Fees, Taxes, Rent
- Residue Disposal Costs
- Transfer and Transport Costs
- Maintenance
- Environmental Compliance
- Administration/Public Relations

Revenue Components

- Energy Sales
 - Electricity
 - Steam
 - Permit limits
- Tipping Fees
 - Contract
 - Spot
 - Quantity
 - Special Wastes
- Interest on Reserves

Figure #7

Energy Prices

Projected versus Actual

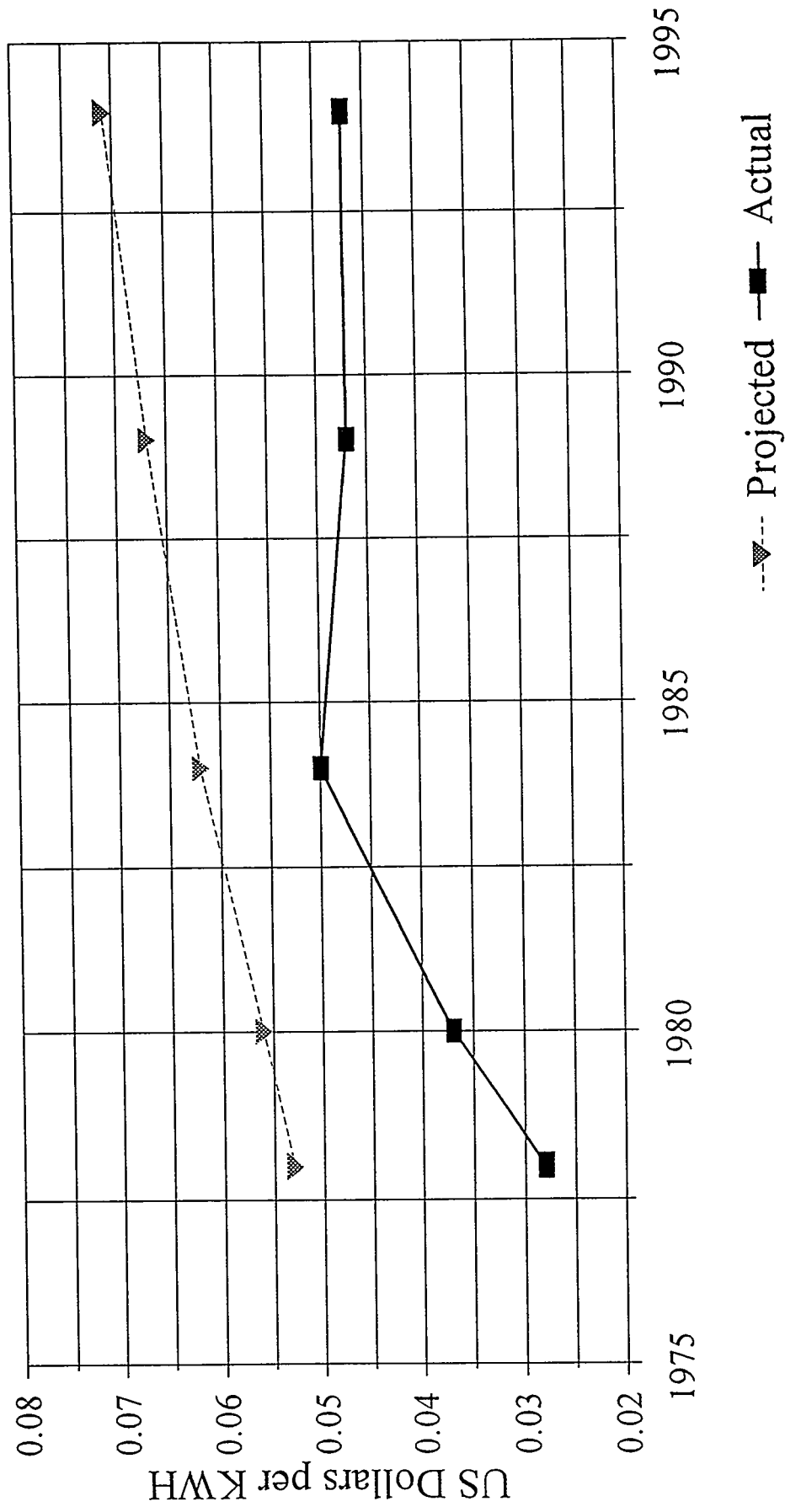
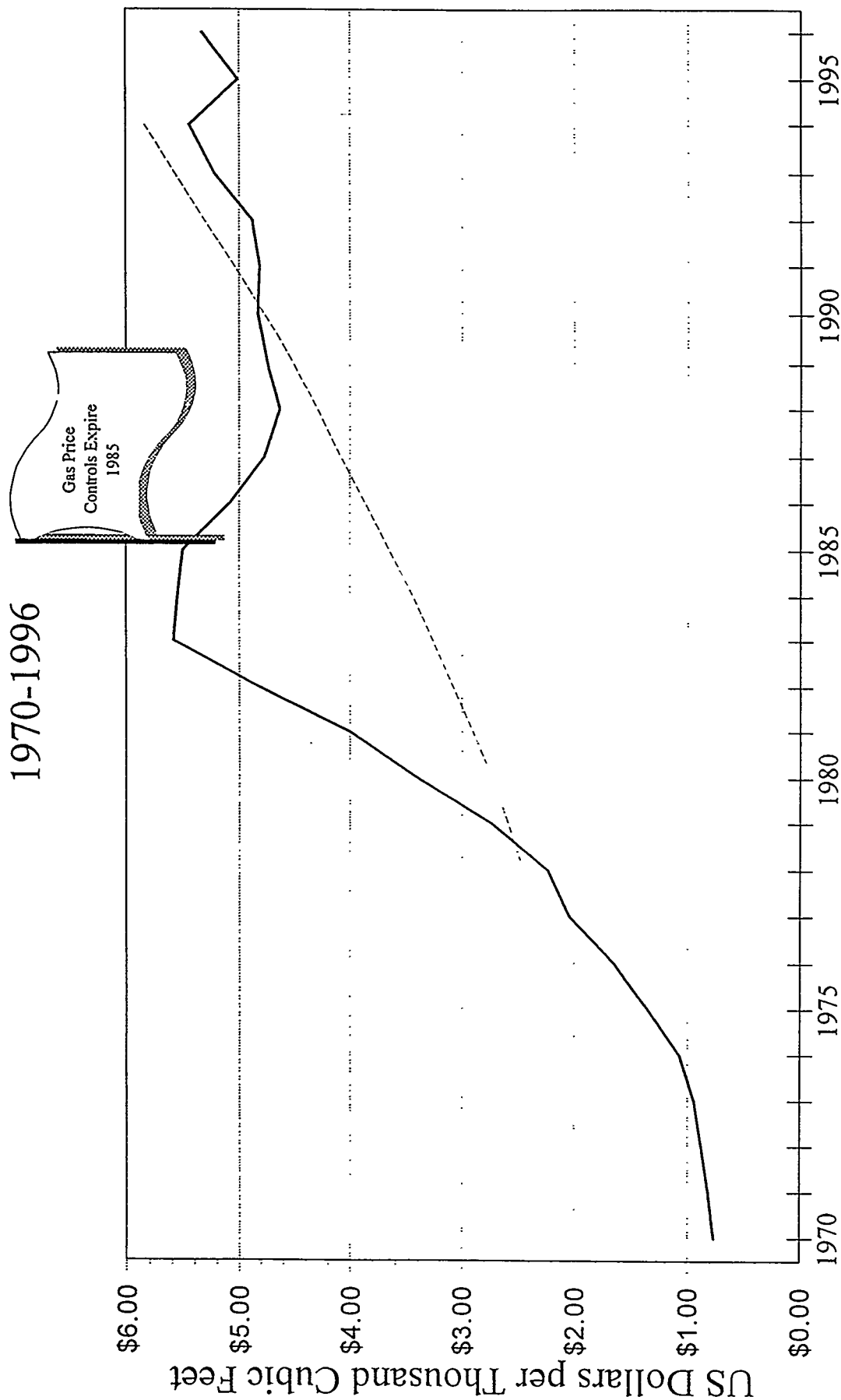


Figure #8

Commercial Natural Gas Prices

1970-1996



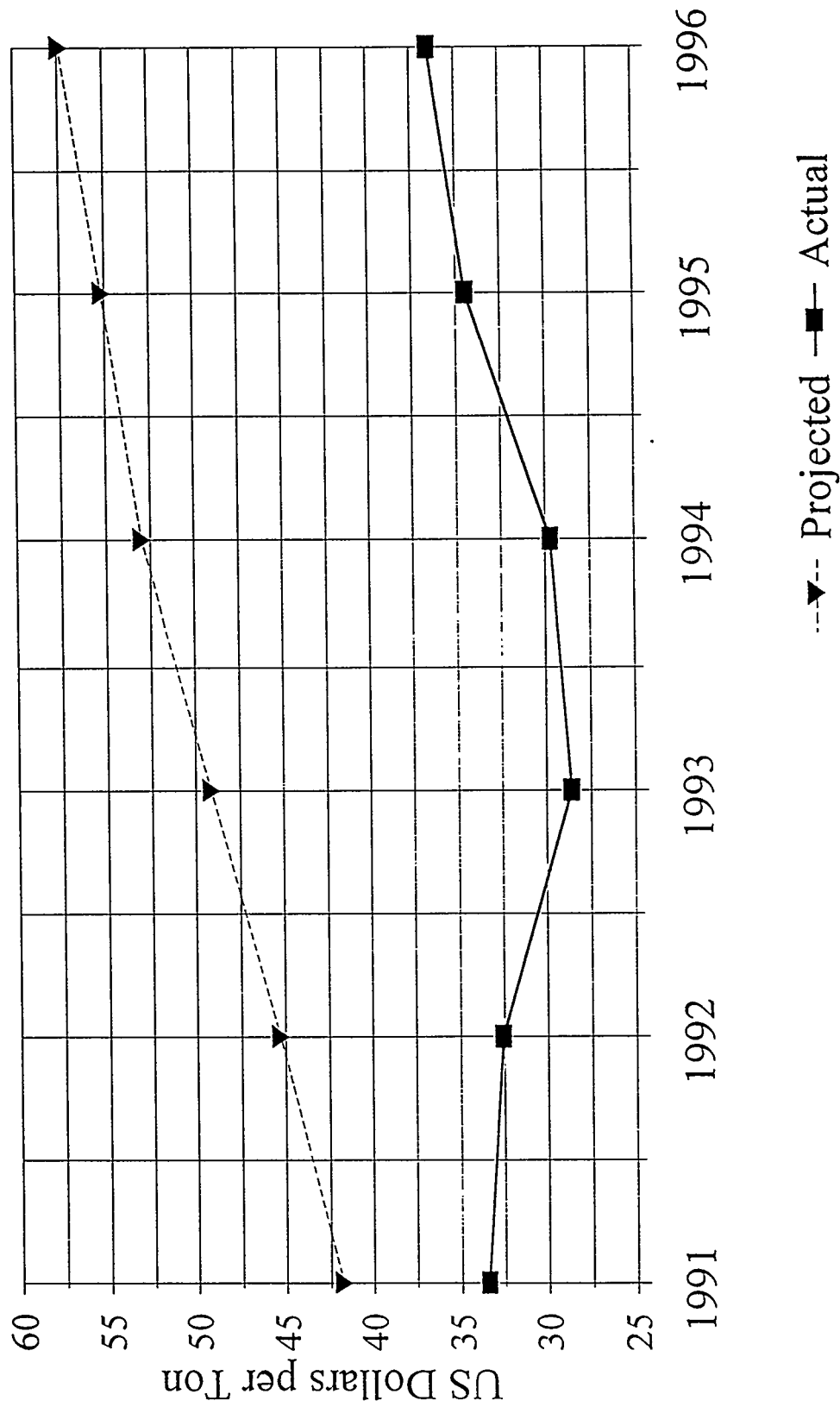
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----- Projected Gas Prices

Figure #9

Projected versus Actual Tip Fees

SEMASS Resource Recovery Facility



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Figure #10

The Inside Story on the Legal Challenge
to EPA's Municipal Waste Combustor Rule:
The Mouse That Roared, Round 1

Larry S. Jenkins
Wood Quinn & Crapo, L.C.
500 Eagle Gate Tower
60 East South Temple
Salt Lake City, Utah 84111

INTRODUCTION

An article in the Deseret News, one of two general circulation newspapers in Salt Lake City, Utah, dated December 13, 1996, reported that "David" took on "Goliath" and won. The article referred to the Davis County Solid Waste Management and Energy Recovery Special Service District's (the "District") victory on its challenge to the EPA's municipal waste combustor rules. On December 6, 1996, the United States Court of Appeals for the District of Columbia Circuit ruled that the EPA violated the plain language of Section 129 of the Clean Air Act,¹ when it wrote size categories for municipal waste combustors ("MWCs") based on aggregate plant capacity, rather than unit capacity. The District argued that Congress divided the universe of MWC units into two categories: those with unit capacities above 250 tons per day, and those with unit capacities equal to or less than 250 tons per day. The EPA, however, had set the dividing line at 248 tons per day* aggregate plant capacity in its municipal waste combustor rule. The Court said this was wrong.

The Deseret News report certainly echoed the feelings of the District. Those of you familiar with the EPA, the process of judicial review of administrative ruling making, and the Biblical story of David and Goliath, however, will quickly see that this is not the best metaphor to describe what happened. When David slew Goliath, that was the end of Goliath. He didn't get back up. Of course, that will not happen to the EPA in the Davis County case. Like an 800-pound gorilla, it will always get back up after being challenged by a mouse.

What happened, therefore, is probably described best by reference to a book I enjoyed as a teenager, the Leonard Wibberley novel about the Duchy of Grand Fenwick: *The Mouse that Roared*. The Davis County District is the mouse. It has roared a mighty roar with its victory in the Court of Appeals. Yet, despite its mighty roar, the EPA is still there. And, an 800-pound gorilla is much bigger than a mouse -- even a mouse that roars. More than likely, this is just the end of Round 1.

This paper tells the story of the challenge to the MWC rule from the District's perspective. The District has not been popular with either the EPA or many industry players. But, the District was faced with a real problem that, given the District's location and the local economy, forced its hand in this case.

BACKGROUND OF THE DISTRICT

Those of you from the East will, no doubt, wonder why a municipal waste incinerator was even built in Utah, which is famous for arid deserts and other vast wastelands that would seem perfect spots for landfills. Indeed, one of the largest subtitle D landfills in the country — 2400 acres worth — is permitted and operating in eastern Utah. Movies like *Independence Day* were filmed in Utah to take advantage of our deserts. The District's burn plant is the only one in Utah, and the only one in the EPA's Region VIII. It also has some of the highest disposal fees in the area. Yet, when it was conceived, it was a very good idea and made perfect economic sense. Changes over the last decade and the precarious position the District now finds itself in speak volumes for why the District mounted the challenge to the MWC rule.

* The "dividing line" was set at 248 tpd due to EPA's use of the metric system. The court directed EPA to use 250 tpd, as required by statute.

Formation of the District

Geographically, the District is comprised of Davis County, Utah and all cities in Davis County, except for the City of Bountiful where I live. It also includes Morgan County and the City of Morgan. The governing bodies of each municipality and county formally elected to participate in the District. Davis County is a narrow strip of land bounded by mountains on the east and the Great Salt Lake on the west. Given these geographic limitations, few, if any, appropriate sites remained for construction of a landfill in the County. In 1984 when the District was formed, the North Area Refuse Disposal ("NARD") landfill, located in Layton, Utah, was rapidly reaching capacity and Davis County needed to examine other options for solid waste management.

To reduce the volume of waste by approximately 90% and extend the life of the NARD landfill, the District was formed and, as part of an integrated solid waste system, as defined by the EPA, a waste-to-energy facility was planned. This approach provided a reasonable solution that was environmentally sound and that at the time was also economically sound. The plan was to incinerate solid waste to reduce its volume, and to use the heat to produce steam to be sold to Hill Air Force Base for use in its heating loop. The price at which steam would be sold to Hill Air Force Base was tied to the price of natural gas. At the time of the original financing, it was anticipated that energy revenues would be substantial because natural gas prices were projected to go through the roof over the following decade. Instead, they went through the toilet.

Establishment of the District was not driven merely by local concerns. The District was established with the encouragement of federal laws, agencies and grant money. The Wasatch Front Regional Council in the early 1980's received a grant of approximately \$750,000 from the EPA, which was authorized by the Resource Conservation and Recovery Act. The purpose of the grant was to study and address solid waste disposal issues in Northern Utah. The culmination of that study, paid for by the EPA, was the establishment of the District. The District's burn plant was also planned and established so that it would qualify and function as a "small power production facility" and as a "qualifying facility" as those terms are used in regulations of the Federal Energy Regulatory Commission, issued pursuant to the Public Utility Regulatory Policies Act of 1978.

Commencement of Operations

In October of 1987, construction was completed on the District's waste-to-energy facility (the "Burn Plant") and shakedown and testing of the facility began. The Burn Plant has two 210 ton-per-day mass burn refractory wall furnaces. Each unit is equipped with a dry sorbent injection system ("DSI") and a high efficiency electrostatic precipitator ("ESP"). In October, 1988, the Burn Plant was accepted by the District and commercial operation commenced. Initially, a private contractor ran the Burn Plant, but the District took over operations in 1991.

The Burn Plant and related facilities and equipment were financed through the issuance of \$54.75 million in municipal revenue bonds. Fifty-one million dollars of the bonds were refinanced in 1993, and the current outstanding indebtedness supported by the bonds is approximately \$45 million. The bonds are not scheduled to be paid off until 2009.

District Revenue Problems and Tipping Fees

Because of decreasing energy prices in addition to concessions on the part of the Utah Public Service Commission to allow Hill Air Force Base to purchase natural gas on the spot market and to transport that gas over Mountain Fuel lines, the energy revenues received by the District were cut by nearly 50% from what was projected at the time construction commenced on

the Burn Plant. Even though the District has a contract with Hill Air Force Base to provide a minimum of 514,600,000 pounds of steam per year, the District still has not reached the total annual energy revenues that Hill Air Force Base anticipated it would pay the District in the first year of operation, which was projected to be about \$2.5 million. As a result, the District was required to raise user fees and enforce flow control to ensure adequate revenues.

Upon assuming operation of the NARD landfill in April, 1987, the tipping fee was \$9.00 per ton. Steady increases over the years saw that tipping fee increase to \$62.00 per ton by July 1, 1995. In contrast, the average tipping fee in Utah in April, 1996, was just \$26.77 per ton.

Waste Flow Control

The District adopted a flow control ordinance in 1986, and additional flow control ordinances in 1992 that contained enforcement provisions. This was necessitated by the rise in tipping fees to well over the market rates for Utah and the strong economic incentive for haulers to take their waste to less expensive facilities.

The District was aware that flow control had been the subject of legal challenges in various parts of the United States. It monitored the development of the case law and was aware immediately when C & A Carbone, Inc. v. Town of Clarkstown² was handed down by the United States Supreme Court. While it was believed that the District's flow control ordinances did not impact interstate commerce and were not affected by Carbone, it was a concern that future changes in the solid waste market, such as construction of a transfer station, could result in the flow control ordinances impacting interstate commerce. Therefore, with the idea of preparing for the future, the District began looking at ways other than flow control to exercise the powers granted under State law to assure sufficient revenues to meet its operating expenses, obligations under the bonds, and future capital needs.

Household Fee Program

On July 1, 1995, the District implemented a household fee program for residential waste. This fee is assessed on a per-household basis. Each household pays \$10 per month for the first container and \$3 per month for each additional container they use. Each city or county that provides collection services tells the District the number of containers to be billed for any given month, and each city or county remits the assessed amount directly to the District on a monthly basis. A household fee is also imposed on apartment units at the rate of \$6.50 per unit, regardless of whether the unit is vacant. It is estimated that these fees are the equivalent of an \$82.00 per ton tipping fee.

Commercial Fee Program

On April 3, 1996, the District adopted a commercial container fee program. This program was carefully prepared over a period of more than one and one-half years. Under the commercial container fee program, a monthly \$2.00 fee is imposed on each billable bulk yard of solid waste generated in the District and collected in commercial containers. The fee is calculated based on the size and compaction ratio of the container collected and the number of times each container is collected in a month.

Laidlaw Litigation

Following the adoption of the household and commercial container fee programs, Laidlaw, one of the largest commercial haulers in the District, filed a lawsuit in federal district court challenging the new fees and the flow control ordinances. The challenge to the flow

control ordinances was based on the Carbone case. The challenge to the new fees was based purely on state law theories. Laidlaw argued that the District did not have power under State law to adopt the new fees it did.

At about the same time the opening brief was due in the D.C. Court of Appeals on the challenge to the MWC rule, the District filed a motion to dismiss the Laidlaw case arguing that there is no interstate market for solid waste within the District, and that the federal tax injunction act precludes a challenge to the new fees in federal court. To the District's delight, and frankly some surprise, the district court granted the District's motion on both issues. Fortunately for the District, Laidlaw chose not to appeal. As such, the District has one of the few flow control ordinances in the Country that has withstood a constitutional Commerce Clause challenge.

BACKGROUND OF THE MUNICIPAL WASTE COMBUSTOR RULE

EPA promulgated the MWC rule pursuant to Section 129 of the Clean Air Act,³ which directs EPA to regulate air emissions from new and existing incinerators of solid waste. Section 129 requires EPA to set new source performance standards ("NSPS") and emission guidelines applicable to existing sources for four categories of incinerator units, including two categories that combust municipal solid waste.⁴ The two municipal solid waste incinerator categories are "solid waste incineration units with capacity greater than 250 tons per day combusting municipal waste" and "solid waste incineration units with capacity equal to or less than 250 tons per day combusting municipal waste. . ."⁵

Section 129(a)(1) also directs EPA to "establish performance standards and other requirements . . . for each category of solid waste incineration units."⁶ A "solid waste incineration unit" is defined as "a distinct operating unit of any facility which combusts solid waste material . . ."⁷ Congress, therefore, established small and large categories of MWCs using unit size as the distinguishing factor.

The statute further requires that emissions standards promulgated pursuant to Section 129 are to "reflect the maximum degree of reduction in emissions of air pollutants . . . that the Administrator . . . determines is achievable for new or existing units in each category."⁸ "The Administrator may distinguish among classes, types (including mass-burn, refuse-derived fuel, modular and other types of units), and sizes of units within a category in establishing such standards."⁹

Section 129 appears in Title III of the Clean Air Act Amendments, through which Congress established a general framework for the EPA to promulgate by source category emissions standards for 189 hazardous air pollutants ("HAPs") based on MACT.¹⁰ Significantly, solid waste incinerators are the only class of stationary sources for which Congress provided specific statutory guidance on the development of emissions standards for HAPs. The detailed instructions in Section 129 for establishing emissions standards for specified categories of solid waste incinerators, moreover, stand in stark contrast to the wide latitude given to EPA in defining other categories of stationary sources for purposes of setting MACT standards under section 112.

EPA's efforts to establish emissions standards pursuant to Section 111 of the Act for MWCs actually predate the enactment of Section 129. The Agency initially proposed emission standards for new and existing MWCs in 1989.¹¹ The 1989 proposed rules set out three categories of MWCs based on aggregate (plantwide) capacities: 1) up to 250 tons per day (tpd); 2) 250 tpd to 2,200 tpd; and 3) over 2,200 tpd.¹² Section 129, however, directed EPA to change its approach and establish emissions standards on a unit basis, rather than an aggregate plant capacity basis, within statutorily defined categories. Consequently, Congress rendered the 1989 proposed rule inapplicable to all except MWC incineration units with capacity greater than 250

tons per day.¹³

The final NSPS and MWC guidelines for MWCs issued by EPA in January, 1991, adhered to these statutory categories of large and small units. Facilities with unit capacities of greater than 250 tons per day were subject to the regulations; those with smaller units were not.¹⁴ Standards were set differently in each subcategory. Therefore, the 1991 rules properly excluded facilities like the District's facility because its units have capacities less than 250 tons per day.

The District was aware of the definitions contained in Section 129 and Subpart Ea, and in the Spring of 1994 argued with the Utah Division of Air Quality (the "DAQ") over whether the 1991 MWC rule was applicable to the District's units. The DAQ believed that it may be, but the District argued that because its units both had capacities less than 250 tons per day, the 1991 MWC rule was not applicable. DAQ sought guidance from EPA Region VIII on the issue, and the District's interpretation was confirmed -- that the 1991 MWC rule applied only to MWCs with unit capacities above 250 tons per day.

THE EPA'S 1994 PROPOSED MWC RULE

Still fresh from this battle with the DAQ, the District was surprised when in the proposed NSPS and MWC Guidelines issued on September 20, 1994, the EPA reverted to its 1989 approach and proposed regulating MWCs on an aggregate plant capacity basis, with the line between large and small plants drawn at 225 Mg/day aggregate plant capacity (slightly less than 248 tons). The proposal clearly ignored the statutorily defined large and small MWC categories based on unit size.¹⁵ Facilities like the District's, which had not been subject to the 1991 MWC rules due to their small unit size, were grouped with the large facilities in the 1994 proposal, and suddenly became subject to the most stringent limits for existing facilities. The EPA did not explain in the preamble its departure from the statutory dividing line of 250 tons per day per unit, nor is any such explanation provided anywhere in the docket.

Under Section 129, the EPA is required to set emission standards for particulate matter ("PM"), opacity, sulfur dioxide ("SO₂"), hydrogen chloride ("HCl"), oxides of nitrogen ("NO_x"), carbon monoxide ("CO"), lead, cadmium, mercury, and dioxins and furan (together "dioxins").¹⁶ Pursuant to the statute, the standards are to

reflect the maximum degree of reduction in emissions of air pollutants listed under section (a)(4) that the Administrator, taking into consideration the cost of achieving such emission reduction, and [other factors], determines is achievable for new or existing units in each category.¹⁷

When setting these standards, the EPA cannot set a standard less stringent than "the average emissions limitation achieved by the **best performing 12 percent of units** in the category" ¹⁸ The standards the EPA is to set are known as "MACT," or "maximum achievable control technology," and the average of the best performing 12 percent of units is known as the "MACT floor."

When it proposed the MACT floor for the regulated pollutants, the EPA admitted that it was supposed to find the best performing 12 percent of the units for each category of existing units, but suggested that it could not figure out how to do that. It noted that about 45 percent of the existing units were "being operated with the best emission control technologies," and stated:

Based on the examination and analysis of the emission data available from these units, the EPA has not found a basis for separating the top 12 percent of these

units from the remaining units in the subset of those units that are well-equipped, maintained, and operated.¹⁹

Because it could not figure out how to do what Congress directed, the EPA instead proposed taking the permitted emissions limits for each pollutant for each MWC unit and ranking them from lowest to highest.²⁰ Then it proposed taking the cumulative average of the top 12 percent of the permitted emission limits for each pollutant as the MACT floor.²¹

Based on this method for large plants the EPA proposed setting MACT at its calculated floor for PM, SO₂, and HCl.²² The EPA went beyond its calculated MACT floor for the other pollutants.²³ For small plants the EPA did a similar pollutant-by-pollutant analysis and set most standards beyond the MACT floor.²⁴

The EPA's proposal to set MACT at its calculated floor for large plants for SO₂, PM, and HCl was based on its consideration of the costs associated with setting MACT lower. For large plants, the EPA considered only the costs associated with meeting MACT for plants with a spray dryer ("SD") and either an ESP or a fabric filter ("FF") to control air pollution.²⁵ The EPA did not consider the costs for a large facility with DSI/ESP control to meet MACT. The EPA determined that existing facilities with SD/ESP controls could meet the MACT floor for SO₂, HCl, and PM, but that they could not reach the levels of control obtained by facilities with SD/FF controls.²⁶ The EPA then examined the cost of retrofitting an SD/ESP with SD/FF to determine whether MACT should be set lower. It wrote:

[T]he cost of requiring existing SD/ESP systems to retrofit an SD/FF to meet SO₂ controls levels more stringent than the MACT floor **would be prohibitively expensive and is considered unreasonable.** For example, at a typical 1,400 Mg/day MWC plant already equipped with an SD/ESP, the capital cost to remove the ESP and retrofit a new FF . . . would be about \$14 million. This cost would be in addition to paying the remaining debt for the relatively new ESP (about \$5 million including interest payments) and would result in a relatively small increase in control device efficiency. The incremental **cost of control for requiring a retrofit from an SD/ESP to an SD/FF would be greater than \$10,000/Mg of acid gas reduction** and would increase removal efficiency by only about 6 percent.²⁷

A cost of \$10,000 per megagram is about the same as \$9,075 per ton.** This same rationale was cited for setting MACT for HCl and PM at their MACT floors, and was used for not setting MACT for cadmium and lead any lower than a facility with SD/ESP could achieve.²⁸

The EPA did not even consider the retrofit costs for units like those at the Davis Facility -- refractory walled furnaces equipped with DSI/ESP technology.²⁹ The EPA did, however, know that the Davis Facility is equipped with DSI/ESP controls.³⁰

The EPA also discussed the proposed rules for small plants. When determining where it would set MACT for small plants with DSI/ESP, the EPA noted that,

[r]etrofitting a new SD/FF system would achieve greater acid gas control and small additional reductions in other MWC pollutants, but **the associated costs of**

** A megagram is equivalent to 2,204 pounds.

such retrofits at small MWC's would be prohibitively high (greater than \$10,000 Mg of acid gas reduction).³¹

The EPA also labeled the cost of such a retrofit as "unreasonably expensive."³² The EPA based MACT for small plants for other pollutants on DSI/ESP control levels.³³

THE DISTRICT'S COMMENTS TO THE PROPOSED RULE

The District filed comments objecting to the EPA's failure to adhere to the 250 tons per day per unit dividing line set by Section 129, by setting the dividing line at 225 Mg/day aggregate plant capacity.³⁴ In particular, the District wrote:

Section 129(g)(1) of the Clean Air Act defines the term 'solid waste incineration unit' as a distinct operating unit of any facility. In Section 129(a)(1)(A) the Administrator is charged with establishing standards for categories of solid waste incineration units with capacity greater than 250 tons per day. Section 129(c)(1)(C) requires that separate standards be developed for solid waste incineration units with capacity equal to or less than 250 tons per day. The proposed guidelines have violated the mandate stated in the Clean Air Act by proposing collective standards for facilities with capacity greater than 250 tons per day.

This change in categories between the CAA and regulations implementing the CAA lumps extremely large units built to LAER requirements in with those of more moderate size designed to meet incinerator standards. The effect is to require moderate sized units to meet the limitations economically met by extremely large units without following the legislated process or obtaining necessary amendments. The categories originally specified by the law should be analyzed first. Separate standards should be developed for units that combust more than 250 tons per day and units that combust less than or equal to 250 tons per day.³⁵

The District also explained that it has a DSI/ESP system and that calculations done in 1993 showed that it would cost in excess of \$15,000 per ton of acid gases removed to retrofit an SD/FF at the Davis Facility.³⁶ Fifteen thousand dollars per ton is equal to approximately \$16,500 per megagram. Finally, among other things, the District commented on the EPA's pollutant-by-pollutant approach to setting the MACT floors. The District primarily was concerned that by using this approach, the EPA would come up with emissions limitations for the regulated pollutants that no single plant in the United States could simultaneously attain.³⁷

THE FINAL MWC RULE

On December 19, 1995, the EPA published final regulations setting MACT for new and existing MWCs pursuant to Section 129.³⁸ The EPA kept the 225 Mg/day aggregate plant capacity dividing line between large and small plants from the proposed regulations.

Also as in the proposed regulations, the EPA set the MACT floor by analyzing the permitted emissions limits for each pollutant for each MWC unit, ranking them from lowest to highest, and taking the cumulative average of the top 12 percent of the permitted emission limits as the MACT floor. For large plants, this time the EPA set MACT at its calculated MACT floor

for PM, SO₂, HCl, lead, and NO_x. Because of projected retrofitting costs and based on the comments received, the EPA calculated the MACT floor for NO_x separately for each subcategory of combustor type and set MACT for each subcategory at the MACT floor.³⁹

The EPA went beyond its calculated MACT floor for cadmium, mercury, and dioxins and furans, but set the limits at levels that can be achieved by a plant with SD/ESP control.⁴⁰ The EPA set two different dioxin limits -- a high one for SD/ESP plants and a lower one for SD/FF plants. The basis for this was the "prohibitively expensive and unreasonable" cost for retrofitting an SD/ESP plant with SD/FF.⁴¹ For small plants, the EPA did a similar pollutant-by-pollutant analysis and set most standards beyond the MACT floor, but again at levels that can be achieved by plants with DSI/ESP control.⁴²

The EPA did not respond to the District's comments about ignoring the size categories set by Section 129 of the Clean Air Act or about the cost to the District to retrofit its units with SD/FF. The EPA did respond to the argument that it should not have set MACT floors on a pollutant-by-pollutant basis, but wrote only that:

EPA believes that the statute and case law support its interpretation that it is legally permissible for the EPA to set the MACT floor pollutant-by-pollutant, as long as the various MACT floors do not result in standards that are not achievable.⁴³

Because the EPA viewed its interpretation as reasonable, it concluded that the pollutant-by-pollutant approach was permitted.

Under the Guidelines, States were required to submit plans to implement and enforce the Guidelines by December 19, 1996.⁴⁴

THE DECISION TO SEEK REVIEW

The decision to seek review of the MWC rule was not difficult for the District to make given this background. Because the Davis County facility has aggregate plant capacity of 420 tons per day, it was considered a large facility under the guidelines. Preliminary results from testing conducted in November, 1995, just prior to the promulgation of the final rule, indicated that, while the District's facility could meet many of the guidelines for large MWC's, all of the standards for small facilities could be met at low cost. To meet the small plant standards, the District would only have to install powdered activated carbon ("PAC") capacity to its DSI system. This modification would cost between \$150,000 and \$1,500,000 to build with annualized capital and operating costs between \$120,000 and \$295,000 per year. This cost will be incurred irrespective of which standards are finally determined to be applicable to the District's facility because PAC injection is needed to meet both the large and small plant mercury emissions guidelines. PAC injection also reduces dioxins below both the large and small plant emissions guidelines for existing ESP equipped facilities.

Significant additional modification of the District's facility would have been necessary for the District to comply with the guidelines for large plants. If those still applied, the facility would need to install an SD/FF on each unit only to achieve certain compliance with acid gas standards. The District's expert consultant, Dr. Greg Rigo, estimated the cost of construction and covering lost revenues and extra solid waste management costs during the retrofit process to be about \$17,250,000. Including extra operating costs and debt retirement, the increased annual cost to the District would have been about \$2,500,000. Given the financial strain the District already was in, this was a cost it simply could not bear if there was any way around it.

Dr. Rigo also estimated that this cost increase would reduce acid gas emissions from the District's facility by about 150 tons per year, meaning that the cost of the retrofit would have been more than \$15,700 per ton of acid gas removed. (Ironically, as discussed above, the EPA determined that a cost of \$10,000 per megagram of acid gases removed [about \$9,075 per ton] "would be prohibitively expensive and is considered unreasonable" in the preamble to the September, 1994 proposal.)⁴⁵

THE DISTRICT FILES A PETITION FOR REVIEW

Against this backdrop, when the final MWC rule was promulgated on December 19, 1995, the District was prepared to file its petition for review. Of course, Administrator Browner had signed the order actually issuing the regulations on October 31, 1995, so we had a couple of months to review them and the background documents. The petition for review was filed on or about December 21, 1995. The District considered it a worthwhile investment to spend a few hundred thousand dollars to ward off having to spend \$18 million. When the petition for review was filed, the District, perhaps naively, had little doubt that it would win, given what it considered the EPA's clear violation of the plain language of Section 129 of the Clean Air Act. In fact, the District could not understand why the EPA did not seem to take the litigation seriously.

Motion to Expedite and Application to Stay

Shortly after filing the petition for review, on January 22, 1996, the District filed a motion with the court to expedite review. The basis for this motion was the December 19, 1996, deadline imposed by Section 129 for states to submit state plans. Based on our experience with cases in federal courts of appeals, it was not clear that review could be completed by December 19, 1996, even though that was nearly one year off. Moreover, the state plans had to take the form of regulations adopted by the state. If the state of Utah were to go through required regulatory procedures to adopt a state plan, the District estimated it would need to have an answer from the court by August, 1996, so that it could make a decision regarding retrofitting or closing.

On January 22, 1996, the District also filed an application with the EPA to stay the effective date of the regulations. Again, the District emphasized the fact that if the state were going to adopt a state plan through regulatory procedures, the District and the state would need to know by August, 1996, whether the large plant or small plant standards would be applicable to the District's facility. The application for a stay was filed with the EPA rather than the court pursuant to Rule 18 of the Federal Rules of Appellate Procedure, which requires the agency to act on a stay request before a stay is sought from the Court.

In support of both the motion to expedite review and the application for a stay, the District emphasized primarily the EPA's violation of the plain language of Section 129 and the harm it would cause the District from being illegally lumped with the large plants. The District did not advance any other substantive arguments at that time.

The standard for obtaining a stay is quite difficult to meet. The court has listed the factors to be considered in determining whether to grant a stay as:

- (1) the likelihood that the party seeking the stay will prevail on the merits of the appeal;
- (2) the likelihood that the moving party will be irreparably harmed absent a stay;
- (3) the prospect that others will be harmed if the court grants the stay; and
- (4) the public interest in granting the stay.⁴⁶

To justify the granting of a stay, "the movant need not always establish a high probability of success on the merits. Probability of success is inversely proportional to the degree of irreparable injury evidenced. A stay may be granted with either a high probability of success and some injury, or *vice versa*." ⁴⁷

Based on this standard, the District believed a stay should have been granted by the EPA. Congress clearly set, we thought, the dividing line between large and small MWCs at a 250 tons per day per unit level, rather than the 250 tons per day aggregate capacity the EPA adopted. Moreover, application of the EPA aggregate capacity standard to the District's facility pending the court's review could have resulted in the closure of the District's plant because the projected costs to retrofit were too much for the District to absorb with its already high debt load.

On the flip side, the District believed that if a stay were granted, no harm would result to others. The District had conducted health risk assessments that showed that the facility posed no material health risks at its current emissions levels. The District also argued that a stay would also further the public interest, particularly the affected public of Davis and Morgan Counties, Utah, because it would assure the public would not lose a \$55 million investment.

Filing the motion to expedite review was a good move because it forced the EPA to take a position early on concerning its interpretation of Section 129(a)(1). In response to the motion to expedite, the EPA argued that it had properly promulgated guidelines applicable to all MWCs with capacities above 35 Mg/day, and that Section 129(a)(1) merely set deadlines for promulgating the regulations for the different size categories; it did not dictate different standards for the two categories of MWCs.

The court did not give the District a clear victory on the motion to expedite review, but the court did appear to assign an expedited schedule to the case. Following that ruling, the District continued to prepare its case and wait.

In the meantime, two other parties challenged the MWC rule. Waste Energy Partners ("WEP"), which runs a facility in Harford County, Maryland, filed a petition essentially piggybacking on the District's arguments. The Cement Kiln Recycling Coalition ("CKRC") filed a petition challenging the potential application of the MWC rule to cement kilns that combust municipal waste. Ultimately, these petitions were consolidated with the District's and the parties were ordered to prepare joint briefs.

Although the District had filed an application to stay the effective date of the regulations with the EPA in January, by March 5, 1996, the District had not heard anything from the Agency on that application. A telephone call was had that day between Leslye Fraser of the EPA Office of General Counsel, and Larry Jenkins. Ms. Fraser reported to Mr. Jenkins that she did not believe the District had met the standard necessary for obtaining a stay of the effective date of the regulations. She anticipated that she would make a decision sometime in early April, 1996, on the District's application.

By April 22, 1996, the District still had not heard from the EPA on its application for a stay. Counsel for the District wrote to Leslye Fraser that day asking for a decision on the matter. No decision, however, was forthcoming.

On May 10, 1996, representatives of the District were asked to meet with representatives of the Utah DAQ and the Utah Attorney General's office to discuss the state plan the DAQ had to prepare and submit under Section 129. At that meeting, the District was informed that its estimate that the state would have to commence formal state plan promulgation procedures by August, 1996, was accurate. The DAQ representatives informed the District that any input the District wanted to have into the state plan would have to be received by the DAQ no later than August 1, 1996.

After receiving this information, the need for the District to obtain a stay of the effective date of the regulations became clear. The District waited a couple of more weeks for the EPA to act on the application for a stay. Then, on May 28, 1996, when it appeared that the application with the EPA was futile, the District filed a motion to stay with the court advancing essentially the same arguments it had with the EPA. Neither WEP nor CKRC joined in this motion.

On June 28, 1996, just four days after the District, WEP, and CKRC had filed their opening brief on the petition for review, the court shocked the EPA and granted the District's motion to stay. In a short paragraph ruling on the motion, the court wrote only that "Petitioner has satisfied the standards required for a stay pending court review."

The EPA's Motion for Voluntary Remand of Record

The EPA was clearly taken aback by the court's decision to issue a stay of the effective date of the regulations. In response to this, the EPA filed a motion seeking a voluntary remand of the record so that it could explain more fully why it had established the standards and guidelines the way it had. The EPA believed that if it were allowed to explain itself for the record then, it would help the court avoid having to go through oral argument and drafting an opinion. It also believed it could clear things up so that there would be no need to go further. The EPA, however, did not offer to reconsider its decision.

The District, WEP, and CKRC each opposed the EPA's motion for voluntary remand. To the District and WEP, it seemed that no amount of explanation could correct the fundamental problem created by the EPA when it based its MWC categories on aggregate plant capacity and drew the dividing line between large and small plants at 225 Mg/day aggregate plant capacity. That was not a mere procedural error or failure to explain. That error went to the heart of the rule itself and could not be explained away.

On July 31, 1996, the court entered an order denying the EPA's motion we thought would have sent a message to EPA. The court's reasons for denying the motion were listed as follows:

Respondent did not submit its motions until after petitioners had filed their brief, despite having prior notice that petitioners were challenging respondent's failure to respond to the comments submitted by the District and CKRC. . . . Moreover, the petition for review presents threshold issues, that may render unnecessary a resolution of the failure-to-explain questions. In addition, remand would be inappropriate where, as here, the agency does not seek to reconsider its decision. . . . Finally, an agency should provide contemporaneous, rather than *post hoc* reasons for its rulemaking decisions.

We were surprised that after receiving this order EPA did not initiate some form of settlement discussions.

The District's Arguments on Review.

The District and WEP advanced four primary arguments on review: (1) the EPA violated the plain language of Section 129(a)(1) when it regulated MWCs based on aggregate plant capacity and divided the universe of MWCs at 225 Mg/day aggregate plant capacity; (2) the EPA violated the Clean Air Act and the Administrative Procedures Act when it failed to respond to the District's significant comments; (3) the EPA violated the Clean Air Act and the Administrative Procedures Act when it failed to explain its departure from Section 129 of the Clean Air Act in its statement of basis and purpose; and (4) the EPA's failure to consider costs to the District to

retrofit SD/FF was arbitrary and capricious.

ORAL ARGUMENT

Oral argument was held October 3, 1996. As oral arguments go, this one was easy from the perspective of reading the court. The court was only interested in the District's first argument, and repeatedly hammered the EPA's attorney about why the EPA had used aggregate plant capacity, rather than unit size, when differentiating between large and small plants. At least two of the judges even used the word "irrational" when describing what the EPA had done.

The burning question for the court, however, was whether it would have to vacate all of the guidelines for existing plants if they agreed with the District's argument, or whether it could leave the guidelines in place for large units. We had looked at this issue for the District and, while retaining the guidelines for units with capacities larger than 250 tons per day would not impact the District, we did not believe the court could carve up the rule given the fundamental error the EPA had made. When the EPA's attorney was asked this question, he agreed. Only WEP's lawyer argued that the Court could carve up the rule and only vacate the part of the rule applicable to units with capacities equal to or below 250 tons per day.

A few weeks after oral argument, the EPA submitted a letter to the court suggesting that the court could leave the guidelines in place for the large units despite the comment its lawyer made at oral argument. Each of the petitioners responded in various ways with their own letters, but the court never read the letters and ordered that they be returned to the parties.

THE COURT'S DECISION

Apparently trying to beat the December 19, 1996 deadline for states to submit state plans under the MWC rule, the court issued its decision on December 6, 1996. The decision is reported at 101 F.3d 1395.

After going through painstaking detail into the history and background of the MWC rule, the court concluded that it only needed to reach the District's first argument. "In this case, our analysis need not proceed beyond Chevron's first step, for it is clear that the 1995 standards conflict with the plain meaning of section 129."⁴⁸ The court held that:

the most logical and straightforward reading of section 129(a)(1) is that it establishes four categories of solid waste incineration units -- MWC units with a unit capacity above 250 tons/day, MWC units with a unit capacity of 250 tons/day or less, units combusting hospital, medical and infectious waste, and units combusting commercial or industrial waste.⁴⁹

The court found the EPA's argument that Section 129(a)(1) is merely a scheduling provision "implausible in light of the regulatory scheme detailed in the following subsection of the statute, section 129(a)(2)."⁵⁰ Section 129(a)(2) is the section that describes how the MACT floor and MACT are to be set and requires that these be set within each category. "When this MACT methodology set out in section 129(a)(2) is viewed in light of the regulatory deadlines established in section 129(a)(1), it becomes apparent that Congress must have intended large and small MWC units to represent separate categories of solid waste incineration units."⁵¹

When the court came to deciding what to do about the EPA's error, it discussed what impact the shift in the line between large and small units would have on the standards and guidelines. Because the NSPS were the same for both large and small units, it recognized that "[t]his shift likely will not affect the NSPS for new units, regardless of unit capacity."⁵² The

court also recognized that the "new MACT floors for existing units with unit capacities above 250 tons/day [may] be nearly the same as those proposed for the large plant category in the 1995 standards."⁵³ It was also clear to the court that guidelines for existing small units "will become significantly more stringent."⁵⁴

Based on this analysis, the court reasoned that it may only need to vacate the guidelines as applied to existing small units and not everything else. Yet, because at oral argument "counsel for the EPA stated that he believed the 1995 standards would need to be vacated in their entirety if we were to decide that MWC units had to be recategorized by unit capacity," the court vacated the entire MWC rule.⁵⁵

THE EPA'S PETITION FOR REHEARING ON REMEDY

On February 4, 1997, the EPA filed a Petition for Rehearing on Remedy with the court. The EPA asked the court to reconsider only the remedy portion of the opinion. Thus, the Court's reading of the statute will stand. The EPA asked the Court to leave intact the NSPS and guidelines applicable to MWC units with capacities above 250 tons per day. It argued that none of the owners or operators of these units challenged the regulations and to leave these standards and guidelines in place would, therefore, not harm them and would not impact the District's units. The EPA also argued the significant loss of reduced emissions -- as much as 128,000 tons -- that would result if the compliance deadline were moved back by a new promulgation date justified the relief requested. The EPA claimed the court had power to carve up the MWC rule and leave part of it in place under the Court's general equity powers.

The District filed comments to the Petition for Rehearing on Remedy on February 19, 1997. The District agreed with nearly every issue argued by the EPA, except the EPA's argument concerning the court's equitable powers. As a general rule in the past, the court has only exercised its equitable powers to not vacate a rule on remand when the EPA has committed some kind of procedural error it can correct, such as a violation of the notice and comment provisions. That is not what the court found in this case. In this case, the court found a fundamental and substantive violation of Section 129 of the Clean Air Act. No amount of equitable or magical powers will wipe away this violation or make its effects go away.

On March 21, 1997, the court granted the EPA's Petition for Rehearing on Remedy. It modified the December 6, 1996 decision by vacating only the NSPS and guidelines applicable to MWC units with capacities equal to or less than 250 tons per day. The court left the NSPS and guidelines for large units in place and remanded the guidelines for large units for minor adjustment of the MACT floors.

CONCLUSION

Round 1 has been won by the District, but the war may be far from over. Despite the outcome on the EPA's Petition for Rehearing on Remedy, the EPA must still promulgate new guidelines applicable to MWC units with capacities of 250 tons per day or less. Until we see the EPA's proposal, we do not know whether more challenges will be needed. The District, however, has proved a point that others who feel overpowered by the EPA can learn from -- sometimes you can beat an 800-pound gorilla. Never again will the District assume that because the EPA said it, that's the way it must be. When the EPA is wrong, it must be challenged -- even by the weakest among us -- to ensure the sound and proper development of environmental policy and law.

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5. Id.
6. Id. § 7429(a)(1)(A) (emphasis added)
7. Id. § 7429(g)(1) (emphasis added)
8. Id. § 7429(a)(2) (emphasis added)
9. Id. (emphasis added)
10. 42 U.S.C. § 7612
11. The proposed NSPS were published at 56 Fed. Reg. 5488 and the proposed Emissions Guidelines were published at 56 Fed. Reg. 5514.
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13. 42 U.S.C. § 7429(a)(1)(B)
14. 40 C.F.R. 60.32a (1995); 40 C.F.R. 60.50a (1995)
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16. Id. § 7429(a)(4)
17. Id. § 7429(a)(2) (emphasis added)
18. Id. (emphasis added)
19. 59 Fed. Reg. at 48,244 (emphasis added)
20. Id.
21. Id.
22. Id. at 48,245-46
23. Id. at 48,246-47
24. Id. at 48,247-49

25. Id. at 48,245-47
26. Id. at 48,245-46
27. Id. at 48,245-46 (emphasis added)
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29. U.S. Environmental Protection Agency, Air and Radiation Docket No. A-90-45 ("Docket A-90-45"), III-B-1 at 3-13 through 3-16; U.S. Environmental Protection Agency, Air and Radiation Docket No. A-89-08 ("Docket A-89-08"), II-A-065 at 2, 8 and Table 2-3. The tables shown on the referenced pages of Docket A-90-45, III-B-1 show that EPA considered 17 model plants. A comparison of the tables reveals that of the large plants, none has refractory walled units with DSI/ESP technology. In Docket A-89-08, II-A-065, EPA notes that excluded from its models are "Katy-Seghers refractory-wall designs," and at Table 2-3 it specifically lists the Davis Facility as a facility not modeled.
30. Docket A-90-45, II-B-20; Docket A-89-08, II-A-065 at 2, 8 and Table 2-3
31. 59 Fed. Reg. at 48,248 (emphasis added)
32. Id.
33. Id. at 48,248-49
34. The District's comment was not the first occasion on which EPA was presented with this question. In September 1991, at a meeting hosted by EPA, David Sussman of Ogden Martin Systems said: "[I]t [is] irrational to combine MWC II (large plants) and MWC III (small plants) into one regulatory development effort." He said that since MWC III had much better cost effectiveness than MWC II, the combination of the two made the cost effectiveness of MWC II look better than it really is. Mr. Porter of EPA replied that EPA is just responding to schedule pressure, and it is more efficient to proceed with a combined regulatory package. Docket A-90-45, IV-E-12.
35. Docket A-90-45, IV-D-104 at 2
36. Id.
37. Docket A-90-45, IV-D-104 at 4-6
38. See 60 Fed. Reg. 65,387 (December 19, 1995)
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40. Id.
41. Id. at 65,401
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Keeping Society's Options Open

Charles O. Velzy, P.E., DEE
Private Consultant
RR2, Box 304C
Lyndonville, VT 05851

KEEPING SOCIETY'S OPTIONS OPEN

Introduction

Environmental regulations are promulgated to protect public health, safety and the environment. Unfortunately, regulations can become an end in themselves or be used to foster unrelated policy objectives. When this happens, business activity frequently shifts to less regulated, hence artificially less expensive alternatives. Since all human activity – including every waste management practice – consumes energy, generates pollution, and involves risk, such a shift can result in unintended harm to the environment.

After practically minimizing a source's emissions, spending more resources to achieve small gains may cost more than they are worth. Also, emissions' reductions that do not measurably improve public health, safety and environmental quality waste society's limited resources. Good regulation, like good stewardship, treats all society's air, water, land, human and financial resources as limited and precious commodities. They all should be conserved.

Municipal Waste Combustor [MWC] Regulations

Before the Clean Air Act [CAA], municipal waste incinerators were frequently little more than open-burning-dumps-in-a-box. New Source Performance Standards regulating incinerator particulate emissions were among the first promulgated under the CAA. By the later 1970s, the oil embargo, sustained high energy prices under the Public Utilities Regulatory Policy Act [PURPA], and anticipated landfill capacity shortages combined to foster the development of the waste-to-energy {WTE} industry. As more facilities were built, state environmental review laws worked with federal requirements to apply Lowest Achievable Emissions Rate [LAER] technology, technology designed to absolutely minimize facility emissions in poor air quality (non-attainment) areas, to stimulate commercialization of advanced air pollution control systems. Then, plants built in clean-air areas met Best Available Control Technology [BACT] requirements by using this now commercially demonstrated technology. Thus, LAER air emissions control systems cascaded across the country. The process of initiating major technology improvements in poor air quality areas, proving performance and then spreading that technology everywhere steadily ratcheted the emission limitations for new plants down to ever lower levels.

Particulate emissions are an example of the ratcheting process. In the 1960s, burning a ton of municipal solid waste [MSW] emitted about 30 pounds of particulates. In 1971, the New Source Performance Standard [NSPS] for incinerators reduced particulate emissions to approximately 1.9 pounds of particulate per ton of MSW burned, a 94 percent reduction. In the 1980s, the focus changed to minimizing acid gas, trace metal, and dioxin/furan emissions. Advanced control technologies were developed and installed, first in non-attainment areas, then everywhere. New plant particulate emissions have been reduced to below 0.2 pounds per ton of MSW burned since the late 1980s – a 99 percent reduction (from 30 pounds) in about two decades. Each incremental improvement came from technology meeting more stringent emissions criteria. Each incremental improvement also used many more resources – energy, money and human talent – than the previous step.

Dioxin and furan emissions are another example of the ratcheting process. When first measured in the later-1970s, concentrations were 1,000 times greater than those routinely found 10 years later in state-of-the-art plants. The technology to control sulfur dioxide and hydrogen chloride emissions also reduced

dioxin and furan emissions. Multipathway health risk assessments routinely show negligible risk from this level of dioxin and furan emissions. Even so, the 1995 Emissions Guidelines call for these low emitting systems to demonstrate dioxin emissions another 50 times lower. This reduction is the anticipated byproduct of using activated carbon to reduce mercury emissions.

The Maximum Achievable Control Technology [MACT] emission limitations required by 1990 Clean Air Act Amendments [CAAA] show the ultimate effect of the ratcheting process. The philosophical basis for MACT is that if 12 percent of similar facilities have achieved emissions control at a certain level, the rest should meet similar levels to protect citizens from pollution. The CAA recognized the inappropriateness of applying extraordinary measures everywhere by calling for LAER installations to be excluded from the pool of best performing plants when developing emission limitations. The LAER-to-BACT ratcheting process, however, had already spread stringent non-attainment area emissions controls across the entire country. Even though the resulting regulations simply formalize the *de facto* limitations most modern facilities already meet, this process has produced more restrictive regulations than would probably exist without the ratcheting process. They also ensure that any new facility, regardless of where it is built, meets non-attainment area requirements.

Fallacies in Current MWC Regulations

Municipal waste combustor emissions have been drastically reduced. With advances in technology, MWCs achieved progressively lower emission levels, triggering on-going reductions in allowable emissions under federal, state and local regulations for new plants. These reductions came, however, at the price of increasingly higher costs both per ton of pollutant removed and per ton of waste processed. After a little more than two decades of continuous ratcheting down of regulations, MWCs have become a comparatively minor source of combustion related air pollution. Other man-made and natural sources like automobiles, trucks, power plants, fireplaces, wood stoves, metal production furnaces, industrial manufacturing processes, volcanoes and forest fires are now the major known sources of combustion related pollutants.¹

“Real world” engineering practices require that equipment designs provide an adequate margin between expected and required performance. Safety margins are needed to ensure permit compliance regardless of the input and operating condition variations encountered during testing. Thus, facility emission test results are normally well below permitted levels.

The fact that state-of-the-art MWCs achieve ever lower emissions levels, albeit at a high cost per ton of waste processed, has been used to ratchet down emission limits. When improved emissions control technology has been installed and demonstrated, then more money must be expended to develop new technology to recreate a suitable safety margin. However, the public and business men alike are risk averse. Somebody might be willing to accept the possibility of public castigation, fines and jail terms due to violations produced by normal variability when sufficiently better emissions control technology does not exist, but abandoning the development of new MWCs is the likely consequence of such reductions. The hiatus in new MWC construction reported in the Preamble to the 1995 Emissions Guidelines for existing MWCs² provides strong evidence that the point of uncontrollable risk has been passed. MWCs have been effectively priced out of the market when decision makers compare their cost to the cost of much less regulated solid waste management alternatives.

Society tends to purchase the least expensive alternative believed to meet its needs. For example, when a single waste management option is singled out for disproportionately stringent pollution control, while alternative management techniques are not so burdened, prices become distorted. Shifting disposal to comparatively less regulated, hence artificially lower priced, options is the natural consequence of regulating only one of several competing alternatives. The distortion may cause environmental quality to actually decrease. Well-regulated incinerators, for example, sterilize, stabilize and reduce the volume of material requiring final disposal while recovering energy from otherwise wasted resources. Competing disposal options also involve risk, pollute the environment and consume resources. However, these alternative disposal options are not subjected to the same rigorous environmental regulations as MWCs. The potential for doing more harm than good is particularly acute when the less regulated alternatives are not well studied or simply assumed to be environmentally benign.

In addition to price distortion caused by uneven regulations, excessive regulation can result in inordinate cost to control specific pollutants. For example, EPA's cost estimate for MWC NO_x reductions is \$4,275/megagram [Mg, about 1.1 tons].³ The proposed utility boiler rule costs only \$230/Mg of NO_x removed.⁴ Because MWCs began employing LAER-like NO_x controls across the United States in the late-1980s, today they have to spend much more than the utility industry to eliminate a megagram [Mg, about 1.1 tons] of NO_x. Since utility boilers make a much larger contribution to the national NO_x burden than MWCs, on either a per-unit or industry-wide basis, society would get 19 times as much environmental improvement if the money spent reducing MWC NO_x emissions was spent on reducing emissions from utility boilers instead.

When emissions reductions do not produce discernible improvements, the point of diminishing returns has been reached. Ambient air quality studies typically find no difference between upwind and downwind pollutant concentrations at state-of-the-art MWCs and hazardous waste incinerators.^{5,6,7,8,9,10} Further regulation of these pollutants is an exercise in control-for-control's-sake rather than an effort likely to produce measurable environmental gains. Spending money on more controls that do not result in detectable improvements in environmental quality simply wastes our limited resources; it does not measurably improve public health and safety or the environment.

Figure 1, known in quality assurance engineering as the Pareto Principle,¹¹ illustrates the point that initial emission control costs are low and pollution reduction high, while each subsequent increment of pollution reduction is increasingly costly and progressively smaller. The cost analysis accompanying the December 19, 1995 Municipal Waste Combustor regulations also illustrates the point. For facilities without acid gas control, emissions reductions cost about \$1,400/Mg of HCl and SO₂ removed. Retrofitting existing dry scrubber and electrostatic precipitator equipped facilities with fabric filters to achieve a small incremental improvement in acid gas emissions costs more than \$11,000/Mg.¹²

Lessons That Should Have Been Learned

Public and private resources are limited. There are competing national priorities. Environmental expenditures that produce minimal improvements in public health or environmental quality reduce the funds and human resources available to address other major societal needs, such as health care, education, fire and police protection, to name a few. Therefore, it is very important that environmental policy focus our nation's resources where they will produce the greatest public health benefits and do the most environmental good.

Today's implicit regulatory approach – ratcheting emissions ever downwards and uneven regulation of competing alternatives – should be reconsidered based on thoughtful answers to the following questions:

- Will increasingly stringent emissions limitations for a specific source category (e.g., incinerators) make any discernible difference in ambient air quality?
- Do less stringently regulated, hence economically preferable, options either produce greater net risk to society or consume more resources than the more strictly regulated alternative?
- Will measurable overall gains in public health, safety and environmental quality occur if society continues to ratchet down emissions well past the point of diminishing returns?

In my opinion, thoughtful answers to the above questions will result in regulations based on sound scientific and engineering principle and valid total cost accounting which will, in turn, enhance mankind's total environment. Specific recommendations are:

- Systematically compare the environmental and health impacts of all major alternatives.
- Determine the level at which emissions limitations become reasonably protective of public health and the environment.
- Scrutinize further reductions for cost effectiveness and significantly correlated health benefits.
- Base policy on properly promulgated consensus risk assessment and risk management techniques.
- Implement policies that produce the maximum public health and environmental benefits by encouraging the use of the most practicable and cost-effective combination of alternatives.
- Simultaneously regulate competing alternatives to avoid unintended biasing of the market.

Conclusion

The history of municipal waste combustor regulation provides an instructive case history of what can happen when regulatory policy loses sight of the purpose of environmental regulation. The current MWC regulations in effect tend to encourage the use of alternative, less regulated, waste disposal options. The lessons learned need to be applied to how we regulate all pollution sources based on actual impact to the environment and in a cost effective manner. It is a factor to consider in the current regulatory reform and commonsense initiatives fostered by both the Administration and the Congress.

Once protective emissions levels have been achieved, society must concentrate its resources elsewhere to get the maximum benefit from each dollar expended. Emissions limitations that exceed adequate protective levels and are unevenly applied waste society's limited money and human resources and squanders our air, land and water resources.

Acknowledgments

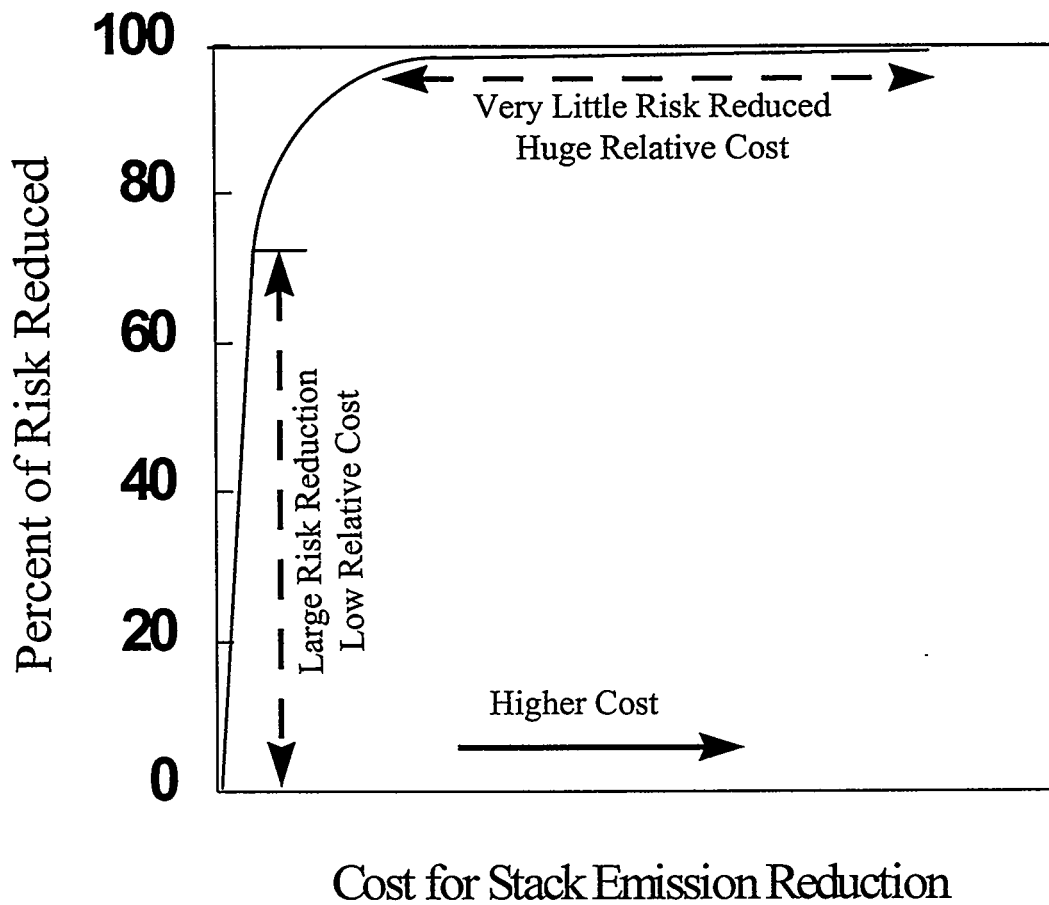
This paper is based largely on a position paper prepared by the Research Committee on Industrial and Municipal Wastes of the Board on Research and Technology Development of the American Society of Mechanical Engineers [ASME].

In addition to this author the following individuals provided substantial input in developing the position paper; K. C. Lee, Greg Rigo, Dave Hoecke and Floyd Hasselriis.

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Figure 1



The Pareto Distribution

(Adapted from J. M. Juran, "Managerial Breakthrough, A New Concept of the Manager's Job")¹¹

Comparison of U.S. EPA and European Emission Standards
for Combustion and Incineration Technologies

Anthony Licata, Technical Advisor
L. & C. Steinmüller GmbH
345 Concord Road
Yonkers, NY 10710-1848

Hans Ulrich Hartenstein
L. & C. Steinmüller GmbH
Fabrikstrasse, 1
Gummersbach D-51641, Germany

Louis Terracciano
Licata Energy & Environmental Consultants, Inc.
345 Concord Road
Yonkers, NY 10710-1848

ABSTRACT

There has been considerable debate, misunderstanding, and controversy when comparing emission standards used in Europe and the United States. One of the first questions you hear whenever U.S. EPA publishes a new emission standard is , "Is it as restrictive or is it the same as the German standard".

Although both systems of regulation call for the use of CEMS for compliance, there are substantial differences in how emission standards are structured in Europe and in the U.S. They include reference points, averaging times, sampling methods, and technology. Generally, the European standards tend to be more restrictive, due in part to the fact that the facilities are of necessity sited in close proximity to residential areas. In Germany, for example, regulations in general are comprehensive and include both design standards and emission limits while U.S. EPA's rules are source specific and, in most cases, limited to numerical emission standards.

In some cases, comparisons can be made between emission standards and, in some cases, comparisons can only be made with restrictive caveats. The paper will present a comprehensive overview of the emission standards and how they are applied.

INTRODUCTION

The emission standards promulgated in Europe and in the U.S. by the EPA are standards intended to control air pollution from MWCs. In this sense, the standards are very similar but they differ markedly in their philosophical approach. The U.S. EPA approach is to balance the economics of the waste combustor and health benefits of the country. The European approach is to control emissions to the lowest value possible which is technologically achievable regardless of economic considerations.

To make any rational comparisons to each other, emission standards in Europe and in the U.S. must be related to each other in equivalent units. The air standards in most of Europe are on a dry basis and referenced to eleven percent oxygen content, whereas most American standards are on a dry basis and referenced to seven percent oxygen content. The U.S. EPA considers standard conditions to be at a temperature of 68°F (20°C) and a pressure of 29.92 inches of mercury (101.3 kPa), while in Europe, standard conditions are at a temperature of 0°C (32°F) and a pressure of 101.3 kilopascals (29.92 in. of Hg)¹. The American standards are based on the English system of weights and concentration (i.e., grains, pounds, cubic feet, parts per million by volume, etc.), while in Europe the standards are based on the metric system (grams, cubic meter, liters, etc.).

In addition to the different units of measurement, the emission standards of both utilize different averaging periods. There are also differences in sampling and testing methods which are to develop emission standards. The European standards are different for each country and vary between ten-minute averaging periods to daily averaging periods, while the American standards are based on averaging periods specific to each pollutant.

(1) The European standard flue gas condition is referenced to as a normal cubic meter (Nm³) whereas the American standard flue gas conditions are referenced to as a dry standard cubic meter or foot (dscm or dscf) respectively.

U.S. and European regulations also differ in other ways such as in the measures for the calibration of the instruments which are different even among the countries of Europe.

U.S. EPA EMISSION STANDARDS

Table 1 is a listing of the U.S. EPA Emission standards for both new² and existing³ MWCs which are based on a conversion to 7% O₂. In addition, these standards reflect two MWC facility size categories, the first category includes (small) facilities whose aggregate capacity is greater than 38 tons per day (but less than 250 tons per day) and the second category includes (large) facilities whose aggregate capacity is greater than 250 tons per day. Note should be made that at the time of this writing, all of the U.S. EPA Emission standards discussed herein are subject to change pending the final ruling in Davis County vs. U.S. EPA. However to facilitate the comparison of existing standards, this paper uses U.S. EPA's emission standards as published on 12/19/96.

The standards listed in Table 1 reflect the maximum reduction in emissions of air pollutants that the U.S. EPA determines is achievable, taking into consideration health impacts, environmental impacts and energy requirements. These final standards as shown in Table 1 establish emission levels for particulate matter (PM), opacity, heavy metals (cadmium, lead, and mercury), carbon monoxide, nitrogen oxides, acid gases (sulfur dioxide, hydrogen chloride) and dioxins/furans.

A review of Table 1 will illustrate U.S. EPA's regulatory philosophy of determining achievable emission requirements that take into consideration health impacts, environmental impacts and energy requirements. Generally, large units, which provide better economics of scale with a concurrent cost-effectiveness of operation, are more restricted in their emissions than small units. The following is a listing of difference in emissions requirements for new large units versus existing large units under the new regulations (all values are corrected to 7% O₂).

- PM emissions are limited to 24 mg/dscm for new units and 27 mg/dscm for existing units.
- Cadmium emissions are limited to 20 µg/dscm for new units and 40 µg/dscm for existing units.
- Lead emissions are limited to 200 µg/dscm for new units and 490 µg/dscm for existing units.
- NO_x emissions are limited to 150 ppmv (for the first year of operation the limit is 180 ppmv) for new units and 200 - 250 ppmv for existing units
- SO₂ emissions are limited to 30 ppmv or 80% removal for new units and 31 ppmv or 75% removal for existing units. The emission limit is met based upon the less restrictive of the criteria.
- HCl emissions are limited to 25 ppmv or 95% removal for new units and 31 ppmv or 95% removal for existing units. The emission limit is met based upon the less restrictive of the criteria.
- Dioxin/Furan total emissions are limited to 13 ng/dscm (for the first 3 years of operation the limit is 30 ng/dscm) for new units 30 (or 60)⁴ ng/dscm for existing units.

Based on the U.S. District Court's ruling on 3/21/97 which vacated the US EPA's standards for existing small MWC units, this category is not addressed.

(2) New units are defined as having commenced construction, modification or reconstruction after 9/20/94.

(3) Existing units are defined as having commenced construction, modification or reconstruction before 9/20/94.

(4) 30 ng/dscm when using a fabric filter and 60 ng/dscm when using an ESP.

Table 2 is a listing of the U.S. EPA Emission standards for both new and existing MWCs which are based on the European conversion to 11% O₂ and are converted to European units (i.e., gr/dscf and ppmv to mg/Nm³, etc.) and is provided to allow the reader to conveniently review these standards in metric units and to allow easy comparison to specific standards of countries which employ the metric system. However, it is important to understand the specific characteristics of the emission legislation of the particular European country when comparing the standards in order to correctly weigh the meaning of the comparison.

AMERICAN VERSUS GERMAN EMISSION STANDARDS

In the U.S., the emission standards have historically and consistently been presented on a dry basis to avoid any dilution effects due to moisture. Prior to 1990, the German emission standards were on a wet basis. Since then, they have required conversion of emission results to a dry basis. In the U.S., separate emission standards are in effect for both new and existing units, as well as for small and large units respectively and for each type of waste (i.e. municipal waste, sewage sludge, hazardous waste, and medical waste). In contrast, the German standards, as well as those of the European Union, apply to all waste facilities, new or existing, large or small, and regardless of type of waste incinerated (i.e. municipal waste, sewage sludge, hazardous waste, medical waste, chemical waste, industrial waste, contaminated soil, treated wood waste, etc.). With respect to MWCs, the European Union regulations are still in draft form while the hazardous waste incineration (HWI) regulations for new units have been in effect since 6/29/93. The grace period for existing HWI units to reach compliance will expire in 1998.

The individual standards also have subtle but nonetheless distinctive differences. Some differences are as follow.

- In the U.S., for some pollutant emissions such as SO₂ and HCl, an percentage reduction alternative is provided to the allowable emission level (e.g. from Table 1, the U.S. EPA emission limit for HCl is 25 ppmv or 95% reduction, whichever is less restrictive). The European standards generally and the German standards specifically do not provide for the alternative of a percentage reduction as an alternative to a fixed emission concentration level.
- In the U.S., federal regulations require emissions to be corrected to 7% O₂, regardless of the O₂ level of the tested facility. Although this is generally true for most U.S. state and local regulations, other locally adopted corrections are commonly used across the country such as to 12% CO₂ in some localities and to 3%O₂ in the state of California. Alternatively, the German standards and those of the other European countries and the European Union with the exception of the Netherlands (Canadian standards are the same as the Netherlands) require conversion to 11% O₂ only if the O₂ level of the tested facility exceeds 11%. For actual O₂ levels below 11%, a conversion to 11% is not permitted due to the dilution characteristic of such a conversion. In Germany, one exception to this conversion policy exists for the case of CO which is always corrected to 11% O₂ for all flue gas oxygen values.
- In the U.S., only SO₂ is required in the reporting of sulfur oxides emissions. The German standards and those of the other European countries and the European Union require the reporting of total sulfur oxides (SO₂ + SO₃).

- In the U.S., dioxins and furans (tetra through octa) are reported on a total mass basis (ng/dscm). The German standards and those of the other European countries and the European Union require the reporting of dioxins and furans on the basis of International Toxic Equivalents (ITEQ). This difference is especially vexing in that there is no basis for direct comparison or conversion of these reporting systems and the ratios between them can be as much as 30 - 100 to 1. In this paper, a ratio of approximately 62.5 to 1 is used for comparison purposes only. The European Union has published only a guideline (target) for dioxins to date and has not established a standard.
- In the U.S., heavy metals are reported on an individual basis. The German standards and those of the other European countries and the European Union require the reporting of heavy metals on the basis of groups (i.e., Class I, Class II and Class III). Each group consists of a summation of several metals and can be composed of different metals by each country to further add to the difficulty in making direct comparison or conversion of the standards. These groupings of the various metals is done to account for their various levels of toxicity and environmental impact.

Table 3 directly compares the U.S. and German standards for large mass burn facilities (i.e., facility capacity greater than 250 tons per day) in terms of European units of measurement (i.e., mg/Nm³ and ng ITEQ/Nm³). Table 3 lists both the short-term and the long-term limits in the respective columns for the German regulations. This table illustrates the more restrictive nature of the German regulations relative to those promulgated by U.S. EPA. A unique aspect of the German regulations is that the correction to 11% O₂ is made only when the actual O₂ exceeds 11%. This detail may be lost to a reviewer when he attempts to compare emissions from facilities worldwide and more importantly frustrates "apples to apples" comparisons of data. Clearly, such a nuance highlights the fact that essential differences exist among regulations and data derived therefrom that ostensibly use the same correction factors. The following is a comparison of major pollutant emission limits in Germany versus the U.S. EPA limits and are illustrative of the more stringent emission limits under the German regulations (all values are in metric units and corrected to 11% O₂).

- SO₂ emissions are limited to 61⁵ mg/Nm³ or 80% removal whichever is less restrictive for the daily average by U.S. EPA, and to 50 mg/Nm³ for the daily average and to 200 mg/Nm³ for the 30-minute average in Germany.
- HCl emissions are limited to 28⁽¹⁾ mg/Nm³ or 95% removal whichever is less restrictive by U.S. EPA, and to 10 mg/Nm³ for the daily average and to 60 mg/Nm³ for the 30-minute average in Germany.
- PM emissions are limited to 17 mg/Nm³ by U.S. EPA, and to 10 mg/Nm³ for the daily average and to 30 mg/Nm³ for the 30-minute average in Germany.
- Mercury emissions are limited to 0.061 mg/Nm³ or 85% removal whichever is less restrictive by U.S. EPA and to 0.05⁶ mg/Nm³ in Germany.
- NO_x emissions are limited to 219⁽¹⁾ mg/Nm³ by U.S. EPA, and to 200 mg/Nm³ for the daily average and to 400 mg/Nm³ for the 30-minute average in Germany.

(5) Based on a 24-hour geometric mean

(6) Based on: 30-minute < averaging time < 120 minute

- CO emissions are limited to 89⁷ mg/Nm³ by U.S. EPA, for MWCs and to 50 mg/Nm³ on a daily average and to 100 mg/Nm³ on a 60-minute average in Germany. As previously stated, CO is always corrected to 11% O₂ regardless of the actual O₂ value.

IMPACT OF OXYGEN CORRECTION FACTORS IN THE REGULATIONS

The oxygen reference point approved in the U.S. to eliminate the effects of dilution on pollutant emissions is 7% O₂. Canada and the Netherlands correct emissions to 11% O₂. For these countries, emission results are always corrected from the actual oxygen value to the corrected value (to 7% in the U.S. and to 11% in Canada and the Netherlands).

Germany, as well as the European Union, on the other hand use a different procedure. The German approach is to correct oxygen to their base value of 11% only when the actual oxygen value is greater than 11%. For actual values less than 11%, no correction is made except in the case of CO. At first thought, this method seems to penalize well engineered, designed, and operated facilities by reducing the mass emissions they are allowed to emit. This seems an apparent contradiction to the intent of creating a correction factor in the first place, namely to prevent poorly operating facilities to dilute their stack gases in order to reduce their emissions to allowable levels. However, the German regulations also require good combustion practices. Therefore, a furnace temperature of at least 850°C (1562°F) after overfire air injection has to be maintained for at least 2 seconds. For hazardous waste incineration, the temperature requirement is raised to 1200°C (2192°F). Therefore to fully comply with the regulations, the units must be operated well below 11% O₂. Typically in the field, this results in an operating range of from 6% to 9% O₂ at the boiler exit and with somewhat higher values of from 8% - 10% O₂ at the stack due to minor air in-leakage.

Figure 1 compares as an example for the heavy metals, the U.S. mercury emission limit of 80 µg/dscm corrected to 7% O₂ to the German (European) standard which is 50 µg/Nm³ corrected to 11% O₂. The U.S. mercury emission limit when adjusted to its German (European) equivalent units turns out to be 61.3 µg/Nm³ corrected to 11% O₂ which illustrates that the U.S. standard is only about 20% higher than its counterparts when the range of actual oxygen values are 11% or above.

However at actual oxygen values below 11%, the emissions concentration allowable under German law deviate significantly from those allowed by U.S. law. Under the U.S. methodology for oxygen correction, the emission concentration effectively remains constant over the range of actual oxygen values. For example, at an oxygen value of 9%, the German facility allowable emission concentration level would be about 2/3 of the concentration level allowed under U.S. law and about 15% less than it would be allowed under German law if it operated at 11% oxygen.

Although this nuance in the interpretation and the application of the oxygen correction factor seems to place a hardship and environmental penalty to the better operated facilities, the regulatory response in Germany is that with the reference point set at 11% O₂ and thus at the upper end of the possible values of actual O₂ content, no conversion is needed for the common fluctuations of O₂ content in the range between 7% and 9% O₂ as commonly found in the field.

(7) Based on a 4-hour averaging time (24 hour average for some technologies)

In summary, this means that under German law with a high reference point of 11% O₂, the mass flow is kept constant above the reference point and decreases below it. Whereas the permissible actual concentration is kept constant below it and decreases above the reference point. Under U.S. EPA's rule, the reference point is set within the realistic range of actual O₂ values attainable with good combustion practice. The mass flow is kept constant over the whole range of the O₂ fluctuation. Due to the correction the actual concentration decreases below and increases above the reference point.

EMISSION STANDARDS FOR SELECTED EUROPEAN COUNTRIES

A listing of the status of air emissions regulations for selected European countries entitled "The Situation in Certain Member States" as it appears in the "Explanatory Memorandum on Integrated Pollution Prevention and Control" (IPC) section of the European Union is included as Appendix 1 to this paper. Appendix 1 provides an interesting analysis of the status of and the philosophy for environmental regulations for each of the selected countries.

In Germany, environmental regulations have taken a three pronged approach to the waste management problem.

First, they have significantly enhanced their recycling efforts by enacting laws such as the "Green Dot" law which requires increased recycling while concurrently forcing reductions in packaging materials usage.

Second, they have enacted very strict regulations governing air emissions and fly ash disposal which are covered in this paper. The consequence of this regulatory severity has been to raise the range of cost for waste disposal to the range of DM 300 - DM 400/tonne (\$180 - \$240/ton). All the bottom ash is currently being recycled or reused in Germany and fly ash is disposed of as a hazardous waste. Presently, there is very little ash recycling or reuse in the U.S. due to poor economics and the uncertain regulatory outlook.

Third, the German government has virtually banned the future use of landfills for MSW disposal. Further, Germany and the EU has banned the exporting of waste to other countries and Germany has greatly limited the flow of waste even from one German state to another. These policies have effectively made waste disposal via recycling and MWCs the only viable game in town. Competition with "cheap" landfills has been eliminated due to their restrictive laws governing landfills i.e. starting in 2005, no material with an organic carbon content (TOC) of $\geq 5\%$ can be landfilled anymore.

Table 4 compares selected European emission guidelines for waste incineration including the German, Austrian, Swedish, and Dutch standards with the draft guideline for the European Union for large mass burn units. It is noteworthy that all the standards included in Table 4 are applicable to all waste incineration except for the draft guidelines for the European Union. Table 6 lists the promulgated emission standards for hazardous waste incinerators of the European Union together with the German and Dutch standards. A review of these tables reveals that they vary widely on the basis of both averaging times as well as in the quantitative emission limits although the measurement units are consistently expressed in mg/Nm³ corrected to 11% O₂. Oftentimes, this variation of averaging time in the basis of the regulations results in difficulty when attempting a direct comparison of one standard to another. To illustrate, a comparison of averaging times for each country is presented as follows.

● Federal Republic of Germany	24-hour average & maximum ½-hour
● Austria	daily mean
● Sweden	monthly mean
● Netherlands	maximum 1-hour mean
● Draft European Directive	½-hour mean & 24-hour maximum

As a result of the above differences, it is not at all clear, for example, if the Netherlands' one-hour mean standard for HCl of 10 mg/Nm³ which is always corrected to 11% O₂ is more or less restrictive than say the German 24-hour average standard of 10 mg/Nm³ which is only corrected to 11% O₂ if the actual O₂ value exceeds 11%. Of course, as the informational data base is expanded over time, the problems associated with the disparity in the regulations will be ameliorated.

In the meantime, what is clear for the foreseeable future is that the European Community, driven largely by the German and Dutch regulations, will require maximum reductions in pollutant emissions together with concurrently high levels of sophistication of air pollution control technology to achieve their regulatory standards. The obvious result of this European regulatory philosophy is the allocation of unlimited economic resources to the application of technology to control air pollution at MWCs.

In the U.S., however, EPA's philosophy is, and will be for the foreseeable future, to have technology represent what is economically practicable and reasonable to the affected community to control air pollution. A new or proposed facility, in order to be constructed, is required to address the concerns of human health by means of a health risk assessment during the siting and permitting process. To this end, the health risk assessment is used to establish the level of technology required by the facility to mitigate the air pollution.

OTHER EMISSION STANDARDS WORLDWIDE

Table 5 is a listing of other standards and guidelines in effect for other selected countries around the world. Although not as comprehensive as those presented in Table 4, they further illustrate the range of values deemed appropriate by the environmental regulators of these nations at this point in time.

CONCLUSION

Although emission standards for MWCs in Europe and in the U.S. are intended to reduce and control air pollution, the similarity seems to end at this point. To the extent that the standards are similar it is in that the standards of both seek to control emission levels for particulate matter (PM), heavy metals (such as cadmium, lead, and mercury), carbon monoxide, nitrogen oxides, acid gases (sulfur dioxide, hydrogen chloride) and dioxins/furans. Differences are evident in the structure and philosophical approach to the regulation of air emissions from MWCs in Europe and in the U.S. Structurally, these differences include reference points for the emissions (i.e. to 7% O₂ in the U.S. vs. 11% in Europe), averaging times (generally based on a country in Europe and on a pollutant in the U.S.), sampling methods, and technology. Philosophically, the U.S. EPA's approach is to balance the economics of the MWC and health benefits of the country. The European approach is to control pollution to the lowest value possible which is technologically achievable regardless of economic or other considerations.

The German standards, however, are more comprehensive compared to those adopted in this country. The German standards cover all waste management facilities regardless of whether they are new or existing, their size, the type of waste processed, the type of combustion technology used (e.g. fluid bed, rotary kiln) or the type of front-end waste processing (RDF). By contrast in the US, the regulations provide different limitations for the type of waste processed, for new or existing units, unit sizes, the type of combustion technology used (e.g. fluid bed, rotary kiln) and for the type of front-end waste processing (RDF).

Comparison of data between European standards and results with those of the US cannot be accomplished without knowing the flue gas oxygen value which is often not reported⁸. German emission results, for example, cannot be converted to 7% O₂ and U.S. measurement units unless the actual flue gas O₂ is provided. U.S. results on the other hand can readily be converted to German units without difficulty. It would be an improvement to the information transfer process if a common basis for reporting results could be developed.

However, the review of all the environmental regulations covered indicates the diversity of approach to air emissions regulations across the globe. This regulatory diversity reflects the traditions, the environmental and economic priorities, and the regulatory mind-set of each country and should not be viewed in terms like better or worse, or right or wrong.

The authors have presented comparisons of the most recent emission standards as promulgated by the U.S. EPA, the European Community, and several major European countries to provide the reader with a capsule understanding of the similarities, the differences, and some pitfalls to the gathering of data and information which presently exist among them.

⁽⁸⁾ as well as the particular reference point (temperature, pressure) and the averaging time, which are generally reported.

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Table 1. U.S. EPA emission standards⁽¹⁾ for MWCs as of 12/95.

Pollutant	Units	Emission Limits @ 7% O ₂			
		Existing MWC Facilities		New MWC Facilities	
		>38 T/D	>250 T/D	>38 T/D	>250 T/D
PM	mg/dscm (gr/dscf)	70 (0.03)	27 (0.012)	24 (0.010)	24 (0.010)
Opacity	6 min. avg.	10%	10%	10%	10%
Metal Emissions					
Cd	μg/dscm	100	40	20	20
Pb	μg/dscm	1,600	490	200	200
Hg	μg/dscm or % reduction	80 or 85%	80 or 85%	80 or 85%	80 or 85%
CO	ppmv	100	100	100	100
NO _x	ppmv	no limit	200 ⁽²⁾	no limit	150 ⁽³⁾
SO ₂	ppmv or % reduction	80 or 50%	31 or 75%	30 or 80%	30 or 80%
HCl	ppmv or % reduction	250 or 50%	31 or 95%	25 or 95%	25 or 95%
Dioxins/Furans	ng/dscm mass	125	60 (ESP) 30 (FF)	13	13 ⁽⁴⁾

(1) Subject to change pending results of the Davis County case

(2) Can use off-site credits or "Bubbling".

(3) For the first year of operation, the NO_x limit is 180 ppmv; then 150 ppmv thereafter.

(4) For the first 3 years of operation, the Dioxin/Furan limit is 30 ng/dscm; then 13 ng/dscm thereafter

Table 2. U.S. EPA emission standards⁽¹⁾ for MWCs as of 12/95 (European equivalents).

Pollutant	Units	Emission Limits ⁽¹⁾ @ 11% O ₂ & 0°C			
		Existing Units		New Units	
		>35 Tm/D	>225 Tm/D	>35 Tm/D	>225 Tm/D
PM	mg/Nm ³	53.5	20.6	18.3	18.3
Opacity	6 min. avg.	10%	10%	10%	10%
Metal Emissions					
Cd	μg/Nm ³	76.4	30.6	15.3	15.3
Pb	μg/Nm ³	1,223	374	153	153
Hg	μg/Nm ³ or % reduction	61.1 or 85%	61.1 or 85%	61.1 or 85%	61.1 or 85%
CO	mg/Nm ³	89	89	89	89
NO _x	mg/Nm ³	N/A	292 ⁽²⁾	N/A	219
SO ₂	mg/Nm ³ or % reduction	162.6 or 50%	63 or 75%	61 or 80%	61 or 80%
HCl	mg/Nm ³ or % reduction	280 or 50%	34.7 or 95%	28 or 95%	28 or 95%
Dioxin/Furan ⁽³⁾	ng ITEQ/Nm ³	≈2.0	≈1 (ESP) ≈0.5 (FF)	≈0.2	≈0.2

(1) All emission data based on mass burn water wall technology

(2) Can use off-site credits or "Bubbling".

(3) EPA dioxin standards are on a mass basis. There is no direct correlation to ITEQs and only an approximate conversion can be made with a ±50% error.

Table 3. Comparison of German and U.S. EPA standards for MWCs ⁽¹⁾.

Pollutant		Germany Bundesgesetzblatt -1990 All Sized Units		U.S. EPA Promulgated 12/95 New Large Units
SO ₂	mg/Nm ³	200	50	61 or
	% reduction	N/A	N/A	80%
	Avg. time-hrs.	0.5	24	24
HCl	mg/Nm ³	60	10	28 or
	% reduction	N/A	N/A	95%
	Avg. time-hrs.	0.5	24	24
PM	mg/Nm ³	30	10	18.3
	Avg. time-hrs.	0.5	24	-
Cd	mg/Nm ³	Included in Class I	0.05	0.0153
	Avg. time-hours	Metals ⁽²⁾	(>½ hr & <2 hr)	-
Pb	mg/Nm ³	Included in Class	0.5	0.153
	Avg. time-hours	III Metals ⁽²⁾	(>½ hr & <2 hr)	-
Hg	mg/Nm ³	Included in Class	0.05	0.061 or
	% reduction	II Metals ⁽²⁾	N/A	85%
	Avg. time-hours.	-	(>½ hr & <2 hr)	-
Dioxin Furan ⁽³⁾				
	ng ITEQ/Nm ³	-	0.1 ⁽⁴⁾	≈0.2 ⁽⁵⁾
	ng/Nm ³ mass	-	N/A	13
	Avg. time - minutes	-	>500 m & <960 m	-
NOx	mg/Nm ³	400	200	219
	Avg. time-hrs.	0.5	24	24
CO	mg/Nm ³	100	50	89
	Avg. time-hrs.	1	24	4

(1) All emission data based on mass burn water wall technology

(2) Class I Heavy Metals: Cd & Tl

Class II Heavy Metals: Hg

Class III Heavy Metals: As, Co, Cr, Cu, Mn, Ni, Pb, Sb, Sn, & V

(3) Germany requires a minimum combustion zone temperature of 850°C for 2 seconds.

(4) U.S. EPA dioxin standards are on a mass basis. There is no direct correlation to ITEQs and only an approximate conversion can be made with a ± error.

(5) U.S. EPA requires control of temperature at APC system.

Table 4. Waste incineration emission guidelines for some European countries (mg/Nm³ dry at 11% O₂).

Basis	German 17th BImSchV 11/90	Austria LKR-K 15.07. 1988	Sweden	Netherlands BLA 1993	Draft EU Directive for MWC Facilities
Measurement	Corrected only when >11% O ₂	daily mean	monthly mean	All Waste Plants Corrected at All Times max. 1 hr. mean	Corrected only when >11% O ₂
	24 hr. avg	max. ½ hr.			24-hour
					½-hour
HCl	10	15	100	10	5
SO (SO ₂ + SO ₃)	50	100	-	40	25
HF	1	0.7	-	1	1
NOx (NO ₂)	200	100	-	70	-
CO (always corrected)	50	100	-	(Boiler) 50	50
C (organic)	10	20	-	10	10
Particulate	10	25	20	(8 hr. avg.) 5	5
Heavy Metals					
Class I	Cd + Tl $\sum$ = 0.05 (>½ hr & <2 hr)	Hg = 0.05 Cd = 0.05	Hg = 0.6 max 0.3 aim	Hg = 0.05 (8 hr. avg.)	Cd + Tl = 0.05
Class II	Hg = 0.05 (>½ hr & <2 hr)			Cd = 0.05 (8 hr. avg.)	Hg = 0.05
Class III	Sb,As,Pb,Co,Cr,Cu, Mn,V,Sn,Ni $\sum$ = 0.5 (>½ hr & <2 hr)	As,Co,Ni $\sum$ = 1 Pb, Zn, Cr $\sum$ = 4		Sb,As,Pb,Co,Cr,Cu,Mn, V,Sn,Ni,Te,Se $\sum$ = 1 (8 hr. avg.)	Sb,As,Pb,Co,Cr,Cu, Mn,V,Sn,Ni $\sum$ = 0.5 (>.5 hr.)
PCDD/PCDF (ng/Nm ³)	0.1 ITEQ (>500 min & <960 min)	0.1 ITEQ	0.5 -2.0 Stndrd 0.1 ITEQ aim	0.1 ITEQ (8 hr. avg.)	0.1 ITEQ Recommended
C o m b u s t i o n Temperature	850°C >2 sec. for MSW and MWI >6% O ₂ ; 1200°C >2 sec. for Sludge >6% O ₂			850°C at >6%O ₂ >2 sec.	850°C at >6%O ₂ >2 sec.

Table 5. Waste incineration emission guidelines for other selected countries (mg/Nm³ dry at 11% O₂).

Basis	Denmark 1991 Standards	Switzerland 1992 Standards >350 kw	England 1990 Standards	Japan	Taiwan
Measurement	daily mean				
HCl	65	20	30	700 ⁽¹⁾	50
SO ₂	300	50	300	-	100
HF	2	2	2	-	2
NO _x (NO ₂)	-	80	350	514	370
CO	100	50	-	63	-
C (organic)	20	20	-	-	-
Particulate	40	10	30	20	10
Ammonia (NH ₃)	-	5	-	-	-
Heavy Metals					
Hg	Hg + Cd Σ = 0.2	0.1	0.1	-	-
Cd	Hg + Cd Σ = 0.2	0.1	0.1	-	-
Other Metals					
Pb	1	Pb + Zn Σ = 0.2	-	-	-
Ni + As	Σ = 1	-	-	-	-
Pb + Cr + Cu + Mn	Σ = 5	-	-	-	-
PCDD/PCDF (ng ITEQ/Nm ³)	Recommended Value = 0.1	Recommended Value = 0.1	0.1	0.5 ⁽²⁾	-
Combustion Temperature	800°C at >6%O ₂ ; >2 sec.				

(1) Dependent on area & stack height

(2) Guideline only

Table 6. HWI emission guidelines for some European countries (mg/Nm³ dry at 11% O₂).

Basis Measurement	German 17th BImSchV 11/90		Netherlands BLA 1993	EU Directive	
	Corrected only when >11% O ₂		Corrected at All Times	Corrected only when >11% O ₂	
	24 hr. avg	max.½ hr.	max. 1 hr. mean	max.½ hr.	24 hr. Max
HCl	10	60	10	10	5
SO (SO ₂ + SO ₃)	50	200	40	50	25
HF	1	4	1	2	1
NOx (NO ₂)	200	400	70	-	-
CO	50	(hr.) 100	(Boiler) 50	-	50
C (organic) .	10	20	10	10	5
Particulate	10	30	(8 hr. avg.) 5	10	5
Heavy Metals					
Class I	Cd + Tl $\sum$ = 0.05 (>½ hr & <2 hr)		Hg = 0.05 (8 hr. avg.)	Cd + Tl $\sum$ = 0.05 (>.5 hr.)	
Class II	Hg = 0.05 (>½ hr & <2 hr)		Cd = 0.05 (8 hr. avg.)	Hg = 0.05 (>.5 hr.)	
Class III	Sb,As,Pb,Co,Cr,Cu, Mn,V,Sn,Ni $\sum$ = 0.5 (>½ hr & <2 hr)		Sb,As,Pb,Co,Cr,Cu,Mn,V Sn,Ni,Te, Se $\sum$ = 1.0 (8 hr. avg.)	Sb,As,Pb,Co,Cr,Cu, Mn,V,Sn,Ni $\sum$ = 0.5 (>.5 hr.)	
PCDD/PCDF (ng/Nm ³)	0.1 ITEQ (>500 min & <960 min)		0.1 ITEQ (8 hr. avg.)	0.1 ITEQ ⁽¹⁾ (8 hr. avg.)	
Combustion Temperature	1200°C >2 sec.		850°C at >6%O ₂ >2 sec.	850°C at >6%O ₂ >2 sec.	

(1) Guideline only.

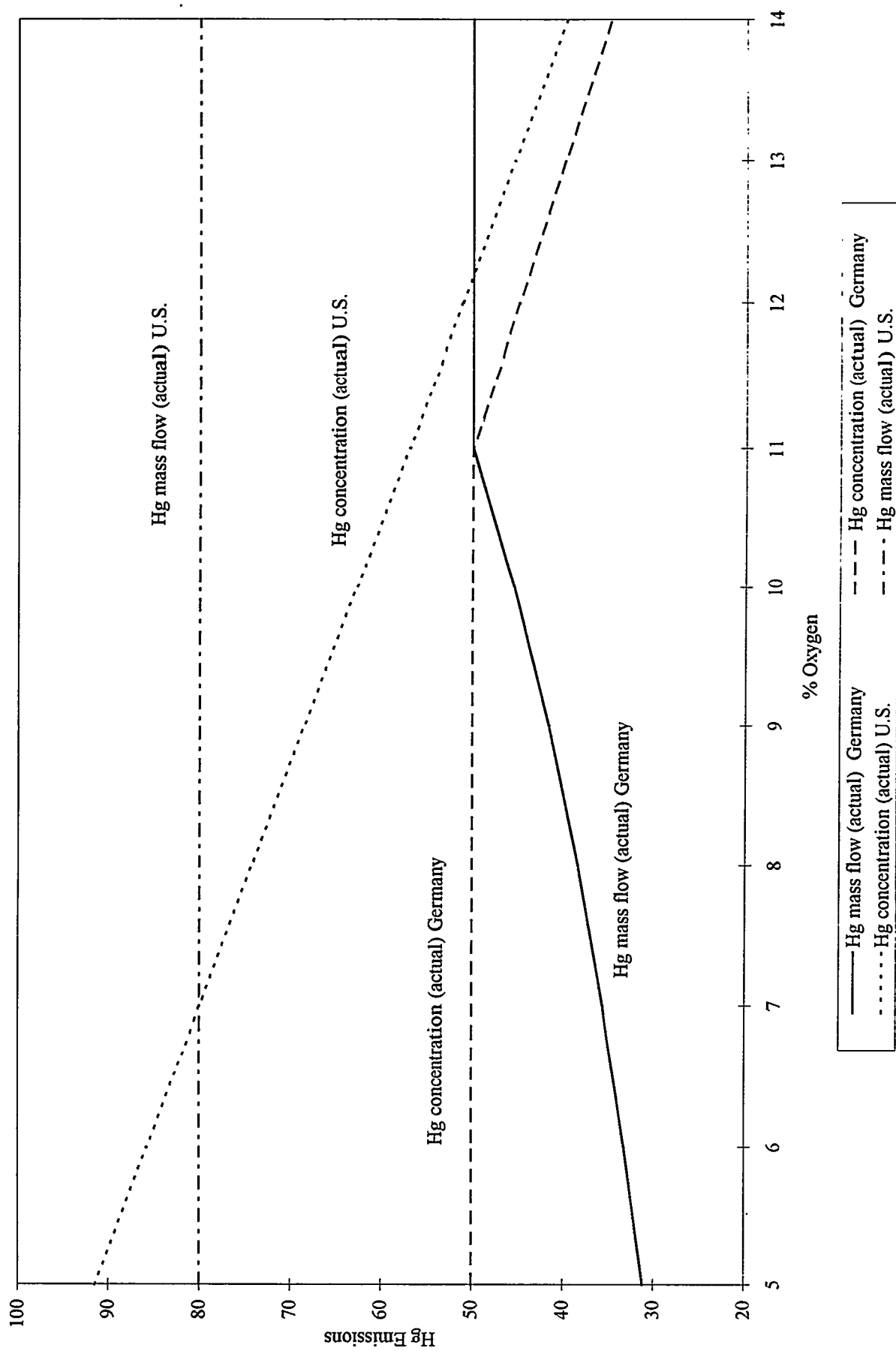


Figure 1. Comparison of Hg emissions legislation U.S. vs Germany

Appendix 1
THE SITUATION IN CERTAIN MEMBER STATES
(November 30, 1992)

Belgium

In Flanders the 'Milieu-Natuurlijk Plan' of January 1989 contained a chapter on an integrated environment and nature management and in 1991 a law was passed by which the previous "exploitation permit" was replaced by a more integrated one covering emissions to the environment.

Denmark

Denmark has had a system of integrated pollution control since 1974. It was revised most recently in 1991. The purpose of the Act is to ensure a sustainable social development in respect of human conditions of life and for the protection of flora and fauna. The objectives of the 1991 Act include the prevention and combating pollution of air, water and land; the nuisances resulting from vibration and noise; the reduction of use and wastage of raw materials and other resources; and the promotion of recycling and the reduction of problems in connection with waste disposal. In the administration of the Act, weight is given to results achievable by using the "least polluting technology". In the design and operation of the plant, including choice of production processes, raw materials and auxiliary substances, measures shall be taken to minimize the use of resources, pollution, and generation of waste. When determining the extent and nature of measures to prevent pollution, consideration is given to the nature of the physical surroundings, and the likely impact of pollution on those surroundings and the whole cycle of substances and materials, with a view to minimizing wastage of resources.

Germany

Pollution control in the Federal Republic of Germany has traditionally been media oriented. Most laws and regulations still focus on one environmental medium only. Beginning in the mid-eighties, however, some elements of integrated pollution control have been introduced into German legislation and emphasis is continuing to be placed on integrated environmental technologies (and therefore integrated environmental regulations). Cooperation among different competent authorities already takes place in the context of the Federal Air Quality Control Act (BImSchG); most authorities do not issue a separate license but their viewpoint is consolidated in the BImSchG license. However, water related activities require a separate license according to the Water Management Act.

France

An integrated approach to pollution control has been taken in France since 1810. The most recent legislation was the law on "Registered Installations for the Protection of the Environment" of 1976. Installations which present the greatest problems or risks must receive a prior authorization given by the préfet. However, in order to avoid considerable distortions in the implementation of the regulations, the Ministry of the Environment distributes notices containing technical prescriptions. Pollution is controlled by a "parallel approach" - that is, a technical/economic approach which consists of using the best available anti-pollution techniques (not entailing excessive costs) to control pollution as a whole from the installation **and** by ensuring that pollution which does occur does not entail irremediable repercussions or damage to the environment (a quality target approach). Classified installations are inspected not by the préfet but by a

separate inspection service (DRIRE) which, in fact, is also usually consulted by the operator before an application for a permit is made.

Ireland

An Act was passed earlier this year to set up a system of integrated pollution control to be operated by a new Environmental Protection Agency. The integrated permit will replace the existing system of separate licenses for control of water pollution, air pollution and waste and will also incorporate noise control. The Agency will be under a duty to operate under five general principles. The most important of those for IPC are to promote sustainable and environmentally sound development, processes or operations to have regard to the need for precaution in relation to the potentially harmful effect of emissions, and the need to ensure a balance between the need to protect the environment and the cost of such protection.

The agency may not grant an integrated license unless it is satisfied that environmental quality standards will be met and that the best available technology (not entailing excessive cost) will be used to prevent, limit or abate any emissions from the activity.

The Netherlands

Pollution control in the Netherlands has traditionally been sectoral. Most laws and regulations focus on one environmental medium alone. In 1980, the Environmental Protection Act came into force laying down the basis for more general provisions concerning, among other things, advisory bodies, planning, and the issuing of permits (such as procedures concerning public access to information). Parliament is currently considering proposals to extend this Act in such a way that it will also serve as a means of implementing an integrated approach. For example, it contains provisions relating to environmental quality requirements, environmental impact assessment, monitoring obligations, licensing and general rules, enforcement and, in particular, coordination procedures such as the bringing together of the Nuisance Act and several provisions of other environmental laws.

Portugal

A new decree covering the authorization of industrial activity was published in 1991. Under the regulation a "coordinating entity" is responsible for the granting of a permit. The regulation also establishes that those authorities with responsibilities relating to the environment have the right to have their conditions and demands to be included in the conditions of any permit. In addition, the coordinating entity may decide, where it thinks it appropriate, to make an authorization dependent upon a license for discharging effluent, which is obtained through a separate licensing procedure.

United Kingdom

The belief that as long as control of the environmental media remained separate then the end result would be a haphazard disposal of pollutants unrelated to an overall assessment of the optimum environmental solution came to be widely held in the 1970s and 1980s. The Environmental Protection Act of 1990 in Great Britain set up a system of integrated pollution control. In setting the conditions within an authorization, the competent authority is under a duty to ensure that certain objectives are met. Most importantly, the act requires best available techniques (not entailing excessive cost) to be used to first of all prevent, and only

when that is not practicable, minimize the release of substance to the environment that releases which do occur are rendered harmless and do not cause the breach of environmental quality requirements and that the "best practicable environmental option" is achieved so that emissions from installations have the least effect on the environment as a whole.

TECHNICAL SESSION IV

Ash Utilization

Planning and Implementing the New York/New Jersey Ash Paving Demonstration

Edith G. Tanenbaum, Ph.D.
Long Island Regional Planning Board
220 Rabro Drive, P.O. Box 6100
Hauppauge, New York 11788-0099

PLANNING AND IMPLEMENTING THE NEW YORK/NEW JERSEY ASH PAVING DEMONSTRATION.

Abstract

The saga of the multi-agency ash demonstration project, while not yet ended, has passed the climactic moment, the installation of the ash amended asphalt paving and a conventional control section on Center Drive, a Port Authority owned roadway in Elizabeth, New Jersey. Environmental and physical monitoring is under way, and the participants are breathing a communal sigh of relief.

It's been a difficult eight years for the members of the Project Management Team (PMT), the ad hoc body created to manage the demonstration on behalf of the participants. Initially strong, but ultimately wavering or even vanishing local political support, forcing the abandonment of the original project site and of a second, even better site on Interstate Route 80, wreaked havoc with the project schedule and added years to the time from initial planning to pavement installation. Personnel and policy changes, especially the New York State Energy Authority's late 1993 decision to withdraw from further active participation and support, also contributed to costly delays.

PMT selection of a new, publicly owned and controlled site, coupled with determination to proceed and a further infusion of funds, brought the effort close to fruition. However, it finally took the intervention of the New Jersey Attorney General to prevent the destruction of the ash stockpile in Warren County and to defeat the City of Elizabeth's attempt to halt the paving project. The ash amended paving was installed during the night of June 19, 1996; the control section, the following night.

Now that the field demonstration has progressed from proposal to reality, it's time to revisit the events of the past eight years and attempt to extract the implementation lessons they offer.

Two major lessons emerge. The first and most important is that failure to anticipate the non-technical impediments to implementation can doom the best designed field demonstration to failure. The second is that achieving and maintaining an ongoing multi-agency supported demonstration requires an extraordinary effort, doggedness and administrative creativity.

A brief account of implementation problems and ultimate solutions is presented in support of the above assertions.

The Long Struggle

I am delighted to have the opportunity to share some of the insights obtained and strategies employed during the struggle now known in my agency as the "ash wars." The wars are not over yet, but the Long Island Regional Planning Board (LIRPB) and its partners have finally scored a major victory. A short stretch of ash amended paving and a comparable control section are now in place on Center Drive in an

industrial park in Elizabeth, New Jersey and monitoring is proceeding as planned.

Long Island's interest in ash goes back close to fifteen years when, legally forced to abandon landfilling by 1990 because of concern for the area's sole source aquifer, municipality after municipality made the decision to avail itself of state financial assistance and to rely on waste-to-energy for the disposal of its ever increasing municipal waste stream. Following an unsuccessful State-sponsored attempt to establish a single ashfill to serve all of Nassau and Suffolk Counties, the New York State Energy Research and Development Authority (the Energy Authority) and the regional office of the State Department of Conservation (NYSDEC) approached the Board with an offer of co-funding for a research and demonstration project to investigate the potential for the beneficial use of MSW combustor residue.

In early 1986, the Board, aided by the two counties, fourteen of the fifteen towns and the two small cities put together the local share of the funding, obtained the services of Chesner Engineering and formulated a two state program for approval of the co-funders and submission to the Energy Authority. Although the proposal was accepted by October, execution of the funding agreement was delayed until the end of March, 1987, because of unacceptable contract language.

Sample collection for physical and chemical characterizations was just getting under way when the Board received the first hint that externalities might affect the R and D effort. Owners or managers at two of the facilities where ash was to be collected expressed reluctance to allow access because of the recently filed Environmental Defense Fund (EDF) legal action. However, when all involved agreed not to divulge the source of the ash, permission to collect the necessary samples was granted. Subsequently, management of a third facility also requested that it not be identified.

In late spring 1988, the New Jersey Department of Transportation (NJDOT), a member of the New Jersey Interagency Engineering Task Force, and the Port Authority of New York and New Jersey (PA), also a member, and owner of the Essex County Resource Recovery Facility then under construction, approached the Planning Board's consultant indicating a possible interest in a joint NJDOT, PA, Energy Authority and LIRPB project to demonstrate the feasibility of using waste-to-energy facility ash in road paving. Following an initial exploratory meeting in Hauppauge, the participants decided to continue discussions and to ask the New Jersey Department of Environmental Protection (NJDEP) to bring its expertise and support to the proposed undertaking.

The Board was delighted with what appeared to be a win/win opportunity. Aware that raising the additional funds and finding a site or sites for the demonstration phase of its program within the bi-county area would be difficult if not impossible, the LIRPB welcomed the chance to participate in an interstate, interagency cooperative undertaking at modest financial and virtually no potential political cost to itself. The Energy Authority viewed the proposed arrangement as further support for its beneficial use initiative and a means of leveraging its already considerable investment.

The Board, its consultant and the Energy Authority took the lead in formulating the project scope and establishing an acceptable management organization. Two problems immediately emerged: the first, designing an acceptable work plan, was well within the technical competence of the group and the consultant; the second, setting up an administrative structure to handle program management and the receipt and disbursement of funds, required a modicum of political and legal creativity.

Today those of us who are or have been involved in the New York/New Jersey ash paving demonstration project feel considerably older and wiser for the experience. An account of the group's eight year

struggle to implement a carefully planned research and development demonstration project provides a cautionary tale, an extreme example of the vicissitudes that can accompany a seemingly non-controversial undertaking.

Very briefly, the paving project is a multi-agency effort to test the engineering and environmental feasibility of the beneficial use of bottom ash from a waste-to-energy facility as a substitute for a portion of the natural aggregate normally used in asphalt paving. It has included the physical and chemical characterization of the combined residue as well as the component ash streams from the Warren County, New Jersey MSW combustor, the first in the Garden State; the construction of a 500 ton bottom ash stockpile and the monitoring of runoff and dust resulting from the outdoor storage and handling of the ash; the preparation and laboratory testing of various ash/aggregate/asphalt paving mixes; the installation of a 700 foot section of ash amended pavement and a conventionally paved 725 foot control section on Center Drive in an Elizabeth, New Jersey industrial park; and the physical and environmental monitoring that commenced in late June of 1996 and continues today. Intensive interagency monitoring is scheduled for a period of two years, after which the New Jersey participants will monitor on a less frequent schedule for up to seven years. Summaries of the engineering and environmental data will be available for general distribution as soon as possible after completion of the first two years of monitoring. Arrangements are in place for removal of the paving in the unlikely event of excessive wear or an unexpected environmental condition that might pose a risk to the public.

Although the demonstration is not yet at an end, it is far enough along to permit a review of problems encountered, obstacles overcome and, most important, lessons learned.

What problem or problems posed threats to the continued viability of the project, imposed additional costs and added two and one half years to the time required to put the demonstration paving in place? In retrospect, it appears that the proponents and their local allies, the Freeholder Director and the Pollution Control Finance Authority of Warren County (PCFAWC) were incredibly naive. There was a price to pay for the failure to anticipate the delays associated with a multi agency undertaking and to recognize the vast gap between perception and reality in environmental matters.

It didn't take the study team long to learn that while development of a comprehensive, technically sophisticated, environmentally vetted research and development program designed to further an innovative solution to a current problem may be sufficient to foster interagency cooperation and assure public funding, it is hardly a guarantee of public acceptance, let alone approval. Thanks in part to the EDF, combustor ash, once the concern of solid waste planners and scientists, had surfaced as a newsworthy environmental issue and the term "toxicash" had replaced the two word description in the media's lexicon.

Start up delays also contributed to the problem since the two year period from initial discussion of the proposal through technical and administrative design to completion and execution of legal documents coincided with increasing public disaffection with combustion as the key to solid waste management, especially when coupled with a reduction in governmental support.

The initial task, formulating a technically acceptable, comprehensive study plan required six drafts before all five participating agencies were in agreement. Cost estimates were prepared and oral commitments for cash and in-kind services obtained. It was necessary to devise an administrative structure, the Project Management Team (PMT), that would permit work to proceed without exposing any single agency to claims for environmental liability. It was agreed that all management actions

would require the unanimous consent of the five agency representatives who constituted the Project Management Team. Others, especially support staff and the project consultant could advise, but final responsibility for technical, administrative and budgetary decisions would rest with the PMT. Since most agencies, especially those with deep pockets, were reluctant to be the first to make a legally binding commitment to the project, the Long Island Regional Planning Board and the New York State Energy Research and Development modified an existing ash research funding agreement to provide for participation in the ash paving project, effective upon the execution of agreements between the Energy Authority and the three other participants. A supplemental memorandum of understanding between the NJDOT and the NJDEP established responsibility for pavement removal and cleanup, if required; and another, assured cooperation between the NJDEP and the Waste Management Institute Laboratory at SUNY Stony Brook, a Long Island Regional Planning Board subcontractor.

The PMT, having already dealt with a mountain of preparatory minutiae and having weathered a change of administration in New Jersey, assumed that once all the documents had been approved and signed, it was simply a matter of proceeding with the tasks as outlined in the work plan. To that end, it established a Technical Working Group (TWG) consisting of knowledgeable staff from the two New Jersey agencies and the Port Authority, the Energy Authority project officer and Warren Chesner, the ash expert and project engineering consultant. Chesner Engineering undertook the tasks of site evaluation and the preparation of detailed plans for various project activities, with the input and/or actual assistance of the other members of the TWG, and the cooperation of the Warren County Engineer.

Work proceeded uneventfully until late March, 1991, when the PMT and the project engineering consultant received a wake up call. Informed by the PCFAWC's ashfill manager of growing local opposition to the use of the PMT's preferred site and to the program itself, the group was invited to listen to a tape recording of constituent complaints and allegations and asked to prepare a defense of the undertaking to be presented at the regular PCFA meeting in April.

The PMT members were taken aback! Suddenly they were forced to defend a project whose value and built-in environmental safety had seemed beyond question. Ill-prepared to deal with the emotionally charged allegations of a small but noisy group of Hackettstown residents and allied anti-combustion activists, the PMT attempted to provide the PCFAWC, Freeholders, Mayor and Council in Hackettstown and any others who cared to listen with a factual description of ash, of the project activities completed or to be undertaken, of safety measures provided and of potential fiscal benefits for Warren County.

Between April and the end of June 1992, the PMT's technical experts made numerous presentations and answered countless questions, appearing before the PCFA, the Hackettstown Mayor and Council and Hackettstown residents. The Mayor, stating that he was not opposed to the project, requested funds to support local review of the proposed paving by the Town's engineering consultant and a second review by the consultant to the Hackettstown Municipal Utility Authority (HMUA). The PMT assented; the LIRPB drafted the necessary agreements and forwarded them to Hackettstown.

Meanwhile the activists were busy turning up the heat, including the proposed site in a statewide "toxic tour", organizing a petition drive condemning the ash paving and the arrangements for Town and HMUA review, issuing press releases and circulating a flyer depicting a skull and crossbones and exhorting readers to join the Concerned Residents Against Ash Paving to fight State and County efforts to find a cheap and convenient way to dispose of "toxic ash".

In February 1992, Hackettstown, having decided that it really didn't need any technical evaluation,

enacted a resolution opposing the paving. In March, the HMUA followed suit.

Tired of responding with too little and too late, the PMT decided to take the offensive and scheduled an information session for the press immediately preceding the activists' well advertised baby stroller and poster media event planned for the April 29, 1992 PCFAWC meeting. At that meeting, the project team announced that the demonstration paving would be limited to a single segment containing a small percentage of bottom ash rather than two segments, one containing bottom ash and one containing combined ash. Still not satisfied, the opponents threatened civil disobedience, litigation and reprisals at the polls if they didn't get their way. The press, in an unusual display of evenhandedness, observed that the noisy attendees included a large number of outsiders, many of whom didn't even know what public entity was hosting the meeting.

Reluctant to appear unresponsive to legitimate local concerns, the project participants agreed to make one last effort to explain the proposed demonstration to an orderly meeting of Hackettstown officials and other residents. Soon thereafter, the Democratic Mayor found an ally in the Republican Speaker of the Assembly, Chuck Haytaian, a resident of a neighboring town. Haytaian, acting at the Mayor's request, contacted the Deputy Commissioner of NJDEP and the Director of the Division of Solid Waste. The message to the PMT was a clear, "Find another site, perhaps Interstate 80."

Considering that the environs of Route 80 in Warren County were home to far more deer than voters and that the NJDOT was planning to resurface the paving in that area in 1993, Route 80 seemed like a promising alternative. The PCFAWC had approved the arrangements for stockpile construction at the ashfill and, at the PMT's request, the engineering consultant and the TWG undertook the evaluation of several new potential sites, including Route 80.

Not content with a victory in the Hackettstown, the critics continued their barrage of allegations, personal attacks and demands -- for more information, for a citizens' advisory panel and a citizen supported laboratory to conduct reviews -- and to press for enactment of town resolutions prohibiting the use of ash on any local roads.

In an effort to seize the offensive, to be proactive rather than reactive, the PMT, with the assistance of the Freeholder Director and Chairman of the PCFAWC scheduled a mid-September information meeting at the Warren Hills High School. Although the session was poorly attended, the usual anti-combustion die-hards were there.

In January, 1993, the PMT formally approved and notified Warren County and the Town of Allamuchy officials of the selection of the Interstate 80 site. The Hackettstown opponents immediately refocused their efforts and rushed to the aid of the Allamuchy residents. Once again, they stepped up the attack with a flurry of letters to the editor; statements warning of imminent danger, especially to children; demands for further delay or immediate abandonment; promises of litigation; and election year maneuvering.

The Town of Allamuchy, having already acted at the behest of its environmental council, was on record as opposing the use of ash on any site. With the Route 80 paving scheduled for the fall, a new spokesperson affiliated with the local school administration came forward to lead the fight, insisting on a meeting with the New Jersey members of the PMT and technical personnel and requesting even more information, which was subsequently provided. It didn't matter. Facts and reason had become irrelevant!

With the press faithfully reporting every allegation or threat of civil disobedience or ballot box reprisals, the once strong support of the PCFAWC, the Freeholder Director and other elected officials rapidly melted away. In late September, the Freeholders passed a resolution rejecting ash paving on Route 80 and urging abandonment of the project. Counsel for the PCFAWC publicly asserted that the Authority "owned" the ash in the stockpile and could therefore decide whether or not to release it. Next the Freeholder Director and Chairman of the PCFAWC, in a last ditch effort to salvage his political career, joined the chorus requesting postponement of the paving. The NJDOT notified the Freeholders that paving of the Allamuchy section of the Interstate would not occur until the spring of 1994. Meanwhile, by a vote of three to two, the PCFAWC resolved to ban the use of the ash in Warren County but to maintain the integrity of the stockpile pending clarification of legal issues.

In October, Assembly Speaker Haytaian, the Republican Party Chairman, anxious to ensure the election of Governor Whitman, turned down a PMT request for support the demonstration project. In so doing, he rejected a project undertaken pursuant to a New Jersey law that he had co-authored and on a site he had selected. Reluctantly, the PMT voted to abandon Route 80 and look for a third site, this time on property owned and controlled by the Port Authority. Meanwhile, the Energy Authority, under the management of a newly appointed chairman who had no use for waste-to-energy or for New Jersey, was rapidly losing interest in the project. This became clear at the October 5, 1993 PMT meeting when the Energy Authority member indicated that he could not agree to the language of the resolution abandoning the Route 80 site nor to the resolution relating to the identification of alternate sites. At the meeting he did approve the resolution requesting that the PCFAWC preserve the stockpile and two days later signed an Energy Authority amended version of the resolution abandoning Route 80.

A weakened PMT now faced a decision whether to cut its losses and close down the project, limiting further efforts to the preparation of a brief stockpile monitoring report and tabular presentations of the raw environmental and engineering test data; whether to close down the project but provide a more extensive set of reports, including several assessment reports; or whether to attempt to proceed with the field demonstration, including the necessary planning, design and environmental assessments and final reports.

Four of the five PMT members were not yet ready to give up. Technical staff from the NJDOT and NJDEP and the engineering consultant joined the Port Authority PMT member in a tour of potential sites. The NJDOT representative agreed to discuss interagency working arrangements with the Port Authority and the NJDEP representative agreed to initiate discussions with the Chairman of the PCFAWC to see what, if anything, could be done to ensure the continued availability of the stockpiled ash and thus avoid the need to obtain, characterize and stockpile a comparable supply of bottom ash from the Essex Waste-to-Energy Facility. The DOT and the DEP pledged continued in-kind support and, in order to conserve project resources, the PMT decided to discontinue the stockpile monitoring at the end of one year (December 31, 1993) and cover the stockpile.

While the PMT and the TWG were attempting to regroup and to organize a last effort to complete the demonstration project in which they had already invested so much time and money, the environmental activists kept up their local media blitz with accusations of official shortcomings and governmental failure to respond to requests for "critical information" or to provide "guarantees". They continued to press their demand that the PCFAWC destroy the stockpile.

The PCFAWC, divided on the issue and unsure of the ownership of the ash, was looking for a way to end the attacks, make certain it could retain the PMT provided stockpile weather station and get on with

its normal activities; the PMT needed assurance that the stockpile would be preserved. A series of discussions between the PCFAWC's attorney and Deputy Attorney General, Dale Lessne representing the PMT, finally culminated in a Draft Ash Agreement that declared the PMT owner of the ash and responsible for any future liability related thereto. In return, the PCFAWC agreed to release the ash to the PMT upon request and to dispose of any ash that was not needed for the demonstration.

With the stockpile dilemma apparently about to be resolved, the PMT faced a new problem, the reluctance of the Energy Authority to continue its involvement in the project. The NJDOT and the Port Authority noted their willingness to commit additional resources and to move ahead at a new site. All parties agreed that maintaining Energy Authority involvement was critical and asked the LIRPB to draft a letter from the PMT to Frank Murray, the Chairman of the Energy Authority, requesting the agency's continued participation. Months passed without any response to that letter, to a subsequent communication from the PMT or to numerous letters of support from local and New York State officials stressing the importance and value of the demonstration.

By April, it was clear that paving in 1994 was no longer feasible and, that unless the PMT could reach a "go" or "no go" decision by early May, the 1995 season could be lost as well. Noting that establishment of a new administrative structure to allow the group to act without the Energy Authority would be difficult and time consuming, the PMT decided to appeal to Frank Murray once again and to defer consideration of closing down the project until the next PMT meeting.

Meanwhile, the Department of Energy's National Renewable Energy Laboratory demonstrated its support by agreeing to provide approximately \$50,000 to help defray the cost of an Ash Stockpile Monitoring Report, thus assuring documentation and evaluation of ash storage and handling activities.

The absence of the Energy Authority's PMT member at the May meeting meant that no official business could be transacted. However, those present agreed that the LIRPB and its attorney would assist the Deputy Attorney General in preparing one final letter to Frank Murray, this time indicating that the Energy Authority's lack of response to PMT communications constituted a de facto abandonment of the project and that in the event of a failure to respond by a specific date all contracts with the New Jersey agencies, the Port Authority and the LIRPB would be considered void. The group also decided that the letter should request the release of the remaining project funds so that the LIRPB and its consultant could apply them to the completion of the expanded stockpile report. Finally, the remaining PMT members determined that they wished to continue the demonstration and agreed to investigate arrangements for a new contract administrator and potential sources of funding.

By late July, the DOT and the Port Authority had come up with an excellent site and sufficient commitments of cash and in-kind services to allow the PMT to proceed, provided the latter could bypass the administrative problems created by the Energy Authority's non-participation. An early August visit to senior Energy Authority management and presentation of a long list of reasons why its continued participation could prove mutually advantageous, even if limited to administrative matters such as interagency contractual relations and the receipt and disbursement of funds, enabled the LIRPB representative to secure the Energy Authority's agreement to continue to provide administrative assistance in a "low profile" or reduced role.

At the next PMT meeting all five agencies were represented, including the PMT member and additional staff from the Energy Authority, who joined in a comprehensive and productive discussion of the proposed site, funding and in-kind service commitments, consultant costs, contract modification

procedures and the need to adhere to an extremely tight schedule if paving was to occur in 1995. The schedule, like many before it, was overly optimistic given the number of participants and the complexity of agency funding and management procedures. Preparation of a revised work plan and consultant budget took longer than anticipated; however, by early November the PMT was able to agree on a revised plan and a consultant services budget that conformed to the requirements of the Port Authority.

In November, Tom Fiesinger announced that, due to a readjustment of priorities, manpower and budgetary resources at the Energy Authority, he could no longer serve as Chair of the PMT or participate in day to day activities. The PMT accepted Tom's resignation with regret.

With financial and administrative matters apparently under control and planning for retesting the now somewhat aged stockpile under way, the PMT again focused on the proposed agreement with the PCFAWC respecting ownership and release of the ash. Noting that it would like the agreement to include language allowing the return of any unused ash and of excess ash/asphalt product, the group asked the engineering consultant to contact the PCFAWC landfill manager to discuss the proposed additions to the draft agreement.

A pre-PMT meeting conference between Ken Afferton representing the NJDOT, Deputy Attorney General Dale Lessne, Warren Chesner and Bart Carhart of the PCFAWC produced a revised draft that was subsequently distributed to those attending the PMT meeting. A newly assigned Port Authority attorney raised numerous questions, requested changes in wording and asked for time to submit additional comments. It was agreed that copies of the final language, including all changes, would be sent to the Port Authority and to the PMT members for further comment, if any, by February 2, 1995. The draft would then be transmitted to the PCFAWC attorney and, if possible, presented for approval at the March 1, 1995 PCFAWC meeting.

Progress reports and discussions of the design and implementation of construction and monitoring occupied the PMT as the Port Authority moved slowly toward official approval and commitment of funds for the project. However, during the winter several members of the PMT and the support staff began to express increasing unease and frustration over what, at best, could be assumed to be confusion associated with an unusual assignment; at worst, deliberate foot dragging. Port Authority demands for elimination of certain items from the budget, for completion of new TCLP tests establishing the ash as nonhazardous, for obtaining an agreement from the PCFAWC guaranteeing access to the ash and for obtaining commitments from asphalt producers -- all before asking the Commissioners for formal approval of the demonstration project -- suggested something more than standard bureaucratic management procedures. As the PMT attempted to come to terms with the Port Authority approval process and with the mixed signals already emanating from the Port Authority, it received welcome assistance from the State of New Jersey. In a move to shore up any flagging enthusiasm and to avert further complications, the Commissioners of the NJDEP and the NJDOT informed the bi-state Port Authority of their interest in and strong support for the paving demonstration.

By early April the Commissioners of the Port Authority had formally approved the undertaking, the PCFAWC had voted to execute the proposed agreement, the stockpiled ash had tested nonhazardous, the DEP expected to issue a Certificate of Authority to Operate (the New Jersey equivalent of an R and D permit) and the precise wording of the Port Authority bid documents was under discussion. The engineering consultant informed the PMT that the draft environmental assessment would be completed by the end of May and suggested a target date of May 22, 1995 for publication of the request for bids.

On April 5, 1995, the relative calm was shattered. Environmental activists monitoring the PCFAWC meeting at which the Authority approved the agreement with the PMT learned that the demonstration project was going to be implemented on a third site, Center Drive, in Elizabeth. Quick to report on a potential controversy, the press interviewed the usual opponents, printed uninformed and inflammatory quotes from the usual sources, including one calling attention to the "danger to children living at the site". Six days later, the Mayor of Elizabeth joined the fray, complaining about not being informed, demanding all test results, reports and studies, generally parroting the allegations of the perennial foes and threatening "appropriate action". Although briefly noting that the Port Authority had offered to sit down and discuss the project with the Mayor, press coverage focused on the comments of a new set of opponents from Union County and the City of Elizabeth, who described the ash as "absolutely toxic" and accused the NJDEP of "tinkering" with its own standards so the demonstration could proceed.

In May, the Concerned Citizens of Union County, together with their Warren and Morris County allies and members of the clergy organized their first paving project media event, a march and protest in front of the Union County Court House. The featured speaker, a Concerned Citizen of Morris County, discussed the topic, "How and Why the Project Was Defeated in Warren County."

On June 26, 1995, the Port Authority advertised for bids but soon found it necessary to delay the release of bid documents pending a design revision to meet federal requirements and its incorporation in an addendum. At about the same time, Port Authority personnel and the LIRPB's consultant noted that the design group had overlooked several major items when developing an estimate of project costs, and that bids could be significantly higher than expected. Faced with pressure to complete the paving of Center Drive, opposition from the environmental activists and Elizabeth elected officials and, now, an apparent escalation of estimated project costs, the Port Authority official in charge of the demonstration agreed to allow the project to proceed to the receipt of bids, but indicated that if they came in too high, as he expected they would, the Port Authority would reject them. Noting that he expected a shortfall of \$300,000 or more, he stated that, "then the PMT will have to decide if the project is too expensive".

Once again, the viability of the undertaking was in doubt. Whether the cause was an agency structure that limited effective coordination and control or the manifestation of a hidden agenda, the demonstration was clearly at risk. The bid opening on August 8, 1995 confirmed the PMT's worst fears. All five bidders came in well above the Port Authority's estimate.

Clearly the situation called for PMT discussion and high level intervention. When the LIRPB member was unable to reach her DEP counterpart, the former shared her concerns with the latter's secretary, who had the good judgement to ask whether the Commissioner should be apprised of the likelihood of unilateral Port Authority action that could end the demonstration project. The response was a grateful "yes" and, within a matter of days, the Port Authority announced its intention to attempt to negotiate with the low bidder.

The first of two well attended negotiating sessions took place August 29th; the second, September 7th. At the second session, the Deputy Director of the NJDOT forced the Port Authority's hand by agreeing to provide an additional \$100,000 to help defray the higher than anticipated costs. Two meetings, with PMT members and others in attendance, and a \$100,000 contribution encouraged a Port Authority and the low bidder to narrow the distance between them. One on one negotiations between the Port Authority official and the contractor enabled them to reach a final agreement. The contract for the installation of the paving and the monitoring equipment was finally executed in mid October.

As early as August, the engineering consultant warned that, even if the Port Authority obtained a satisfactory bid, the fall paving might have to be postponed because of the time required for necessary preliminary work, for purchase and testing of Center Drive monitoring equipment and for completion of the asphalt production plant monitoring arrangements. During the October PMT meeting at which the PMT formally authorized the Port Authority to proceed with the project as set forth in its contract authorization letter to the low bidder, the DOT representative specifically requested that Warren Chesner, the engineering consultant assist the Port Authority staff in coordinating and implementing all project activities.

At the behest of the PMT, the consultant contacted the PCFAWC ashfill manager to discuss possible arrangements for the transport of excess ash and left over ash amended asphalt to the Warren County facility. A week later the PMT had the first draft of a letter agreement and, by mid November, a final version was circulated for signature. By Thanksgiving, all permits and authorizations were in place, the road base was prepared and the contractor was still planning to complete the paving and installation of the monitoring devices before the asphalt plant shut down for the winter.

Once again, Murphy's Law prevailed. Rain, snow and abnormally cold temperatures forced the seasonal closure of the asphalt plant; work on the partially finished Center Drive would have to wait until Spring.

By early December, project foes learned that the contractor was behind schedule and that the PCFAWC had agreed to allow the PMT to return excess ash and to use excess paving mix for the construction of a pad for recycling equipment at the ashfill. Believing that the paving would occur during the week of December 11th, they mounted an all out effort to stop the demonstration once and for all.

The press had a field day as the activists increased the volume, frequency and inflammatory nature of their allegations and castigated the PCFAWC and its ashfill manager for participating in the project. The activists' Freeholder allies considered suing the PCFAWC to prevent the return of leftover ash and ash amended asphalt. While the County Attorney conferred with the PCFAWC Attorney and with the PMT in the hope of heading off an embarrassing law suit, the activists organized another Union County protest.

By the mid-December Freeholder meeting, the PMT and the County Attorney had agreed that there would be no shipment of ash amended asphalt to Warren County and that Warren County would not interfere with the paving in Elizabeth. In an effort to placate their local activist constituency, the Freeholders again passed a resolution opposing the demonstration and petitioning the New Jersey agencies to abandon the project and request the PCFAWC to landfill the ash stockpile.

In January project opponents, along with additional recruits from among the clergy, again focused their energies on Elizabeth, staging a candlelight vigil to protest the paving just before the City Council was to vote to adopt a resolution opposing the project.

Assured by the Port Authority that it, not the City of Elizabeth had authority over Center Drive, the PMT ignored the City Council's threatened passage of a local law prohibiting the use of "toxic ash" in paving and resumed preparations for the installation of the demonstration paving, which was expected to occur in late March.

It didn't. Once again the exigencies of politics thwarted the PMT's plans. It seems that the Mayor of Elizabeth was facing a June 13th primary and was most anxious to postpone further Center Drive

controversy until after that date. The opponents, who didn't know that the paving had been postponed until mid June, kept up a steady barrage of attacks, demanding more information and calling for public hearings. Finally, after having provided local officials and avowed opponents with information about every aspect of the demonstration project, the PMT said, "Enough!" Since the law did not require a public hearing, there would be none.

Meanwhile, due in part to changes in the PCFAWC membership, arrangements for release of the ash were coming unglued. One old member had publicly rejected the existing agreement and called for burial of the ash. Two new members insisted on meeting with the DEP and demanded answers to a list of questions. A coalition of anti-incineration, anti-paving activists and like minded clergy kept up a campaign of political and religious pressure.

The Deputy Attorney General, in a letter to Jim Broschius, counsel to the PCFAWC, acknowledged the PMT's concern respecting the PCFAWC's intentions and reminded him that the State considered the April 11, 1995 Stockpile Agreement as remaining in force and fully binding and expected all parties to fulfill their obligations under the Agreement. On a more conciliatory note, she indicated that the DEP would be contacting the PCFAWC to set up a meeting to discuss the members' request for additional information. Shortly after that meeting and the subsequent receipt of a written response to their list of questions, the PCFAWC members yielded to the well organized clamor and, meeting in closed session, voted to landfill the stockpile. The project opponents and the Elizabeth officials were elated. Not reported in the press was the fact that the PCFAWC also voted to delay action for two weeks, ostensibly as a courtesy but also in the hope that the State would move quickly to force the Authority to honor the Agreement, thus allowing the PCFAWC to avoid legal consequences and providing political cover.

Once again, Commissioner Shinn (DEP), joined by Commissioner Wilson (DOT), reiterated the State's support for the project. Both requested the Attorney General's Office to seek the approval of the Governor's Office for the initiation of legal action against the PCFAWC in order to prevent the imminent destruction of the stockpile. Permission was granted, and on May 14, 1996, a Deputy Attorney General, acting on behalf of DEP and DOT, appeared before the Superior Court of New Jersey seeking an Order to Show Cause with Temporary Restraints to prevent the PCFAWC from touching the stockpile. The judge granted a temporary restraining order and instructed the State and the PCFAWC attorneys to submit documents in support of their respective allegations and indicated that he would set a date for oral arguments and a decision on the State's request that the Court make the temporary restraining order permanent and require the PCFAWC to comply with the terms of the April 11, 1995 Agreement.

At a PMT teleconference on June 4th, the Deputy Attorneys General handling the litigation informed the conferees that a letter requesting surrender of the ash by June 17th had been sent to the PCFAWC counsel for action at the Authority's meeting the next day. They indicated that if the response was negative as expected, they would immediately file for Summary Judgment on Short Notice.

On June 7th, Judge Diana found in favor of the State, noting in his decision that the papers showed that, "there will be no measurable risk" and that, "the State should not be denied the potentially invaluable opportunity to determine the utility of ash as a paving material". On the 10th, the PMT notified the Mayor of Elizabeth and the Chairman of the Union County Board of Freeholders that the Port Authority would be paving Center Drive during the week of June 17th.

Defeated in Warren County, the hard core crusaders turned to Michael Gordon, an environmental

lawyer, who proceeded to attack the State alleging violation of its own solid waste management plan by bringing ash to Union County without prior County approval. Elizabeth officials, invited to join the activists' litigation, did so, alleging that installation of the paving would violate a local ordinance.

On June 14th, the Deputy Attorneys General were in another court before another judge and still fighting to protect and preserve a seven year old interagency demonstration project. Judge Beglin, after indicating that he lacked the authority to rule on the City's complaint, deferred his ruling on the environmentalists' allegation pending the submission of legal arguments by the attorneys for both sides. However, in recognition of the expense and inconvenience that would be incurred as a result of extended delays, he agreed to announce his decision early in the day on June 19th, barely nine hours before the PCFAWC was scheduled to release the ash to the Port Authority's contractor.

While awaiting the decision, the Port Authority and its contractor made preparations to install the ash amended pavement during the night of June 19th-20th and the control section the following night, the predicted heavy rains notwithstanding. Then, on the morning of the 19th, as Judge Beglin upheld the legality of the DEP's actions, the trucks that were to collect and transport the ash to the asphalt plant began to roll. By the time the contractor was ready to put down the paving, the rain ceased and the task was accomplished, with only one or two unhappy opponents on hand to videotape the proceedings. On June 21st, the local daily carried the headline, "Critics Fume As Ash Pavers Strike In The Night". The PMT and TWG members, the engineering consultant and involved Port Authority, DOT and DEP staff expressed their relief and satisfaction that, with the able assistance of the Deputy Attorneys General, the "good guys" had finally won the battle.

With the paving on Center Drive in place and subject to heavy traffic for about ten months, and ongoing monitoring of its physical condition and regular collection of runoff and soil samples, it's time to reflect on the events of the past eight years, to identify the non-technical insights gained and to share conclusions and caveats with those who may be tempted to undertake controversial R and D projects.

In my opinion, the ash paving project has made it abundantly clear that 1) failure to understand and anticipate the non-technical impediments to implementation can doom the best designed field demonstration and 2) achieving and maintaining an ongoing multi-agency managed and supported demonstration requires an extraordinary effort, doggedness and administrative creativity.

In retrospect, it seems that the proponents were surprisingly naive. As residents of the highly urbanized Northeast, the project participants shared a conviction that MSW combustion together with energy production and, if possible, the beneficial use of sizeable portion of the residue represented an essential, if not the essential component of a practical, environmentally friendly municipal solid waste management program.

The New Jersey participants viewed the project as an environmentally friendly effort undertaken in partial fulfillment of a legislative mandate directing the NJDOT to investigate the feasibility of using secondary materials in paving. At the time the demonstration was conceived, the DOT had already been experimenting with crumb rubber, New York City was using ground glass and there was increasing interest in the beneficial use of ash. Assuming that ash could be recycled in paving without contravention of any NYSDEP standards, who could possibly object?

The Port Authority, unaccustomed to controversy over "small" projects, was concerned with finding a beneficial use for at least some of the residue to be generated at its Essex County waste-to-energy

facility then under construction. As an agency involved in the construction and operation of major public facilities, it was sensitive to potential environmental concerns and liability issues but was ready to accept the NJDEP approval as assurance that the project was safe and would go forward.

The New York State Energy Research and Development Authority, originally a relatively independent agency dedicated to fostering innovative energy producing or conserving technology, had little experience with and little expectation of public controversy. Willing to assume a major role in program design and administration, the Energy Authority appeared to regard the road paving and stockpile construction and monitoring as an appropriate follow up to the Energy Authority assisted LIRPB study of the potential for beneficial use of residue from municipal solid waste combustors.

The LIRPB, with two small and three larger waste-to-energy facilities already operating or in start up within the bi-county area, was aware of local resistance to further planned construction. Relieved that the proposed paving site was located in New Jersey rather than on litigious Long Island, the Board staff chose to accept the Freeholder Director and the Pollution Control Finance Authority assurances that Warren County had a suitable site, and refrained from asking questions. Furthermore, since NJDOT funds were to pass through to Warren County which would then pay construction costs, the Board regarded the DOT/Warren County arrangements as a given. In so doing, it failed to call for consideration of the need for some kind of public outreach to inform local officials and community leaders of the importance and safety of the project.

The participants failed to recognize that today a field demonstration project is often not just a scientific real world test of a promising technology but a made-to-order opportunity for individuals and organizations to further a variety of goals, many of them unrelated to the demonstration. This was clearly the case in Hackettstown where the initial opposition came from alarmed residents of the Willow Grove Street area, who were soon joined by persistent enemies of the PCFAWC, other foes of incineration and environmental fellow travelers energized by the prospect of excitement, publicity and the opportunity to further their respective causes.

Empowered by their victory in Hackettstown, most of the original opponents simply transferred their attention to the Route 80 site in Allamuchy where they managed to enlist new recruits. Again, public officials, in an attempt to preserve a semblance of rational impartiality, asked questions and requested stacks of reports and reams of data. Then they promptly acceded to the activists' misinformation-based demands. When the PMT decided to move to Center Drive, the activists took up the fight on two fronts, capitalizing on their support in Warren County by trying to force the PCFAWC to destroy the stockpile and joining their Union County and Elizabeth allies in protests and a lawsuit.

Had the PMT been more proactive in seeking broader public support, in providing information and explaining the demonstration project before being forced to defend it and in observing political niceties, such as notifying the Mayor of Hackettstown before he read about the project in the newspaper, the PMT might have succeeded on the first try. It seems unlikely, however, since the demonstration addressed a problem of little immediate public concern and was therefore unlikely to attract the strong support needed to offset the allegations of the organized nay sayers.

The forced abandonment of the Route 80 site can be credited to the increasingly effective tactics of the anti-incineration alarmists, unfortunate timing and the foolish assumption that adherence to the recommendation of a powerful politician automatically guarantees his support. Start up delays and the time lost in attempting to site the demonstration in Hackettstown caused the paving of Route 80 to be

scheduled in a critical election year, thus endangering political support for an already controversial activity.

Successful project implementation at the Center Drive site can be attributed to three factors: public agency ownership of and unquestioned jurisdiction over the site, the unwavering support of Commissioner Shinn of the DEP and the willingness of the Governor's office to permit the Attorney General to initiate or defend against legal action as necessary to preserve the stockpile and to allow the paving to proceed.

Achieving and maintaining interagency consensus and coordination proved to be complicated, sometimes frustrating but ultimately manageable. Initially there were some sticky issues of governance, of authority and liability, of technical competence and work plan scope; later, of Energy Authority support, of the procurement of additional funding and the maintenance of administrative coherence and continuity.

Creation and maintenance of an ad hoc management organization was only the first of several challenges. If the demonstration was to go forward, it was essential to find a way to make management by committee actually work. The establishment of a Project Management Team consisting of representatives of the five agencies committed to decision by consensus and the subsequent creation of a Technical Working Group to advise the decision makers ensured responsible and relatively efficient project governance and administration.

Establishment of contractual arrangements for a cooperative endeavor involving two New York, two New Jersey and one interstate agency was also no easy matter. The key was the retention and modification of an existing Energy Authority agreement of 1987 covering the scope and funding for a then ongoing but virtually completed investigation of the potential for beneficial use of MSW combustor ash. That agreement was amended by the addition of language describing work to be accomplished, cash and services to be provided and administrative and technical responsibilities to be assumed by each of the cooperating agencies, effective only upon execution of the amended Energy Authority/LIRPB agreement and the execution of parallel agreements between the Energy Authority and NJDOT, the Energy Authority and NJDEP and the Energy Authority and the Port Authority.

This arrangement accomplished three things, not the least of them securing the approval of five sets of independent-minded attorneys. It also allowed the group to maintain uninterrupted access to the Board's highly qualified engineering consultant without contravening the rules or contracting procedures of the New Jersey or interstate partners. And, finally, by assigning primary responsibility for PMT administrative matters and fiscal management to the Energy Authority, it allowed policy determination by consensus without impairment of day to day progress.

Interagency consensus building and maintenance have proved time consuming but critical throughout the course of the project. Even before the drafting of the Energy Authority/LIRPB contract amendment and the new agreements, the consultant and agency experts wrote and revised five versions of a relatively detailed work scope and a clear, task by task, assignment of responsibilities. Except for the changes necessitated by the need to plan for three different sites, the project scope is essentially the same as in the initial interagency agreements.

The project schedule and budget are another matter. If any of the participants had envisioned the probability and potential consequences of normal bureaucratic and/or environmental activist related

delays, they might well have questioned the feasibility of the undertaking.

Fortunately, the group had a lot going for it. The idea of interagency cooperation was and remains tantamount to governmental "motherhood" and therefore clearly a plus. The fact that the program was designed to build on already completed publicly-financed research and represented an attempt to reduce the cost of MSW management through an environmentally friendly beneficial use of combustion residue demonstrated genuine concern for both the local taxpayer and the environment.

On balance, the strong leadership and "can do" attitude of the DOT representative and the willingness of the DEP and the Port Authority to stay the course, the agencies' ability to reallocate or provide additional funds or services when needed, and the unparalleled access to engineering, environmental and legal talent and services provided by the project consultant and agency staffs more than offset the difficulties encountered in maintaining a continuity of effort and expertise in the face of agency downsizing and reorganization.

Finally the strong, timely support of a dedicated public official, willing to defend government's ability to pursue and test innovative solutions to current problems, through legal action if necessary, proved critical to the PMT's ability to pave Center Drive.

In closing, let me leave you with a personal observation. I've spent a lot of time thinking about the events of the past eight years and of the changing milieu in which we now find ourselves. The ash project has confirmed my suspicion that there is a "Gresham's Law" of environmental politics. Substitute the word "science" for the word "money" in the principle that bad money tends to drive good money out of circulation and you have a succinct description of one of the key factors affecting our ability to engage in and benefit from a demonstration project. A suggested restatement of Gresham's time honored principle of economics might say that, "Almost inevitably, junk science -- the exciting vehemently asserted, emotion-laden half truths and misinformation -- will rapidly replace the less simplistic but technically valid findings and conclusions derived from properly collected and scientifically analyzed data as the currency of political dialogue. In our case, public acceptance and media repetition of activists' outrageous claims and demands for proof of the unprovable quickly precluded rational discussion. Legitimate concerns were transformed and project participants demonized in order to support a multiplicity of agendas in a local power struggle with statewide and national implications.

**The Importance of the pH Buffering Capacity – Comparison of Various Methods to
Estimate the pH Properties of a Waste Material**

Catharina Bäverman
Chemical Engineering and Technology
Royal Institute of Technology
SE-100 44 Stockholm
Sweden

ABSTRACT

The final pH of the leach water controls the leaching of many metals from MSWI ash in construction materials and landfills. The buffering properties of the ash determines the final pH of the leachate and is therefore one of the most important properties of a waste material. In this study three different methods to investigate the pH buffering capacity of ashes have been compared; two batch methods and one flow-through method. The results of this study showed that the MSWI bottom ash used here had a large buffering capacity in the pH region where the solubility of most pH-sensitive metals is lowest, around pH 8. The buffering reactions are slow. The duration of an experiment should therefore be about 50 days if all material should have time to react. A comparison of the results of the experiments showed that at least 50 % of the buffering capacity in a batch system comes from dissolved constituents, that would not buffer in a flow-through system.

INTRODUCTION AND BACKGROUND

Solid residues, like ashes and slags, often have physical properties that make them suitable for utilisation in civil engineering applications. This can save large quantities of geological material and also substantially decrease the amount of waste sent to landfills. Before utilising a residue, the environmental impact of the construction has to be studied. One of the main concerns in utilising an ash is the long-term mobility of heavy metals. The mobility of metals is controlled mainly by the pH of the leachate. The effects of pH on leachability have been studied in several investigations.^{1,2,3,4,5,6} The pH has a significant influence on the aqueous concentrations of Al, Ca, Cd, Cu, Fe, Mn, Ni, Pb and Zn. The pH range for minimum leaching is often pH 8-10. At a pH above 10, the potential leaching of Cu, Pb and Zn increases. At a pH value below 7, there is a sharp increase in the leachability of metals within one or two pH units. To avoid the mobilisation of trace elements, the amount of acidic degradation products must not be significant in comparison with the acid neutralisation capacity of the waste material.

Somewhat aged MSWI bottom ash has a pH slightly over neutral, the region where the leaching of many toxic elements is low. In time, the pH buffering capacity will be depleted by intruding acidic rain, oxidation of organic material or metals, and reactions with carbon dioxide. This will decrease the pH value of the leachate and thereby increase the solubility of pH sensitive metals, sometimes by several orders of magnitude. As the pH buffering capacity in the upper layer is depleted first, while the buffering capacity at lower levels remains, a pH front will be formed between these regions. At the pH front the pH in the leach water will change from acidic to more alkaline within a very short distance. At this front trace metals can accumulate because the solubility changes with pH. This phenomena has been observed in natural systems. When the acid neutralisation capacity is depleted in all the material, large amounts of metals can be released from the ash within a short time period. The leachate concentration may then exceed the levels that the local environment can tolerate. This phenomena can not be observed in short term laboratory column experiments, nor in field studies of landfill sites where the leachate concentrations for the initial processes are measured. We have, however, observed the accumulation in the serial batch pH titration experiment, described later.

The pH buffering capacity of a material is more important for the final pH of the leachate, and thereby the solubility of trace elements, than the initial pH of the leaching media. The pH buffering capacity has been studied in several investigations.^{1,4,7} In this study three different experimental methods to investigate the pH buffering capacity of a weathered MWSI ash is compared. Two of the methods are batch titration methods: pH static titration, and pH batch titration. The third method is a flow-through pH titration; a serial batch pH titration. The former two are used by several other researchers and the latter is developed within this study.

MATERIALS AND METHODS

Material

The MSWI bottom ash used in this investigation was from Tekniska Verken in Linköping, Sweden. The ash was sorted with a magnet and should, therefore, be free from magnetic metal pieces, but there are still some caps, screws, and coins in the ash. The finest and largest particles of the ash were sorted and the fraction between 2 and 35 mm was used. The ash still contained a small fraction of fine dust. The bulk density of the MSWI ash was about 1.4 tonne per cubic metre. The composition of the ash is shown in table 1.

Preparation of samples

The sample was dried at 105°C to constant weight and stored in a closed plastic container. The ash was ground and sieved until all the material passed the 0.16 mm sieve and most of the material passed the 0.125 mm sieve. A few metal pieces were impossible to grind. These pieces, plus a small fraction of metal grains, were omitted. This fraction was less than one per cent of the total mass of ash.

pH-static experiments

In a pH-static experiment, the pH was kept constant by the addition of acid or base. In this case nitric acid was used. In the experiment, the pH-buffering capacity and the leaching at various pH levels was characterised.

40 g of ground material was put into a 500 ml Nalgene bottle; 200 g of water (Barnstedt quality) was added. The sample was titrated to the pH used in the experiment with nitric acid, using a Metrohm 719 S Titrino, and the pH was automatically kept constant for at least 1-2 weeks by the titration device. The samples were then put into a shaker, and the pH was manually adjusted for several months using a Metrohm 645 Multi-Dosimat and Metrohm 691 pH Meter. A 4 ml sample was taken out after 1 week for analysis.

pH-batch experiments

The aim of this experimental series was to determine the pH buffering capacity and the leaching at different pH levels. All the acid is added to the ash initially. This experiment does not require any equipment to be used constantly and therefore, many different experiments can be run simultaneously. This is a simpler procedure than the one used in the pH-static experiment.

2.5 gram of ground material was put into a 250 ml Nalgene bottle. Nitric acid and water (Barnstedt quality) were added to an L/S ratio of 100. The bottles were placed in the shaking device. The pH was measured after 5 minutes, 1, 7 and 50 days. 4 ml samples were taken for analysis after 7 and 50 days.

Serial batch pH-titration

This version of a serial batch experiment corresponds to a flow-through system where the contact time can be controlled. Sampling is also possible in several parts of the system. The principle of the experiment is shown in figure 1. The results can be used to simulate flow-through systems. The technique can also detect moving reaction fronts. We have previously used this method with pure water^{8,9}.

100 grams of the sample was weighed into each of 10 polypropylene bottles. 100 grams of 0.104 M nitric acid was added to bottle number 1 each time the water was shifted. The interval between water shifts was 2-3 days, sometimes more. The bottles were open to the atmosphere. The pH was measured and a 4 ml sample was taken from the last bottle at each water shift. The pH was measured and samples were taken from all 10 bottles occasionally. The first sampling occasion was when the water left the tenth bottle for the first time. The experiments were continued for 5 months.

Analyses

The samples were analysed by ion chromatography for bromide, calcium, carbonate, chloride, cobalt, chromium, copper, potassium, lithium, magnesium, manganese, sodium, nickel, lead, silica, sulphate, zinc. The ion chromatography system consists of a Dionex model DX-300, with both suppressed conductivity detection and a post-column reaction with UV-detection.

RESULTS

The most important factor controlling the leaching of many metals is the pH. Figures 2a-d show the leachate concentration of Mn, Fe, Cu, and Zn versus pH in the pH batch experiments. The concentrations in the pH static experiments are close to those from the pH batch experiment. The solubility of these metals is strongly pH-dependent. Fe, Cu and Zn have leaching minima at pH's of 6-8, 7-9 and about 9 respectively, whereas the leaching for Mn decreases with increasing pH and was not detected in the samples in which the pH was over 8.

The pH batch experiment series generated pH titration curves. The pH-buffering capacity close to the initial pH was low. The pH was measured at four different occasions during the experiment. The pH titration curves for the different occasions are shown in figure 3. This experimental series shows that the pH-buffering reaction kinetics differ in various regions. Another study of the pH buffering reaction kinetics has been performed (Yan et al., 1996). This study is based on the results of the pH static titration experiments, shown in figures 4 and 5.

The pH buffering reactions have shown to be rather slow. Figure 4 shows the consumption of acid necessary to maintain a constant pH of 8.5 for MSWI bottom ash versus time in the pH static experiment. These results show that the reaction time for solid wastes is rather long and that it is beneficial if the duration of an experiment with MSWI ash is at least 50 days. Only slightly more than 50% of the material has reacted after 24 hours, the normal time for a pH static experiment. This is also confirmed the pH batch experiment in figure 3.

Figure 6 shows the pH in the different bottles of the serial batch pH titration at various occasions. The leachate leaving the system had a constant pH (only slightly higher in the first leachate), whereas in the first five bottles the pH changed with added amount of acid. In this experiment we could observe that the solubility of iron was high in the acidic environment and lower in the neutral. When the experiment was interrupted, bottles number 4 and 5 were rust brown. This colour had followed the pH front developed between the acidic and the alkaline bottles. The dissolved oxidised iron re-precipitated in the first bottle with neutral solution and was later dissolved, when the solution became acidic.

A pH titration curve for a flow-through system was calculated from the data in figure 6. This curve was compared with the pH titration curve for the pH batch experiment and the pH static experiment, shown in figure 5. The pH buffering capacity of the ash is higher in a batch system than in a flow-through system.

DISCUSSION

The pH static method and the pH batch method both generate a pH titration curve for batch systems. The largest difference between those methods is that in the pH batch experiment all the acid is added at the start of the experiment. This leads to a very low pH in the beginning of the experiment. At this low pH, phases may buffer irreversibly, that would not buffer at the final pH. This can lead to errors in the titration curve. In the pH static experiments this problem is avoided as the pH is kept constant, by addition of acid.

In a batch system dissolved buffering species stay in the solution, and will therefore contribute to the buffering capacity. In a flow-through system these species will be flushed out and will not contribute to the buffering capacity. The results of this investigation show that 50% or more of the buffering capacity in the batch titration comes from dissolved species.

The pH batch titration is a simple experiment, but this method also has the most uncertainties of the three methods investigated in this study. The pH static experiment, that gives a more reliable titration curve is time-consuming, as only one pH value (one bottle) at a time can be made with the equipment. In our case every point on the pH titration curve occupied the equipment for at least one week. After that, the pH was adjusted manually. In the pH batch experiment all points on the curve can be run in parallel. This experiment only takes 50 days, with very little effort, and very little equipment. The serial batch pH titration also requires little equipment, but is rather time-consuming.

What method we choose depends on the purpose of the investigation. The batch titrations are more accurate than the flow-through titration, as the latter is sensitive to the concentration of the acid. Buffering agents can be dissolved and flushed out without contributing to the buffering capacity in the experiment. This can lead to an underestimation of the buffering capacity. In the batch titrations, on the other hand, the buffering agents stay in the solution, and buffer even though they should have been flushed out in a real situation (very few landfills and constructions are of a batch system type).

The choice between the pH batch experiment and the pH static experiment has to be a consideration between accuracy, time and cost. The results, shown in this report, indicate that there is no significant difference between the results of the two methods used, but the pH range is rather small. In the lower pH region there were a few points that deviated considerably from the pH batch titration curve, not shown here. We have, incidentally, not yet been able to reproduce these results because our pH static equipment broke down, and there has not been time to repeat them. Those experiments were the last made and may therefore be completely wrong.

The buffering capacity of the MSWI bottom ash is high at the level where the leaching of many metals is minimised. In a water saturated system the pH will remain at this level for a long time. In a partially water saturated system there are several reactions that can consume the pH buffering capacity. Carbon dioxide acts like an acid and will diffuse in from the atmosphere and react with the ash. Another source of acidity is oxidation of metals and uncombusted carbon. Carbonation and oxidation reactions are several orders of magnitude faster in a partially saturated system where air can diffuse into the ash than in a saturated system where the gases first have to dissolve in the water and then diffuse in the liquid phase. The buffering capacity will therefore last much longer in a saturated system than in the partially saturated system.

CONCLUSIONS

From this study some conclusions can be made.

- The pH buffering capacity at the initial pH is very low. The out-flow pH in a flow through system will reach a pH value of 8 fast and remain at that pH for a very long time. In this pH region the leaching of most toxic metals is minimised.
- The pH buffering reaction kinetic is slow. The duration of an experiment with MSWI should be at least 50 days.
- In a batch titration at least 50 % of the buffering capacity comes from dissolved species.
- The pH batch experiment is much easier to perform than the others.

ACKNOWLEDGEMENTS

The author wishes to thank Tomas I Ulväng for his help with the pH batch experiments, and him and Cecilia Möller for their help with the serial batch pH titration. This project was financed by the Swedish Environmental Protection Agency.

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Table 1. Composition of the MSWI bottom ash used in this study.¹⁰ The ash was digested in lithium metaborate melt for main components and with nitric acid in Teflon bomb for certain trace elements (As, Cd, Co, Cu, Hg, Ni, Pb, Zn). All elements were analysed on ICP-AES. ICP-MS was used for low concentrations. Results are means for duplicates.

Element	Concentration	Element	Concentration
Al	5.69%	Cd	5.8 ppm
Ca	8.79%	Co	19.1 ppm
Fe	10.8%	Cr	274 ppm
K	1.43%	Cu	3400 ppm
Mg	1.13%	Mo	16.0 ppm
Mn	0.14%	Nb	13.1 ppm
Na	2.64%	Ni	138 ppm
P	0.45%	Pb	737 ppm
S	0.86%	Sn	130 ppm
Si	20.9%	Sr	285 ppm
Ti	0.62%	V	58.7 ppm
As	16.0 ppm	W	33.9 ppm
Ba	1660 ppm	Zn	3080 ppm
Be	1.78 ppm	Zr	200 ppm
Loss on ignition 550°C	4.3%		

Hg was below detection limit

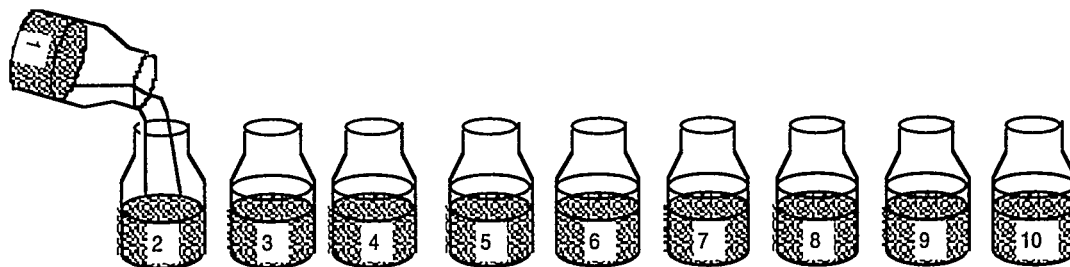
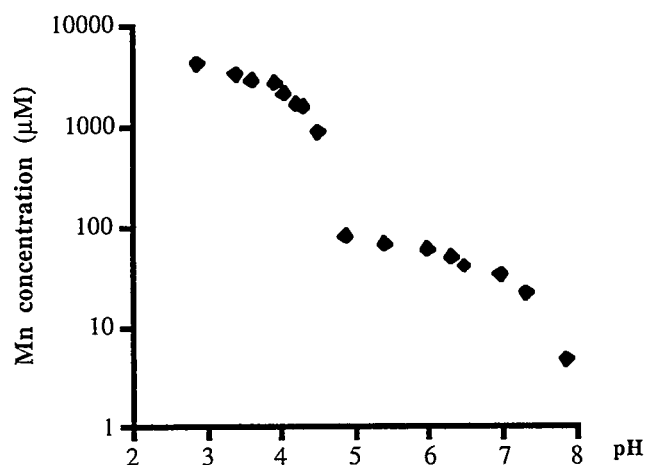
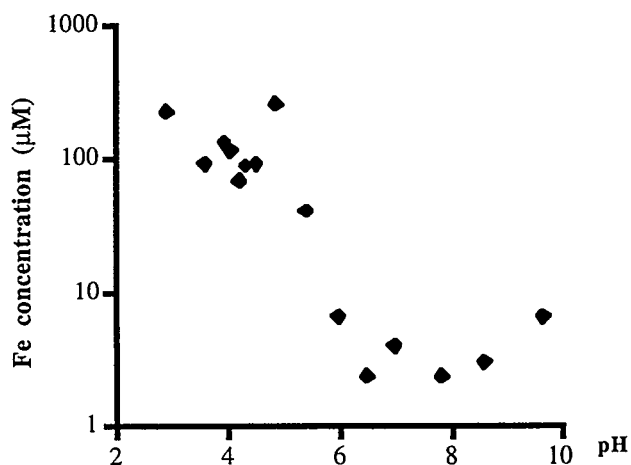


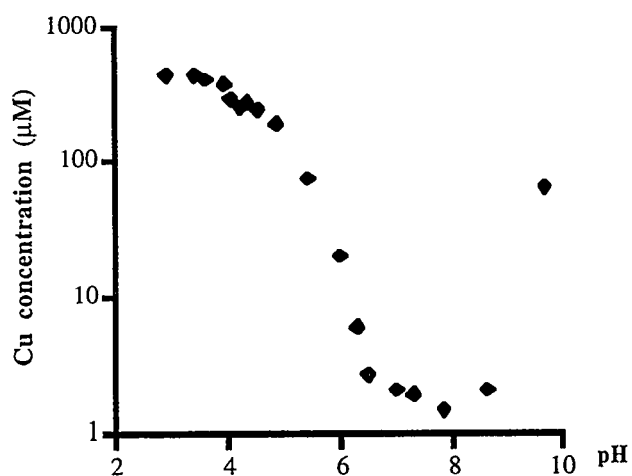
Figure 1. In the serial batch pH titration experiment, the water was poured from the first to the second, from the second to the third etc. at intervals of 2-3 days.



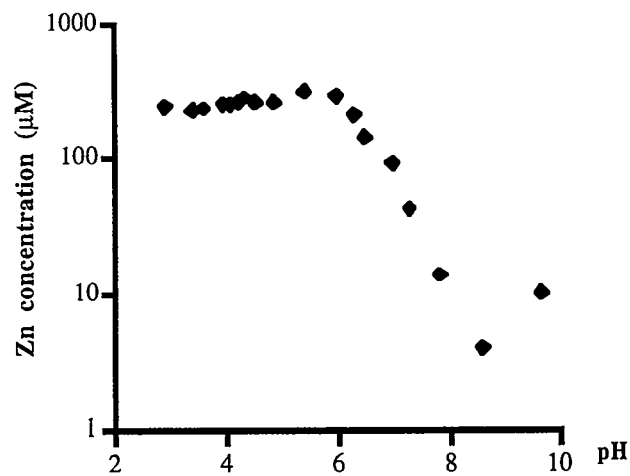
(a)



(b)



(c)



(d)

Figures 2a-d. The leach water concentration of Mn, Fe, Co and Zn in the pH batch experiments after one week of leaching.

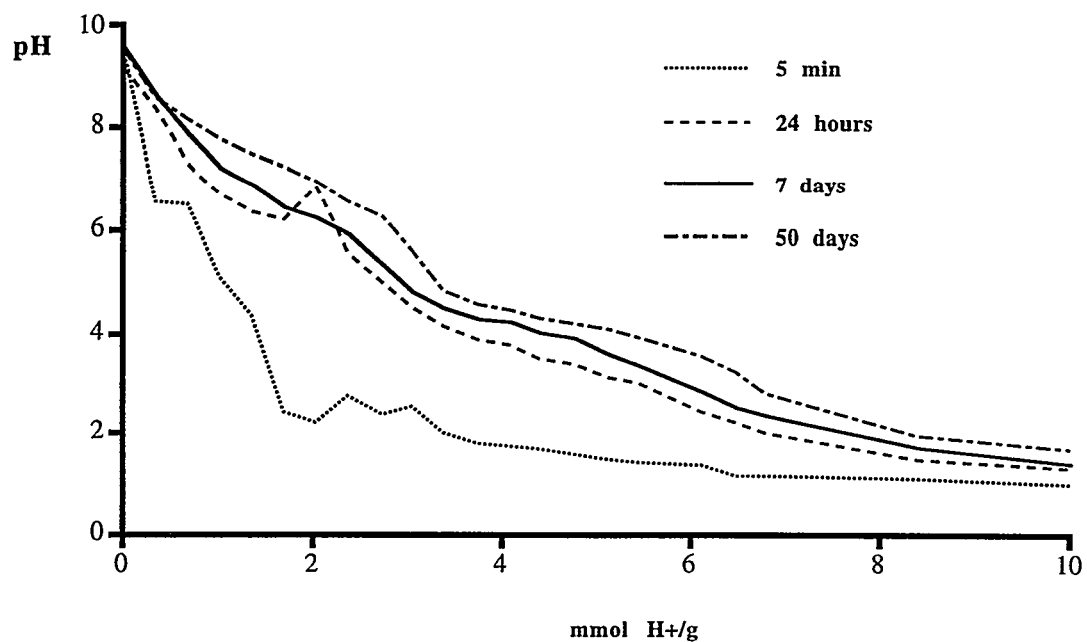


Figure 3. The pH titration curve obtained from the pH batch experiments. The pH is measured on four different occasions.

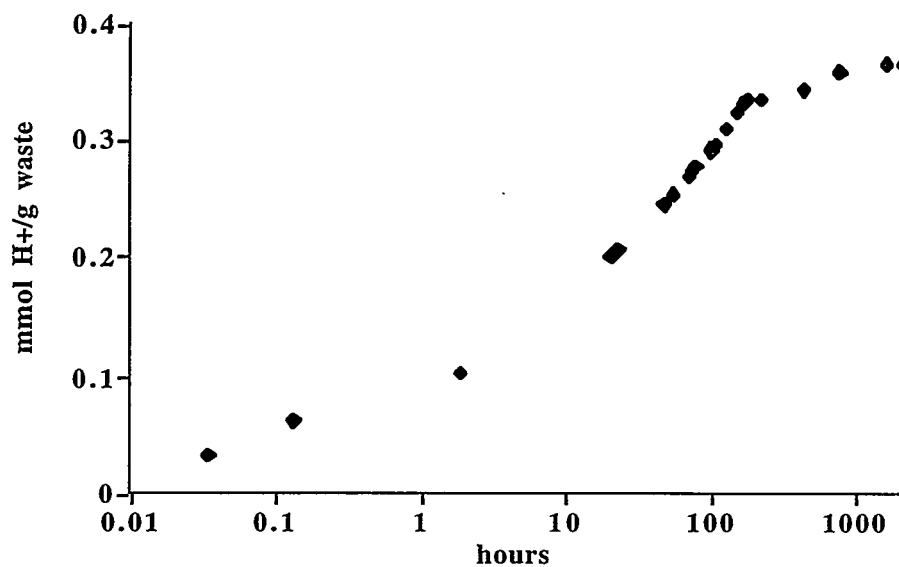


Figure 4. The amount of acid added to maintain the pH in the MSWI bottom ash at 8.5 versus time in the pH-static experiment.

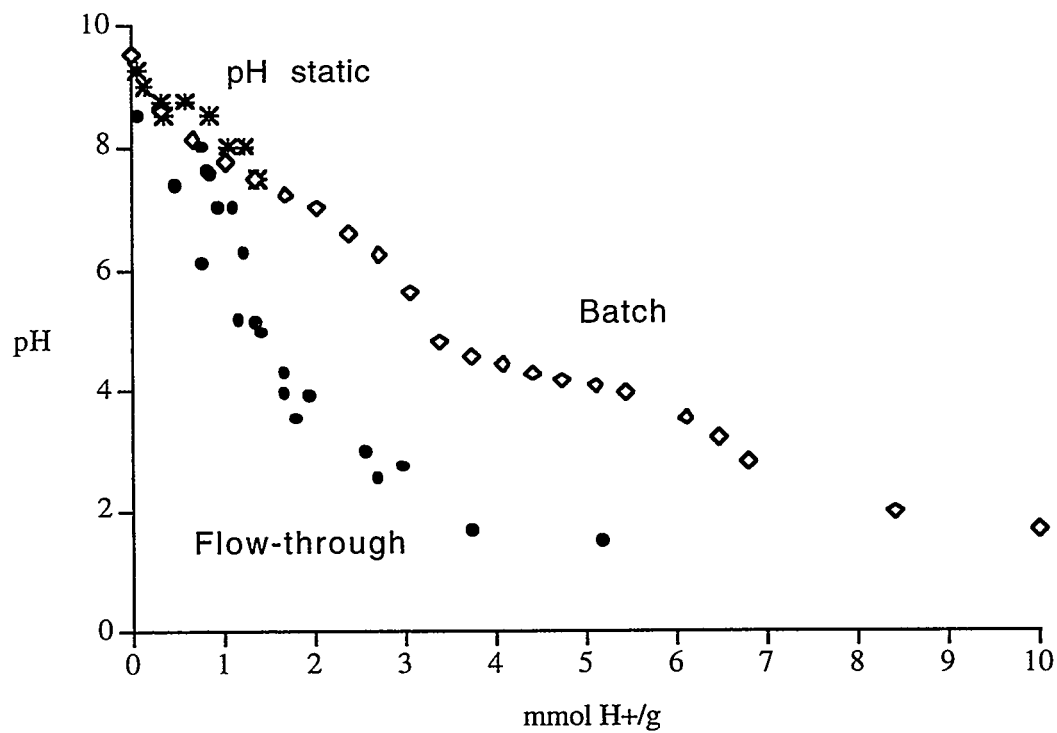


Figure 5. The pH titration curves obtained from the pH batch experiment and the serial batch pH titration.

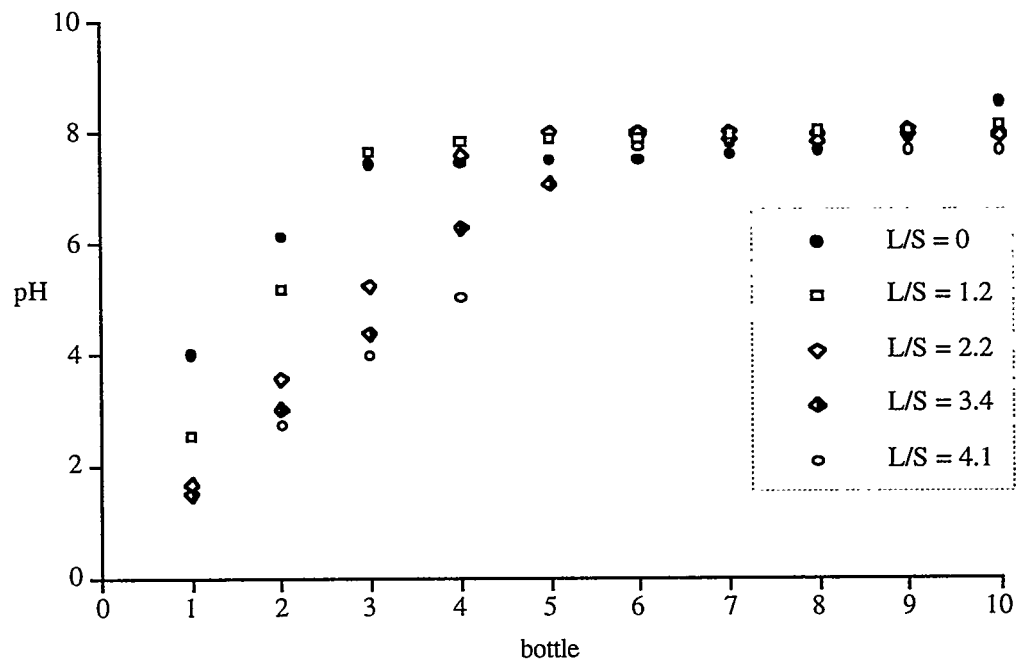


Figure 6. The pH in the different bottles in the serial batch pH titration. The pH is measured on five occasions. The L/S that has passed the bottles at the sampling occasions are indicated.

High Standard Upgrading and Utilization of MSWI Bottom Ash
Financial Aspects

Adrianus C.G. van Beurden
Recycling Maatschappij Feniks B.V.
Bergerweg 150
1817 MN Alkmaar, The Netherlands

Jan G.P. Born
Vereniging van Afvalverwerkers
Catharijnesingel 55
3511 GD Utrecht, The Netherlands

Emile A. Colnot
N.V. Huisvuilcentrale N-H
Jadestraat 1
1812 RD Alkmaar, The Netherlands

Ruud H. Keegel
Recycling Maatschappij Feniks B.V.
Bergerweg 150
1817 MN Alkmaar, The Netherlands

INTRODUCTION

In The Netherlands the utilization of the MSWI bottom ash from Municipal Solid Waste Incineration (MSWI) amounts to almost 100% of that produced. Over the last 10 years, some 600,000 metric tonnes per year have found useful application in road base materials, embankments and the like. Projects with MSWI bottom ash that have been realized vary from 30 tonnes to 1,000,000 tonnes and were ordered by both private contractors and the public sector.

These successful results were possible due to the fact that the following conditions were fulfilled:

1. Allied in an association, MSWI companies have stimulated public authorities as well as the market to introduce regulatory standards for the useful application of MSWI bottom ash.
2. These regulatory measures for MSWI bottom ash have been established by the authorities.
3. The essential physical characteristics for MSWI bottom ash have been agreed with the association of road contractors.
4. High standard upgrading techniques have been applied, in order to obtain a consistent construction material which meets the physical requirements demanded by the market.
5. Certification has been introduced to guarantee mandatory environmental quality, as well as the physical characteristics that are demanded by the market.

PRODUCTION AND UTILIZATION OF MSWI BOTTOM ASH

The principal goal of waste treatment is the reduction of space required for landfill with wastes. As a result incineration of MSW is preferred in The Netherlands. This preference is now embedded in appropriate regulations. Incineration of the MSW results in residues, typically occupying around 10% of the original volume (25% by weight) of the waste. Useful application of these residues reduces the waste, and hence the required space for landfilling, even further. In addition, the heat generated during the incineration process is also utilised; over 0.5 MWh of electrical energy is generated per tonne of incinerated waste.

In 1996 some 3.4 million tonnes of MSW were incinerated in the Netherlands. In 1996 and 1997 several new MSWI's have been or will be completed. As a consequence, the incineration capacity is 4.5 million tonnes per year. Over the last years the amount of MSWI bottom ash per ton of waste has remained essentially the same at 22 - 23 % (m/m); hence the absolute production figures will develop parallel with the throughput of combusted waste.

As Figure 1 shows, for the last ten years almost 100% of the production of MSWI bottom ash in The Netherlands has been utilized. Typical applications are earth and road construction, since MSWI bottom ash is suitable for use in road-base stabilization layers and as embankment material. Given the size of some embankments prepared with MSWI bottom ash - up to 1 million tonnes - sometimes MSWI's keep large amounts of MSWI bottom ash in stockpile for a year before it is required. This phenomenon occurred in 1989 and in 1992, and explains the irregularities in the bar-diagram presented in Figure 1.

COMBINED EFFORT IN THE WASTE PROCESSING ASSOCIATION

In The Netherlands the Waste Processing Association (Vereniging van Afvalverwerkers) is the branch organization for MSW processing plants employing incineration, landfilling and composting activities. The aim of the Association is look after its members' interests with regard to ecologically-sound waste disposal in the broadest sense of the word. This aim is achieved, among other things, by consultations, promotion of research, collective pursuit of quality improvement, exchanging knowledge and experience, and by initiating training, etc. All Dutch MSWI's are members of the Waste Processing Association, and hence the Association is a suitable instrument for consultation with governmental and other authorities concerning future and present legislation.

In particular, with respect to the use of MSWI bottom ash, the Waste Processing Association has proven to be a useful tool in obtaining internal agreement with respect to quality standards. The objective of the Waste Processing Association in respect of MSWI bottom ash is to ensure that it is utilized in a responsible way, both environmentally as well as economically, as a replacement for natural materials. Because of this incentive the Association has shown itself to be an accepted party by other branch organizations, such as the association of road contractors, for making agreements concerning the proper use of MSWI bottom ash from a civil engineering perspective.

POSITIVE APPROACH OF THE AUTHORITIES

Background information

The total consumption of building materials in The Netherlands amounts to around 140 million metric tonnes per year. This consumption - primarily sand, gravel, clay and marl, means a considerable loss of natural resources. Considering that The Netherlands is a small and densely populated nation (compared to the USA 1/250 of the area, but 1/15 of the population) it is the national policy to aim at preserving natural resources; conversely, it aims at reducing wastes to be landfilled in order to preserve space as well. Both aims have led to a positive attitude by the national authorities towards useful application of waste products, such as MSWI bottom ash. At the moment some 15 million tonnes of secondary materials are re-used on a yearly basis, mainly demolition waste and industrial slags.

Like most of all residues to be used as secondary materials MSWI bottom ash also contains some deleterious materials causing potential risk for water and soil. Hence, a paradox exists: the re-use of residues is beneficial for the environment in the sense that it preserves natural resources, whilst the product itself is a potential risk to the environment, through the leaching of contaminants into the ground. To resolve this problem, mandatory measures have been introduced by the authorities for the application of MSWI bottom ash such that any potential hazard to the soil or groundwater is removed.

Scope of the regulatory demands

As a first step in formulating such regulatory standards the Dutch authorities have defined MSWI bottom ash as the product of MSWI's operation according to the following principles:

- operation is according to the present regulations and authorizations
- only MSW or comparable wastes are processed
- in general any hazardous waste is excluded from the process.

Required environmental quality

With respect to the environmental quality the government has decided that MSWI bottom ash should comply with the following requirements:

- free of fly ash (MSWI bottom ash and fly ash are collected separately, and no combined ash is produced)
- storage for at least 6 weeks prior to application
- leaching behaviour should comply with specific standards
- scrap metal content less than 5% (in order to promote the re-use of scrap metal)
- loss on ignition (LOI) less than 6 %
- digestible material less than 2%

Permitted methods of utilization

Finally, guidelines have been formulated for the way in which MSWI bottom ash may be re-used:

- in its application the MSWI bottom ash has to remain at least 0.5 meter above average maximum groundwater level
- use is prohibited in soil or groundwater preserved areas
- measures have to be taken to prevent the infiltration of rainwater into the MSWI bottom ash
e.g.: an asphalt top layer (road pavement) in case of use as a road-base material or
a 200 mm. thick sand-bentonite top layer for use as a bulk fill material.
- a side and top layer has to be applied within 6 weeks after the application of the MSWI bottom ash to prevent infiltration of (rain)water
- where possible the material should be used in larger projects and the location of such projects recorded

In summary, the existence of these guidelines and regulations has shown to be of the utmost importance in order to convince decision makers for civil works to accept MSWI bottom ash instead of sand or gravel. Lack of guidelines or insufficient guidelines are fatal for the market-acceptation of secondary materials. Since national and local authorities as well as municipalities have acted as pioneers in the use of MSWI bottom ash, market-acceptation has steadily grown.

Next to market acceptance, also marketing of MSWI bottom ash is an important factor. Due to limited availability (time, quantity) of secondary materials, design of consultants are generally not based on implementation of these materials. Therefore specific marketing and engineering has to be performed by companies having knowledge of civil and building industries.

REQUIRED PHYSICAL QUALITY DETERMINED BY THE MARKET

In order to improve the acceptance of MSWI bottom ash as a building material, a potential client has to be convinced that the use of the material is equivalent to the use of primary materials. Criteria for the physical quality of MSWI bottom ash have been defined in close co-operation with the association of road contractors in The Netherlands on basis of the existing criteria for primary materials. In addition to the environmental demands, the following criteria have been formulated:

- crushing-resistance factor ≥ 0.65
- granule size according to Table 1

Furthermore, pilot projects have been selected to demonstrate the applicability of MSWI bottom ash in earth or roadwork.

CERTIFICATION OF MSWI BOTTOM ASH

History

Quality control and quality assurance can be regarded as the reason for the present success of MSWI bottom ash in Holland in recent years (Figure 2). Already in 1987 the procedure for certifying MSWI bottom ash had commenced; an independent certification institute was tasked with formulating specifications to which MSWI bottom ash should comply. In February 1989, using the expertise of a number of specialists, this certification institute introduced the definite specifications for MSWI bottom ash. Since that moment the individual MSWI's prepared a framework of internal quality control in which the acceptance of the waste, permits, procedures, process conditions, MSWI bottom ash handling, storage and inspection have been regulated.

Sampling and testing of the product

The physical properties of certified MSWI bottom ash are specified based on guidelines given by the association of road contractors in 1988. The environmental specifications (mainly leaching behaviour and measures required to prevent soil contamination) should comply with the present Dutch regulations formulated in 1986.

As part of the quality control, samples of processed MSWI bottom ash are taken 1 to 2 times a day during a production period of two weeks. In general one sample is analyzed per 5,000 to 10,000 tons of MSWI bottom ash.

In order to obtain a certificate for MSWI bottom ash, the operation of a MSWI must comply with certain rules:

- The environmental quality of the MSWI bottom ash is periodically monitored by an independent laboratory which reports the results to the certifying authority
- The physical properties of the MSWI bottom ash is periodically monitored by an independent laboratory

Random inspections by the certifying institute make sure that specifications are met at all times. Once a MSWI is able to demonstrate its compliance with these regulations for some time the certificate will be awarded.

The certificate guarantees both the physical and environmental quality of the MSWI bottom ash to its users. Consequently, batch-like inspections for the quality of the material are unnecessary, saving both money and time for the customers.

Costs related to certification

Although certification has many benefits, its financial benefits are hard to quantify. Often producers of secondary materials refrain from seeking certification because of the costs. The Waste Processing Association regularly obtains information from its members to monitor the costs of physical and leaching tests. These costs, together with the fee for certification, may be related to the tonnes of MSWI bottom ash. As shown in Figure 3, the total costs of certification of MSWI bottom ash have reduced over the last years, due to the strong competition between environmental laboratories in The Netherlands. Every two years the Waste Processing Association invites laboratories to bid for the required tests. The costs related to certification amounted to some \$ 0.20 per tonne in 1996.

FUTURE DEVELOPMENTS

Dutch legislation for building materials is currently under review. In 1998 new legislation (Building Materials Decree) will be enacted which also applies for MSWI bottom ash. Briefly new leaching tests will be introduced combined with considerably stricter demands. Within this new legislation the present quality of MSWI bottom ash sometimes cannot meet the general standards for building materials. The utilization of MSWI bottom ash in bulkfill however will be allowed by incorporating double protective top and side layers, structural concrete or asphalt concrete.

The Waste Processing Association realizes that this may hamper the utilization. Hence, it is concluded that the quality of MSWI bottom ash has to improve up to the general standards given in the new Building Materials Decree. In 1997 pilot-plant experiments will be performed to validate several techniques to reduce the leaching of the MSWI bottom ash. Furthermore the certification program will change according to the future legislation.

UPGRADING OF MSWI BOTTOM ASH, FINANCIAL ASPECTS AND PARAMETERS

Introduction

Next to policy aspects, as described before, also cost-effectiveness forms an incentive for high standard upgrading and utilization. The MSWI bottom ash used to be landfilled, until environmental legislation and lack of space caused an increase in landfill rates. This disturbed the economics of incineration plants and consequently processing the MSWI bottom ash to re-usable materials became worthwhile.

The processing activities finally resulted into the erection of large scale plants where both MSWI bottom ash and also ferrous and non-ferrous metals were regained in a high quality.

This section shows the different general parameters which form the financial criteria for the upgrading and utilization of MSWI bottom ash.

Basic applications for MSWI bottom ash

Disposal as landfill lasted for many years, until development of environmental consciousness and the “Not In My Back Yard” syndrome, caused a significant rise in landfill costs. Sophisticated and upgraded utilization of MSWI bottom ash was found in the infrastructure, where the ash could be used as a substitute for bulk sandfill.

This new market was supported by thorough research and several pilot projects, and the results were used for legislation and certification. The results of this legislation and certification are discussed before, but the principles can also be seen in the financial aspects of the use of MSWI bottom ash. Usually the buyer receives a gate-fee, which has a triple purpose:

- payment of the costs of transportation from incineration plant to the project and workmanship
- payment of the isolation measures in its final application
- compensation for future removal of the MSWI bottom ash

The level of this fee also depends on the current price for sand fill (approximately \$ 7 per cubic m.), since MSWI bottom ash is a substitute for this material. In The Netherlands the gate fee can be as high as \$ 8 per tonne of the MSWI bottom ash.

Basic recycling solutions

Recycling plants must be capable of producing a granular material with a particle size of maximum 40 mm. Furthermore, these plants must be able to separate the ferrous and non-ferrous metals.

The amount of retrievable ferrous metals in untreated MSWI bottom ash can be up to 9 %, non-ferrous metals up to 0.65 %.

Because these materials give a positive revenue (depending on world market prices and the purity of the metals), upgrading plants form a combination of screening, crushing and magnetic activities.

The block schedule of such a plant (see Figure 3) is based upon the production of a high purity of ferrous and non-ferrous metals.

Financial aspects

To obtain a general view of financial aspects involved in upgrading of MSWI bottom ash and utilization of produced materials the following breakdown can be given.

Processing costs: fixed

- processing area: area required for the recycling plant (interest on capital)
- infrastructure: roads, storage area (interest and depreciation)
- stockpile area: to bridge the production capacity of the incineration plant (continuously, relatively low capacity) to the quantities required for infrastructural projects, a stockpile having a capacity of at least half a year production is required; this stockpile area also includes watersystems and sump (interest and depreciation)
- processing plant: mechanical, electrical, control and foundations (interest and depreciation)
- buildings: isolation (noise, dust) and protection (wind, rain), (interest and depreciation)
- labour: costs of employees (salary costs)
- repair and maintenance: a part of the repair and maintenance costs are independent from production (cleaning, maintenance contracts, spare parts, painting)
- equipment: shovel, dumper and various (interest loss and depreciation)
- miscellaneous: (insurances, taxes, certification, management fee, spare parts in stock, etc.)

Processing costs: variable

- repair and maintenance
- consumables: wear components, electricity, gas, oil
- labour: costs for temporary employees
- miscellaneous: (internal transportation, weighing, certification, etc.)

Material sale costs (including management fee)

- Fee gate for MSWI bottom ash
- Revenues for ferrous metals
- Revenues for non-ferrous metals

An example is given in Table 2, based upon the following parameters:

- capacity: 100,000 tons MSWI bottom ash a year
- labour: one shift of 40 hours per week
- costs for labour, investment, etc. are referring to Dutch circumstances
- anticipated investments:
 - total area: \$ 600,000 (10,000 m²)
 - infrastructure : \$ 250,000
 - building: \$ 500,000 (30 x 40 x 10 m)
 - processing plant: \$ 2,500,000
- Parameters:
 - lifetime upgrading plant 10 years

- percentage of interest: 8 % annual

Restriction

Typical Dutch investments are higher. In The Netherlands MSWI bottom ash recycling plants are built on the premises of incineration plants in dense populated areas usually having to comply with technical, environmental, architectural and availability demands of a round the clock incineration procedure.

CONCLUSIONS

Successful utilization of MSWI bottom ash requires a constructive approach of all parties involved. Existence of generally accepted environmental and physical quality standards is essential. Certification is a useful tool to facilitate the acceptance of the material in the market. Certification also helps to profile MSWI bottom ash as a well defined building material of uniform quality nationwide.

Table 1. Granulometry of certified MSWI bottom ash

coarse type on sieve	roadbase material	roadbase material	embankment material
	(0/20)	(0/20)	(0/40)
	unbounded % (m/m)	cementboundend % (m/m)	% (m/m)
45 mm	0	0	0 - 10
22.4 mm	0 - 10	0 - 10	-
8 mm	10 - 40	10 - 40	-
2 mm	40 - 70	30 - 70	-
63 µm	92 - 100	-	92 - 100

Table 2: financial aspects of upgrading and utilization

Description	Quantity	Unit	Price \$	Total \$
Processing costs: fixed				
- processing area	2,500	m2	30,000	
- infrastructure			40,000	
- stockpile area	7,500	m2	70,000	
- processing plant			330,000	
- buildings			70,000	
- labour	5	persons	190,000	
- repair and maintenance			30,000	
- equipment			40,000	
- miscellaneous			150,000	
				+
Total fixed processing costs				950,000
Processing costs: variable				
- repair and maintenance			130,000	
- consumables			250,000	
- labour			50,000	
- miscellaneous			100,000	
				+
Total variable processing costs				530,000
Material costs				
MSWI bottom ash	90,900	tons	730,000	
ferrous metals	8,500	tons	-300,000	
non-ferrous metals	600	tons	-300,000	
				+
Total material costs				130,000
TOTAL				1,610,000
Landfill	100,000	tons	50 \$/ton	5,000,000

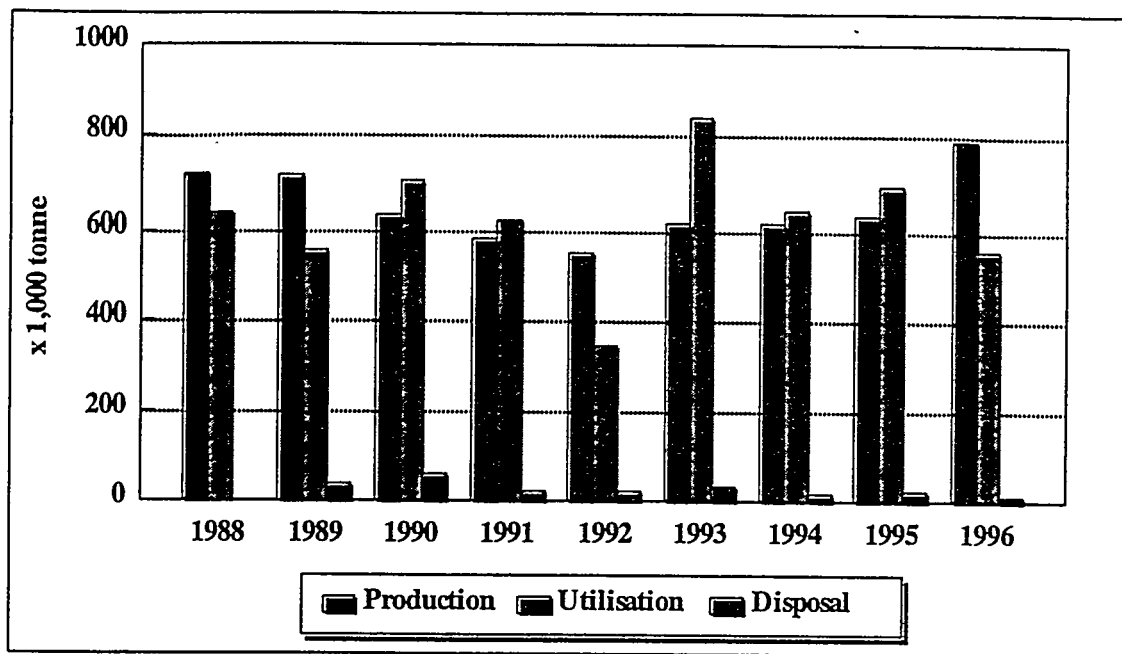


Figure 1. Amount of MSWI bottom ash in The Netherlands

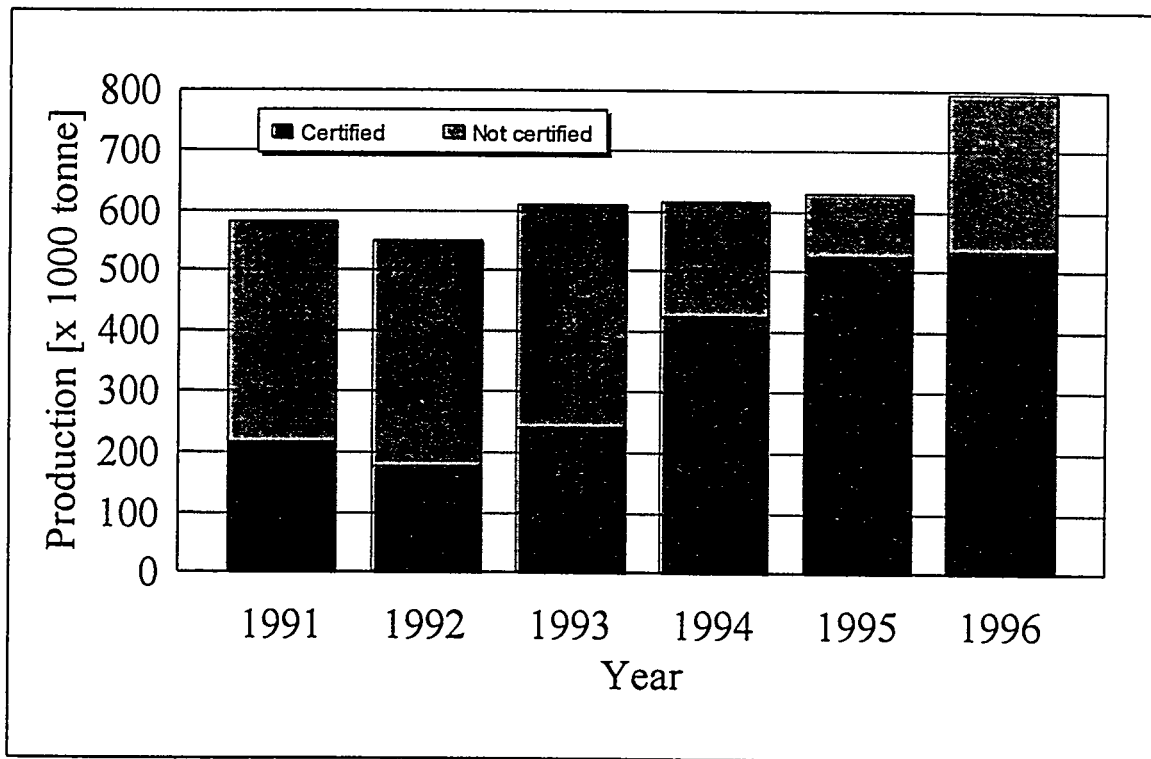


Figure 2 Production of MSWI bottom ash, fraction certified.

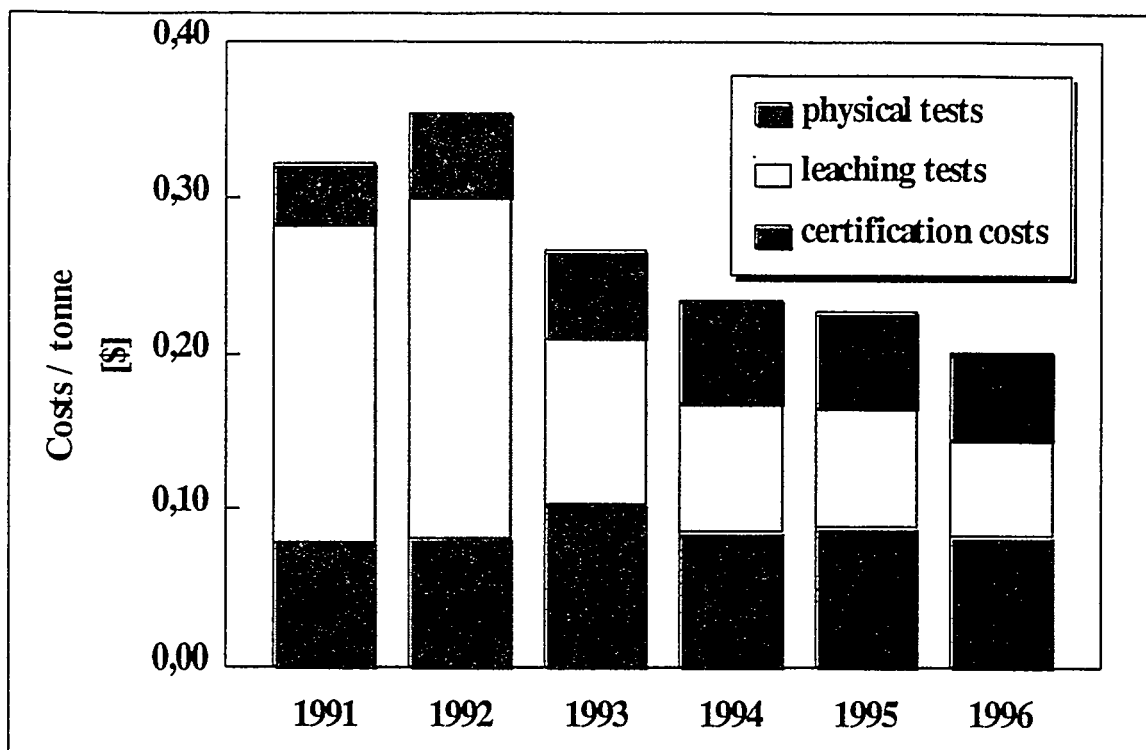


Figure 3 Costs related to certification of MSWI bottom ash

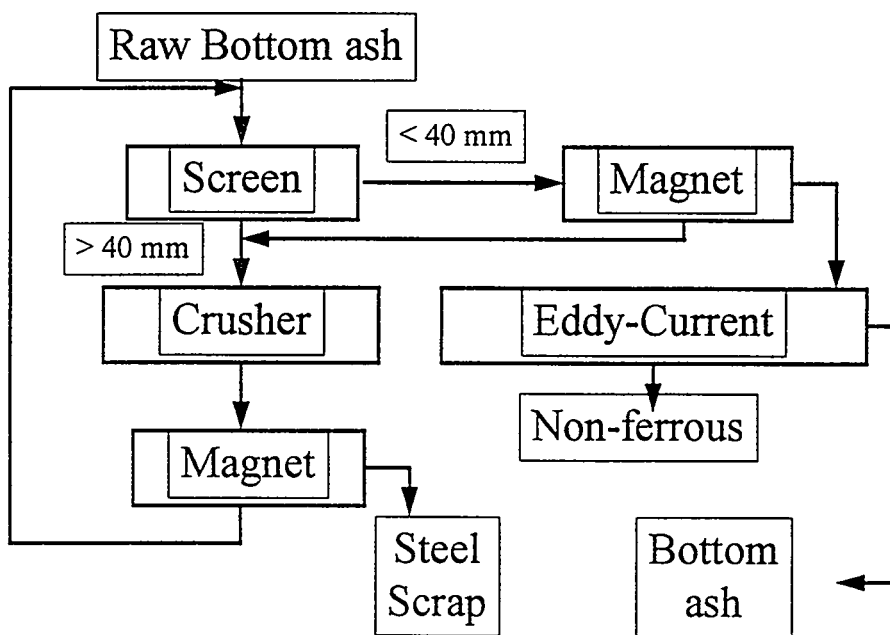


Figure 4 upgrading of MSWI bottom ash: block schedule

TECHNICAL SESSION IV

*Research & Emerging
Technologies*

Dioxin and Trace Metal Emissions From Combustion of Carbonized RDF Slurry Fuels

Mr. Michael Klosky
EnerTech Environmental, Inc.
430 Tenth Street, N.W.; Suite N-104
Atlanta, GA 30318

Dr. Michael Fisher
American Plastics Council
1801 K Street NW
Suite 701-L
Washington, DC 20006-1301

Mr. Arun Singhania
American Plastics Council/Amoco Chemicals
Polymers Business Group
4500 McGinnis Ferry Rd.
Alpharetta, GA 30202-3914

Mr. Pete Maly
Energy and Environmental Research Corporation
18 Mason
Irvine, CA 92718

Dr. Randy Seeker
Energy and Environmental Research Corporation
18 Mason
Irvine, CA 92718

INTRODUCTION

In 1994, the U.S. generated approximately 209 million tons of Municipal Solid Waste (MSW), with 61% landfilled, 24% recycled, and 15% processed through Municipal Waste Combustion (MWC).¹ In order to divert a larger portion of this generated MSW from landfills, MWC will have to play a growing role in MSW disposal. However, recently promulgated New Source Performance Standards (NSPS) for MWC will add an additional financial burden, through mandated emission reductions and air pollution control technologies, to an already financially pressured MWC marketplace.²

In the past, Refuse Derived Fuel (RDF), a solid fuel produced from MSW, has been fired in industrial and coal boilers as an alternative means of MWC. While lower sulfur dioxide (SO_2) emissions provided the impetus, firing RDF in industrial and coal boilers frequently suffered from several disadvantages including increased solids handling, increased excess air requirements, increased air emissions, increased slag formation in the boiler, and higher fly ash resistivity.³

Bituminous and higher rank coals can generally be slurried in water to form pumpable fuels of satisfactory solids loading, and hence heating value.⁴ These slurry fuels, sometimes termed Coal-Water-Mixtures (CWM) or Coal-Water-Fuels (CWF), are commercially fired in pulverized coal and oil boilers.⁵ However, low rank coals and solid fuels like MSW and RDF do not slurry as well. Supported by the U.S. Environmental Protection Agency (EPA), U.S. Department of Energy (DOE), and U.S. National Science Foundation (NSF), EnerTech has developed a process called SlurryCarb[™], which greatly improves the solids loading, heating value, chlorine content, and uniformity of MSW and RDF slurry fuels. It is anticipated that the enhanced carbonized slurry fuels can be effectively fired in pulverized coal or oil boilers without the previously cited disadvantages. This paper summarizes the latest emissions and combustion tests with the carbonized RDF slurry fuel. EnerTech completed this program in conjunction with the American Plastics Council (APC - Washington, DC) and the Energy and Environmental Research Corporation (EER - Irvine, CA).

With EnerTech's SlurryCarb[™] process (see Figure 1), a pumpable slurry of RDF is continuously pressurized with a pump to between 1200 and 2500 psi. The RDF slurry is pressurized above the saturated steam curve to maintain a liquid state when the slurry is heated to approximately 480 to 660°F. Slurry pressure and temperature then are maintained for less than 30 minutes in plug-flow reactors. At this temperature and pressure, oxygen functional groups in the molecular structure of the RDF are split off as carbon dioxide gas. This evolved carbon dioxide gas comprises a significant weight percentage of the feed RDF, but only a minimal percentage of the heating value. While the mass of total solids is reduced approximately 20-70%, the carbonized product still contains approximately 95-98% of the energy content of the feed RDF. The carbonized RDF particles are dramatically reduced in size and can be concentrated to a higher solids loading, and hence specific heating value, comparable to CWM and CWF. In addition, chlorinated organics in the RDF are decomposed to hydrochloric acid, neutralized with alkalis, and removed as chloride salts (along with a majority of other slag forming compounds), producing an essentially chlorine free carbonized RDF slurry fuel.

RESEARCH PERFORMED

The primary objective of this program was to determine the emissions of dioxins/furans, trace metals, and other flue gas pollutants from combustion of the carbonized RDF slurry fuel in a pilot scale pulverized coal boiler simulator. The combustion tests were completed in EER's 800,000 Btu/hr pilot scale Boiler Simulation Facility (BSF). Flue gases were sampled after an electrostatic precipitator, according to EPA

protocols, for dioxin/furans and trace metal emissions. Continuous Emission Monitors (CEMs) were utilized to determine carbon monoxide (CO), nitrogen oxides (NO_x), SO₂, and hydrochloric acid (HCl) emissions.

Carbonized RDF Slurry Fuel Preparation

RDF pellets from Thief River Falls, Minnesota have been used as the source material throughout EnerTech's process development program. This source of RDF was chosen due to its proximity to EnerTech's research facilities, and heating value and ultimate analysis similarity to RDF produced with wet based resource recovery operations (see table 1). The Thief River Falls Material Recovery Facility (MRF) receives mainly MSW, some commercial office waste, and limited agricultural solid waste. The incoming waste is shredded and hand picked to remove glass bottles, aluminum cans, and PET and HDPE plastic bottles. The remaining waste is trommeled, air classified, subjected to magnetic separation, and finally pelletized. The RDF for EnerTech's development program was purchased as pellets and then shredded by EnerTech in a Nelmor granulator to a minus 1/16-inch particle size. It is roughly estimated that the RDF consisted of approximately 60-70 wt.% paper, 15-20 wt.% plastics, and the balance "other" (dry basis).

The carbonized RDF slurry fuel for the combustion tests was produced using the University of North Dakota's Energy & Environmental Research Center's continuous 7.5 ton/day (wet basis) hot-water-drying pilot plant. A detailed description of this facility can be found in previous papers by EnerTech.^{6, 7, 8} In January 1996, a series of experiments was completed with this pilot plant in which the plastic content of the RDF was varied by adding the appropriate amount of virgin plastic materials. The objective of this program was to assess the effect of plastics on carbonized slurry fuel properties. Using a factorial design-of-experiment methodology, RDF total wt.% plastic, RDF plastic composition, reactor temperature, and RDF chlorine content were varied across eight distinct test conditions, and samples of each product stream were analyzed for relevant properties. The carbonized RDF from these eight tests was blended together and used as the carbonized RDF slurry fuel for the combustion tests described in this paper.

Fuel Delivery and Combustion Facility Description

Combustion tests with the carbonized RDF slurry fuel were completed in EER's pilot scale 800,000 Btu/hr BSF. The BSF (please see Figure 2) is a pulverized coal boiler simulator and was designed to provide an accurate simulation of the flue gas temperatures and residence times in a full scale utility boiler. The BSF consists of a burner, vertically down-fired radiant furnace, horizontal simulated convective pass, and electrostatic precipitator. A Moyno progressive cavity pump was used to pump the carbonized RDF slurry fuel to a variable swirl diffusion burner with an axial fuel injector. Compressed air was used to atomize the slurry fuel. In the burner, primary air was injected axially, while the secondary air stream was injected radially through the swirl vanes to give controlled fuel/air mixing. The cylindrical furnace section is constructed of eight modular refractory-lined sections with an ID of 22 inches and an overall furnace height of 22 feet.

The convective section of the BSF also is refractory lined, and consists of three horizontal passes, with each pass having a length of 18 feet and square dimensions of 8 inches by 8 inches. The convective section contains air cooled tube bundles to simulate the reheater, superheater, and economizer sections of a full scale boiler. A tubular electrostatic precipitator is located at the end of the convective pass for particulate control. Numerous coals, oils, and other fossil fuels previously have been tested in the BSF by EER, leading to the development of an extensive database of test procedures and results.

CEMs and Flue Gas Sampling Systems

Flue gas emissions from combustion of the carbonized RDF slurry fuel were determined through extractive manual sampling and a Continuous Emission Monitor (CEM) system. CEM components included a water cooled sample probe, sample conditioning system (to remove water and particulate), and gas analyzers. CEM sampling was performed in the convective pass upstream of the electrostatic precipitator (ESP), at a gas temperature of 600°F. Species analyzed, detection principles, and limits of precision are as follows:

- Oxygen (O₂): paramagnetism, 0.1 vol.% precision
- NO_x: chemiluminescence, 1 ppm precision
- CO: nondispersive infrared spectroscopy, 1 ppm precision
- Carbon Dioxide (CO₂): nondispersive infrared spectroscopy, 0.1 vol.% precision
- SO₂: nondispersive ultraviolet spectroscopy, 1 ppm precision
- HCl: gas filter infrared spectroscopy, 1 ppm precision (Servomex Model 2510 HCl analyzer)

Polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) were determined from combustion of the carbonized RDF slurry fuel through extractive sampling downstream of the ESP by EPA Method 23. The facility was operated such that the ESP inlet temperature was 320°F and the outlet temperature was 280°F where sampling was performed (temperature drop across the ESP was due to radiant and convective heat losses). With EPA Method 23, a flue gas sample is extracted isokinetically from the stack through a heated probe and filter, and directed into an impinger train. The sample trains were recovered immediately after sampling and the samples were sent to an analytical laboratory the next day for extraction and analysis. Analytical work was performed by Alta Analytical Laboratory, Inc. using high-resolution gas chromatography and mass spectrometry (DB5 column only since 2378-TCDD concentration was below 10 pg per sample and DB225 column was not needed). Quality assurance procedures included leak-checks, strict precleaning of apparatus, and charging and recovery of impinger modules under controlled conditions.

Coincident with PCDD/PCDF sampling, emissions of trace metals from combustion of the carbonized RDF slurry fuel were determined using EPA Method 29. Again, a flue gas sample was extracted isokinetically from the stack through a heated probe and filter, and directed into an impinger train. Metal analyses were performed by Research Triangle Institute. Mercury analysis was performed by cold vapor atomic absorption spectroscopy. All other metals were analyzed by inductively coupled plasma mass spectrometry. Rigorous quality assurance procedures again were applied, including leak-checks and strict precleaning of apparatus. Determination of mercury emissions included analysis of the KMnO₄ impinger. This procedure has been updated to prevent cross-contamination by using an empty impinger between the HNO₃ and KMnO₄ impingers. A lab blank also was run which did not reveal any interference or contamination.

RESEARCH RESULTS

Fuel Properties

Table 1 summarizes the fuel and rheological characteristics of the carbonized RDF slurry fuel used for the combustion test. As discussed, the carbonized RDF slurry fuel employed in this study was derived from a densified RDF spiked with additional plastics. When compared to CWFs or CMWs, the heating value and solids loading of the carbonized RDF slurry fuel were comparable. In addition, SlurryCarb[™] has significantly reduced the chloride, mercury, and cadmium content of the carbonized RDF slurry fuel from the Thief River Falls RDF. In order to complete the combustion tests with the worst case scenario

slurry fuel, the carbonized RDF was not washed to reduce chloride content, and the slurry fuel still contained significant chloride (approximately 700 ppm, dry basis). Washing of a small sample of the carbonized RDF reduced the chloride content to below 100 ppm (dry basis).

Slurry viscosity was determined by shearing a slurry sample in the annular space between a rotating cylinder and a stationary cup. The torque necessary to rotate the cylinder at a given speed was measured by a torsion spring. In general, slurry fuels are nonnewtonian fluids. With nonnewtonian fluids, the viscosity is dependent upon the shear rate and as a result, the rotating speed of the cylinder.

Emissions

The baseline firing rate of the carbonized RDF slurry fuel during the combustion test in EER's BSF was approximately 750,000 Btu/hr (approximately 130 lbs/hr, wet or slurry basis). Approximately 20% excess air was provided based upon the ultimate analysis of the slurry fuel. The total combustion air flow rate was 150 scfm. Primary air flow rate was 15 scfm or approximately 10% of the total combustion air. Atomization air also was approximately 15 scfm, with the balance of combustion air as secondary air (approximately 120 scfm). Tertiary air was not used. Combustion air was preheated to 200°F. Flue gas flow rate from the ESP was approximately 145 dry scfm.

EPA Method 23 was used to determine PCDD/PCDF emissions from combustion of the carbonized RDF slurry fuel. Two sampling periods were completed, and the analytical results were speciated into total PCDD/PCDF, five congeners (tetra- through octa-), and nine 2,3,7,8 substituted individual isomers. Table 2 summarizes the results of the two PCDD/PCDF sampling periods and calculated averages. Sampling times and analytical methods were established to provide a level of precision more than an order of magnitude greater than current regulatory NSPS for MWC. Each sampling period lasted approximately 2 hours. As can be seen from Table 2, total PCDD/PCDF concentration averaged 0.38 ng/dscm (7% O₂, dry basis) for the two sampling periods, which is 97% lower than the NSPS for MWC of 13 ng/dscm.

Figure 3 and Figure 4 depict the PCDD and PCDF congeners distribution. Reasonably good agreement was obtained between the total PCDD/PCDF concentration for the sampling periods, although the levels of individual isomers varied between each sampling period. Most species were present in measurable quantities, including all congener groups. The less chlorinated species were more abundant for both the PCDD and PCDF. A few isomers were below detection limits. Most notably, 2378 TCDD concentration was below the detection limit of 0.0013 ng/dscm (7% O₂, dry basis) for both runs.

Table 3 and Figure 5 summarize the 13 trace metal emissions characterized from the two sampling periods and calculated averages. Agreement between the two sampling periods was fairly good. For both sampling periods, arsenic and thallium were below the detection limits of 0.0005 and 0.0008 mg/dscm (7% O₂, dry basis), respectively, while beryllium was below the detection limit for the first run only. As can be seen from Table 3 and Figure 5, mercury emissions averaged 0.0066 mg/dscm (7% O₂, dry basis) for the two sampling periods, which is approximately 92% lower than the NSPS for MWC of 0.08 mg/dscm. Cadmium emissions averaged 0.0017 mg/dscm (7% O₂, dry basis), which is 83% lower than the NSPS for MWC of 0.01 mg/dscm. Lead emissions averaged 0.0346 mg/dscm (7% O₂, dry basis) for the two sampling periods, which is over 65% lower than the NSPS for MWC of 0.1 mg/dscm.

Table 4 includes the average emissions of NO_x, CO, SO₂, and HCl across both sampling periods (approximately 4 hours) and compares them to the recently promulgated NSPS for MWC. CO emissions averaged 59 ppmv (7% O₂, dry basis) with a standard deviation of 22 ppmv. These CO emissions were

comparable to the NSPS for MWC of 50-150 ppmv (7% O₂, dry basis), but were significantly higher than previous reported combustion experiments by EnerTech with the carbonized RDF slurry fuel.⁸ The higher CO emissions likely were due to lower flame temperatures caused by the higher water content of the slurry fuel, and poorer atomization. Please note that CO emissions from the carbonized RDF slurry fuel were achieved with excess air levels of approximately 20%.

NO_x emissions averaged 132 ppmv (7% O₂, dry basis) with a standard deviation of 16 ppmv. These NO_x emissions were approximately 12% lower than the NSPS for MWC, without any catalytic or non-catalytic reduction. The NSPS for MWC of 150 ppmv (7% O₂, dry basis) is based upon selective non-catalytic reduction NO_x control.

HCl emissions from combustion of the carbonized RDF slurry fuel averaged 6 ppmv (7% O₂, dry basis) with a standard deviation of 2 ppmv. Compared to the NSPS for MWC, HCl emissions were 75% lower, without any acid gas scrubbing. Please note that the NSPS for MWC is based upon acid scrubbing for HCl emission control. Based upon the carbonized RDF chloride content, the theoretical HCl emission concentration was 40 ppmv (7% O₂, dry basis) assuming complete conversion of chloride to HCl. This indicates that approximately 85% of the fuel chloride was not converted to HCl or was removed from the flue gas through capture by alkaline ash components.

SO₂ emissions averaged 71 ppmv (7% O₂, dry basis) with a standard deviation of 8 ppmv, or approximately 0.13 lbs SO₂/10⁶ Btu. The theoretical emission concentration was 80 ppmv (7% O₂, dry basis), based on the carbonized RDF slurry fuel sulfur content and assuming complete conversion of fuel sulfur to SO₂. This indicates that approximately 12% of the fuel sulfur was captured by ash mineral matter or not converted to SO₂. SO₂ emissions were higher than the NSPS for MWC of 30 ppmv, and likely would require approximately 60% reduction through sorbent injection to comply with this standard. However, when compared to coal, the carbonized RDF slurry fuel would be considered a premium ultra-low sulfur fuel, even under Phase II of the Clean Air Act Amendments of 1990 (CAAA). The CAAA Phase II SO₂ emission limit for coal boilers will be approximately 1.2 lbs/10⁶ Btu. Under the CAAA, up to 30% of the coal boiler's input could be the carbonized RDF, and SO₂ emissions would be regulated under the 1.2 lbs/10⁶ Btu standard.

Emissions of CO, NO_x, and PCDD/PCDF are not only dependent on fuel composition but also burner design and furnace operating conditions, and comparison to full scale boiler performance requires application of scaling parameters on a boiler specific basis. The CO and NO_x emissions from combustion of the carbonized RDF slurry fuel were near the low end range of CO and NO_x emissions measured for several dozen coals at EER's BSF and should be similar to commercial scale performance of pulverized coal boilers. In general, SO₂ and HCl from EER's BSF are indicative of commercial scale performance and scaling factors are not needed. Insufficient data exists for PCDD/PCDF emissions from coal combustion in EER's BSF to make any inferences about necessary scaling factors and commercial scale performance.

The filter on the EPA Method 23 train was used to measure fly ash loading of the combustion flue gases. During the two sampling periods, the average particulate matter (PM) loading of the exit flue gases from the ESP was 31.2 mg/dscm (7% O₂, dry basis). Compared to the NSPS for MWC, the PM emissions would have to be reduced approximately 50% to comply with the standard of 15 mg/dscm. However, this is easily accomplished through a higher collection efficiency with the ESP. Based upon ash content of the carbonized RDF slurry fuel, approximately 99.6% of the PM was removed by dropout in the BSF and by the ESP.

A high volume sampler with a full page filter was used to obtain an ash sample upstream of the ESP for carbon burnout analysis. Through laboratory analysis, carbon content of the fly ash was determined to be 0.46 wt.% (dry basis). This corresponds to 99.92% carbon burnout, which is extremely good. This carbon conversion also is similar to or slightly better than carbon burnout levels typically obtained with pulverized coal firing.

CONCLUSIONS

The carbonized RDF slurry fuel combusted exceptionally well, under conditions which were typical of a modern pulverized coal or oil boiler. Overall, the emissions from combustion of the carbonized RDF slurry fuel ranged significantly lower to comparable to the recently promulgated NSPS for MWC, especially total PCDD/PCDF emissions. Total PCDD/PCDF emissions were approximately 0.38 ng/dscm (7% O₂, dry basis) or 236×10^{-6} lbs/10¹² Btu, which were 97% lower than the promulgated NSPS.

As a comparison, dioxin and furan emissions recently have been characterized from a number of coal boilers. The emissions from nine of these coal boilers have been summarized in a recent report to the DOE.⁹ In general, the reported concentrations for individual isomers and total PCDDs/PCDFs were at the detection limit values or invalidated by a blank detection at similar concentrations. As an example, the total PCDD/PCDF emissions were determined using EPA Method 23 across three days of stack sampling from Cooperative Power Association's 1,100 MW Coal Creek Station Unit No.1 in Underwood, North Dakota, firing 100% lignite coal from the Falkirk mine. Fourteen out of seventeen of the individual isomers were below detection limits for all three sampling periods. An emission factor then was estimated as a summation of half the detection limit plus the concentrations all isomers detected. Based upon this calculation procedure, the total PCDD/PCDF emissions from the Coal Creek Station were estimated to be approximately 38×10^{-6} lbs/10¹² Btu.¹⁰ These coal-fired dioxin/furan emissions were the same order of magnitude for dioxin/furan emissions from combustion of the carbonized RDF slurry fuel. However, the variety of coal types and boiler configurations is immense and emission data of total PCDD/PCDF limited, so that any conclusions or comparisons should be interpreted cautiously.

The emissions of several trace metals from the nine coal boilers also were summarized in the previously cited report to the DOE.⁹ Unlike PCDD/PCDF emissions from coal boilers, the majority of individual trace metal emissions were higher than the detection limits and could be quantified. Table 5 compares the range of trace metal emissions from the nine coal boilers to the carbonized RDF slurry trace metal emissions. For the majority of the characterized metals, the carbonized RDF slurry fuel emissions were near the low to middle range of the coal boiler emissions, except for antimony and lead which were near or over the high range. It is noteworthy that the coal boiler trace metal emissions generally vary by one to four orders of magnitude, and again any conclusions or comparisons should be interpreted cautiously.

The results presented in this paper and previously cited papers by EnerTech formed the basis for the design and construction of a 20 ton/day (as received MSW basis) demonstration facility of wet resource recovery and SlurryCarbTM. The demonstration facility was designed and constructed in Japan by a consortium of Japanese companies and began operation in February 1997. Future technical papers will discuss this facility.

ACKNOWLEDGMENTS

The research presented in this paper was performed with the support from the American Plastics Council (APC) and the U.S. EPA Small Business Innovative Research Phase II Program. EnerTech thanks the APC and EPA for their support. However, co-sponsors, their employees and members make no warrantee, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, product, or process disclosed in this paper or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process or service by trade name, trademark, or otherwise, does not constitute or imply its endorsement, recommendation, or favoring by the co-sponsors, their employees or members.

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TABLES

	Reno, Nv. Wet RR RDF^{a,b}	Thief River Falls, Mn. RDF	Carbonized RDF Slurry Fuel
Ultimate, wt.%, dry			
Carbon	52.3	45.7	68.4
Hydrogen	7.9	5.6	7.7
Nitrogen	0.9	0.9	0.4
Sulfur	0.3	0.2	0.1
Oxygen (difference)	32.0	39.2	11.4
Ash	6.6	8.4	12.0
Chlorine, µg/g, dry	4,100	3,000	700
Mercury, µg/g, dry	N.D.	0.30	0.09
Cadmium, µg/g, dry	N.D.	1.28	0.50
Lead, µg/g, dry	N.D.	29.8	82.0
Rheology (Sheared)			
Viscosity, cP @ 100 Hz↓	500	500	340
Solids Load., wt.%	11.2	9.1	43.9
Higher Heating Value			
dry, Btu/lb	9,560	7,995	13,350
Slurry, Btu/lb	1,070	730	5,865

a) Wet RR = Wet based resource recovery process

b) Reno, Nevada MSW was processed with Biomass Systems, Inc. (San Leandro, Ca.) wet RR pilot plant

Table 1 - Fuel Properties of Raw RDF and Carbonized RDF Slurry Fuel.

	Sampling Period 1 (ng/dscm) ^a	Sampling Period 2 (ng/dscm) ^a	Average (ng/dscm) _a
Total TCDD	0.0838	0.0167	0.0502
2378 TCDD	<0.0013	<0.0013	<0.0013
Total PeCDD	0.0603	0.0116	0.0360
12378 PeCDD	<0.0017	<0.0017	<0.0017
Total HxCDD	0.0540	0.0273	0.0407
123478 HxCDD	0.0024	<0.0014	0.0018
123678 HxCDD	0.0041	0.0029	0.0035
123789 HxCDD	0.0031	0.0022	0.0027
Total HpCDD	0.0238	0.0233	0.0236
1234678 HpCDD	0.0119	0.0127	0.0123
OCDD	0.0343	0.0360	0.0352
Total PCDD	0.2562	0.1149	0.1857
Total TCDF	0.1050	0.0558	0.0804
2378 TCDF	0.0044	0.0024	0.0034
Total PeCDF	0.0365	0.0385	0.0375
12378 PeCDF	0.0034	0.0044	0.0039
23478 PeCDF	0.0033	0.0039	0.0036
Total HxCDF	0.0217	0.0314	0.0266
123478 HxCDF	0.0050	0.0066	0.0058
123678 HxCDF	0.0028	0.0047	0.0037
123789 HxCDF	<0.0019	0.0031	0.0025
234678 HxCDF	0.0026	0.0034	0.0030
Total HpCDF	0.0182	0.0355	0.0269
1234678 HpCDF	0.0084	0.0223	0.0153
1234789 HpCDF	0.0029	0.0061	0.0045
OCDF	0.0112	0.0344	0.0228
Total PCDF	0.1926	0.1956	0.1942
Total PCDD/PCDF	0.4488	0.3105	0.3799
TEQ^{b,c}	0.0057	0.0063	0.0061

a) All emissions corrected to 7% O₂, dry basis

b) TEQ = Toxicity Equivalency of 2,3,7,8-TCDD (EPA Toxic Equivalent Factors - 1989)

c) Totals include half the detection limits for those compounds that were below detection limits

Table 2 - Summary of PCDD/PCDF Emissions From Combustion of the Carbonized RDF Slurry Fuel.

	Sampling Period 1 (mg/dscm) ^a	Sampling Period 2 (mg/dscm) ^a	Average (mg/dscm) _a
Antimony (Sb)	0.0176	0.0304	0.0240
Arsenic (As)	<0.0005	<0.0005	0.0002
Barium (Ba)	0.0076	0.0120	0.0098
Beryllium (Be)	<0.0001	0.0001	0.0001
Cadmium (Cd)	0.0013	0.0021	0.0017
Total Chromium (Cr)	0.0041	0.0086	0.0064
Copper (Cu)	0.0162	0.0322	0.0242
Lead (Pb)	0.0250	0.0443	0.0346
Manganese (Mn)	0.0233	0.0241	0.0237
Mercury (Hg)	0.0060	0.0071	0.0066
Nickel (Ni)	0.0029	0.0045	0.0037
Selenium (Se)	0.0001	0.0001	0.0001
Thallium (Tl)	<0.0008	<0.0008	0.0004

a) All emissions corrected to 7% O₂, dry basis

Table 3 - Summary of Trace Metal Emissions From Combustion of the Carbonized RDF Slurry Fuel.

	EnerTech		Municipal Waste Combustion	
	Carb. RDF Emissions ^a	Control Technolog y	1995 NSPS ^{a,b}	Required Control Technology
Carbon Dioxide (CO ₂), vol. %	11.1	-----	-----	
Carbon Monoxide (CO), ppmv	59	None	50-150	Good Combustion Practice
Nitrogen Oxides (NO _x), ppmv	132	None	150	SCR or SNCR
Sulfur Dioxide (SO ₂), ppmv	71	None	30	Acid Scrubber
Hydrochloric Acid (HCl), ppmv	6	None	25	Acid Scrubber
Total PCDD/PCDF, ng/dscm	0.38	None	13	Activated Carbon Injection
TEQ ^c , ng/dscm	0.0061	None	0.20 ^d	Activated Carbon Injection
Mercury (Hg), mg/dscm	0.0066	None	0.08	Activated Carbon Injection
Cadmium (Cd), mg/dscm	0.0017	ESP	0.01	Baghouse or ESP
Lead (Pb), mg/dscm	0.0346	ESP	0.1	Baghouse or ESP
Particulate Matter (PM), mg/dscm	31.2	ESP	15	Baghouse or ESP

a) All emissions corrected to 7% O₂, dry basis

b) NSPS = New Source Performance Standards, published December 19, 1995 in the *Federal Register*

c) TEQ = Toxicity Equivalency of 2,3,7,8-TCDD (EPA Toxic Equivalent Factors - 1989)

d) Dioxins are not regulated by TEQ under the NSPS, and TEQ is presented for reference only

Table 4 - Summary of Emissions From Combustion of the Carbonized RDF Slurry Fuel and Comparison to NSPS For MWC.

	Carbonized RDF Slurry Fuel		Range From Coal Boilers ⁹	
	Average (mg/dscm) ^a	Average (lb/10 ¹² Btu)	Low (lb/10 ¹² Btu)	High (lb/10 ¹² Btu)
Antimony (Sb)	0.0240	20.22	0.04	2.4
Arsenic (As)	0.0002	0.22	0.14	3.5
Barium (Ba)	0.0098	8.25	N.A.	N.A.
Beryllium (Be)	0.0001	0.07	0.04	1.7
Cadmium (Cd)	0.0017	1.43	0.03	3.2
Total Chromium (Cr)	0.0064	5.37	0.13	51
Copper (Cu)	0.0242	20.39	N.A.	N.A.
Lead (Pb)	0.0346	29.17	0.53	29
Manganese (Mn)	0.0237	19.95	2.60	30
Mercury (Hg)	0.0066	5.53	0.44	22
Nickel (Ni)	0.0037	3.13	0.55	40.1
Selenium (Se)	0.0001	0.08	0.02	193
Thallium (Tl)	0.0004	0.34	N.A.	N.A.

a) All emissions corrected to 7% O₂, dry basis

Table 5 - Comparison of Carbonized RDF Slurry Fuel and Coal Boiler Trace Metal Emissions.

FIGURES

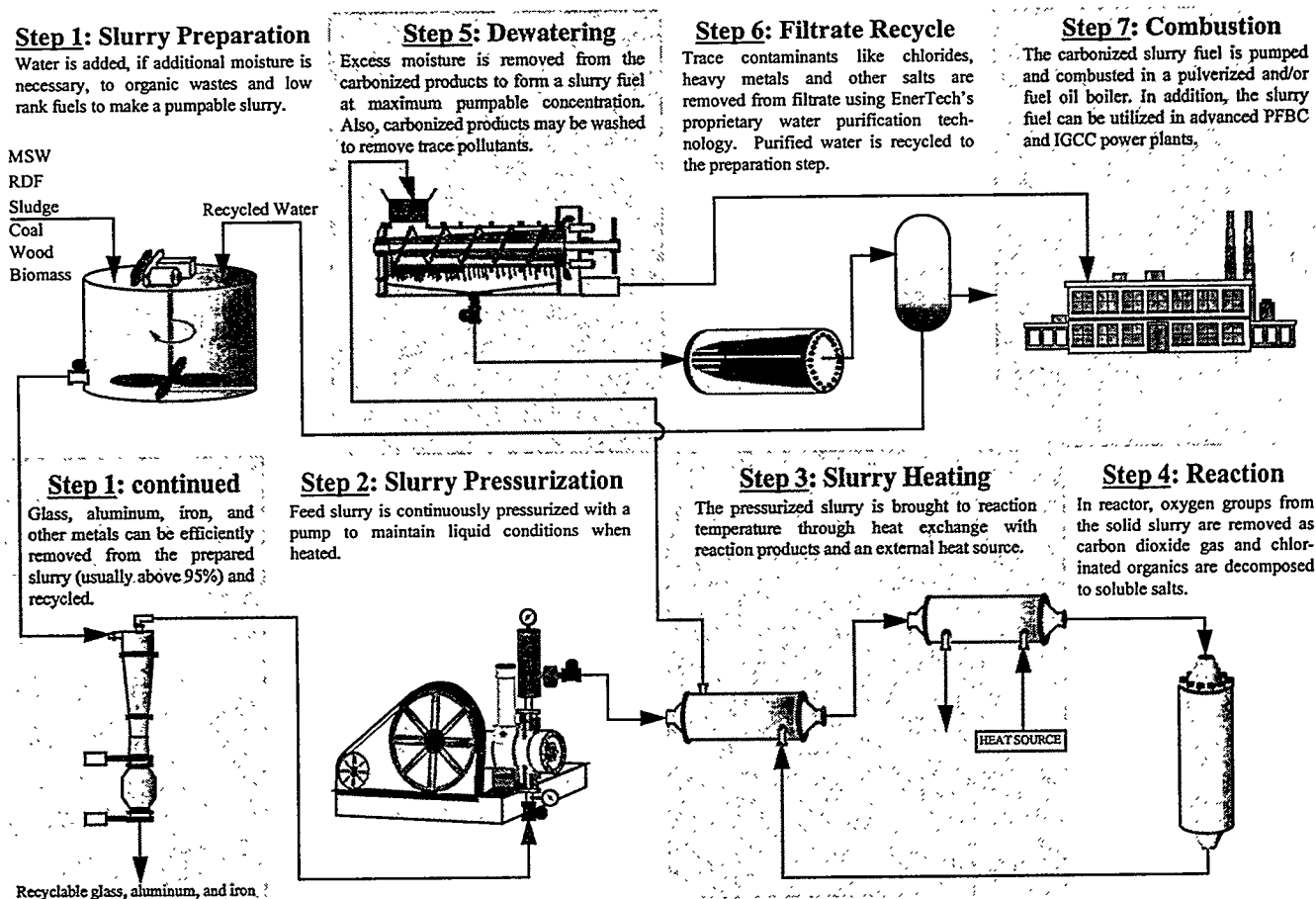


Figure 1 - Simplified Flow Diagram of EnerTech's SlurryCarb™ Process.

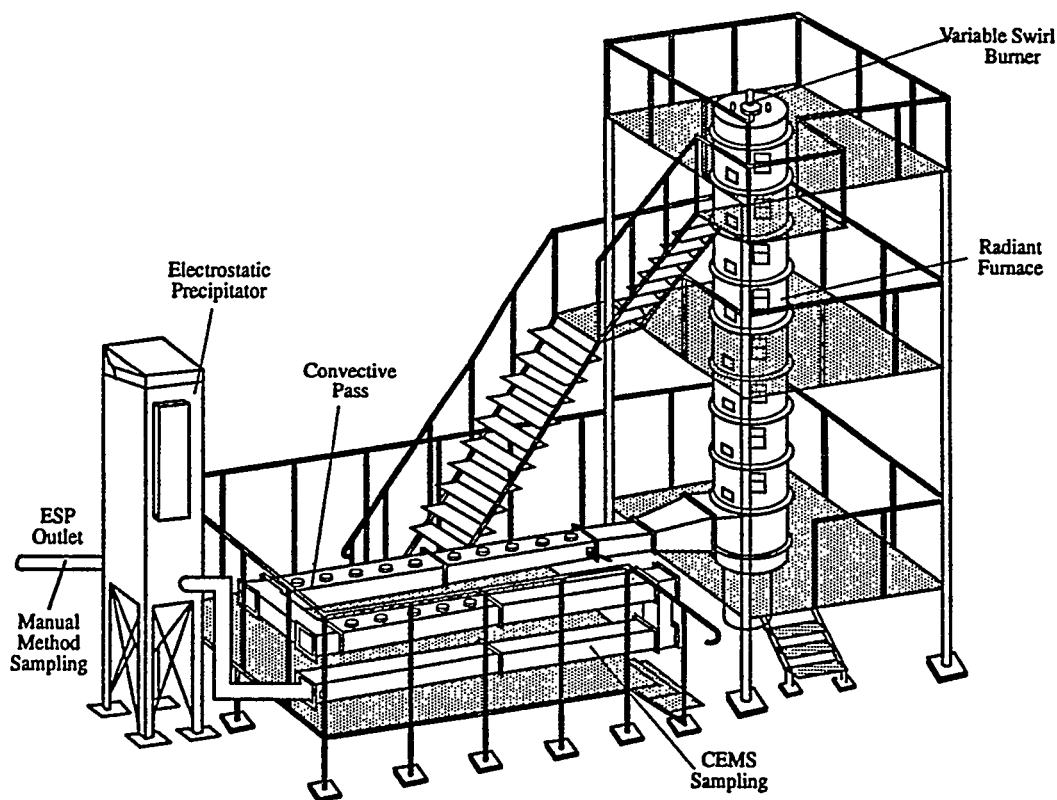


Figure 2 - Simplified Schematic of EER's 800,000 Btu/hr Boiler Simulation Facility (BSF).

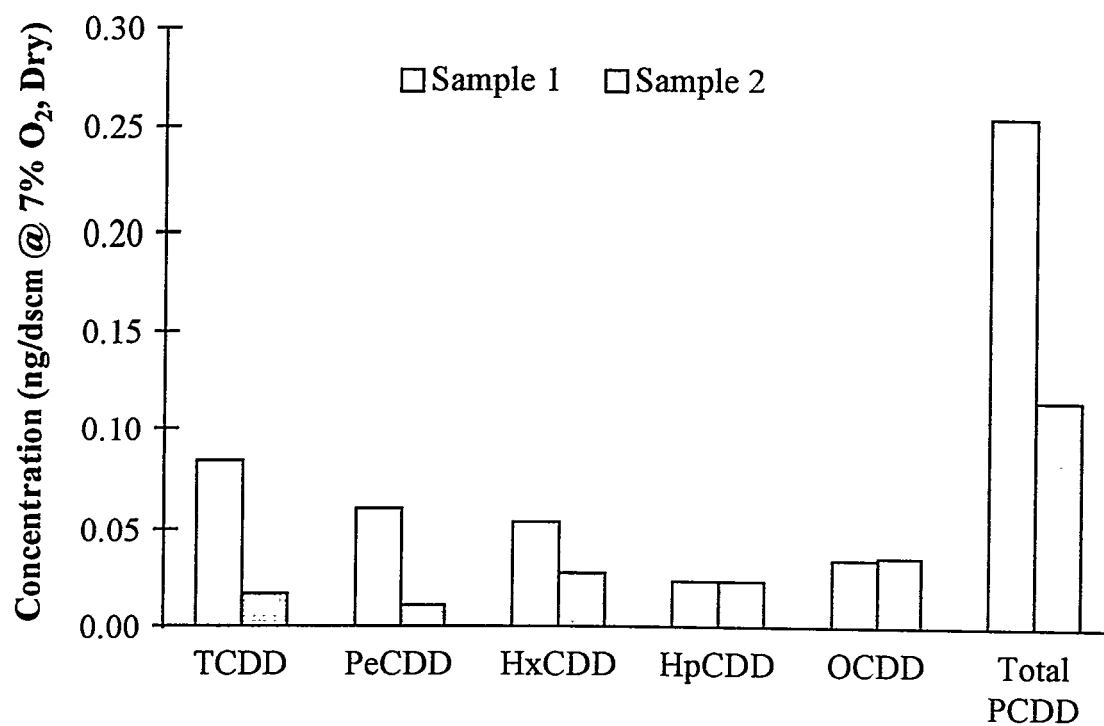


Figure 3 - Distribution of PCDD Congeners From Combustion of the Carbonized RDF Slurry Fuel.

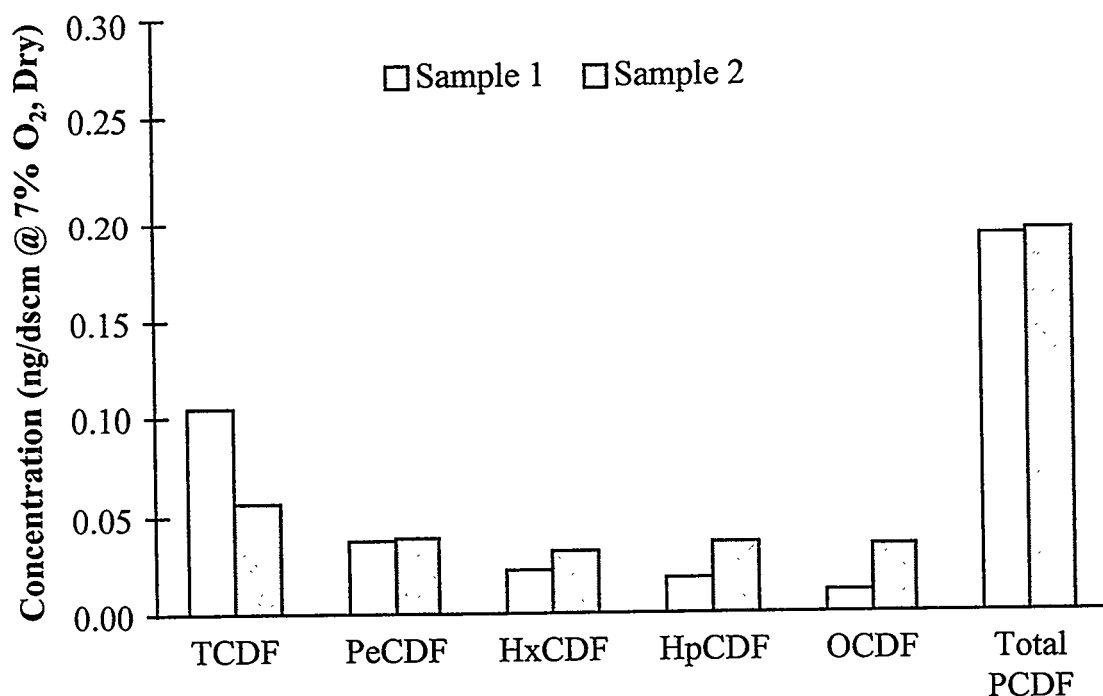


Figure 4 - Distribution of PCDF Congeners From Combustion of the Carbonized RDF Slurry Fuel.

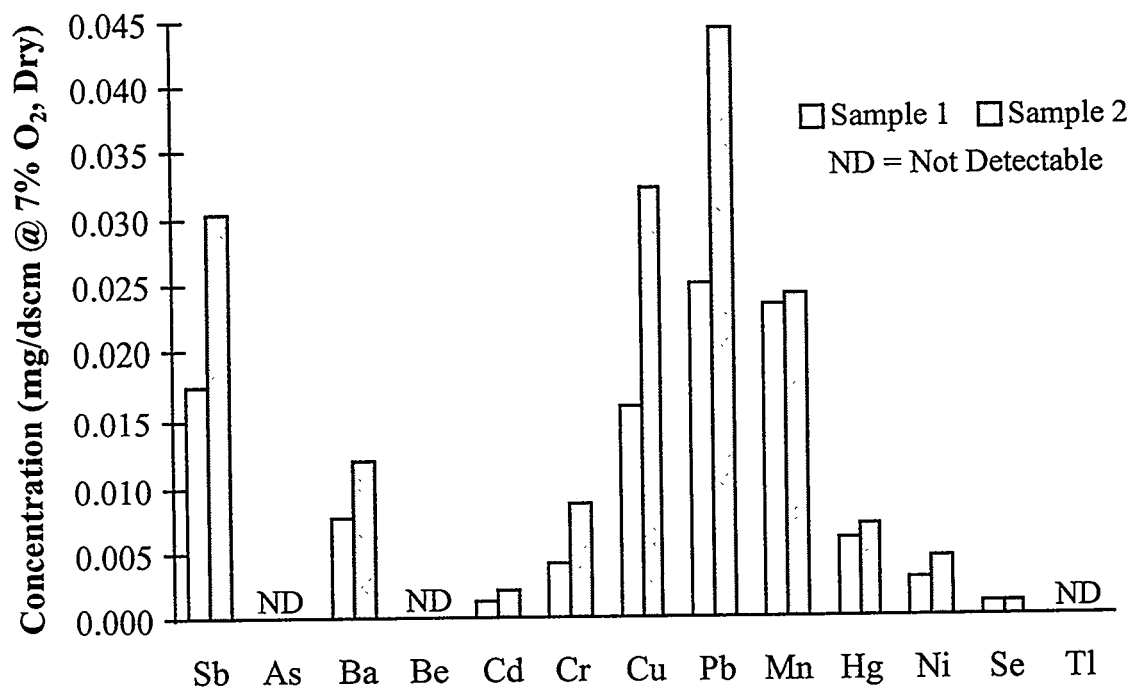


Figure 5 - Summary of Trace Metal Emissions From Combustion of the Carbonized RDF Slurry Fuel.

Prevention of PCDD/PCDF Formation by Coal Co-Firing

K. Raghunathan
Acurex Environmental Corporation
4915 Prospectus Drive
Durham, NC 27713

Brian K. Gullett, Chun Wai Lee, James D. Kilgroe
Air Pollution Prevention and Control Division
National Risk Management Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

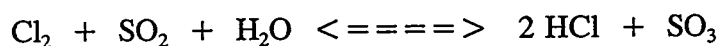
James E. Dunn
Department of Mathematical Sciences
University of Arkansas
Fayetteville, AR 72701

INTRODUCTION

Formation of polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) has been observed in waste combustors. However, PCDD and PCDF yields from coal combustion are relatively insignificant. Previous bench- and pilot-scale research^{1,2} has shown that the presence of sulfur dioxide (SO₂) can inhibit PCDD and PCDF formation, and suggested co-firing high-sulfur coal with refuse-derived fuel (RDF) to reduce the emissions. This work describes research in a large scale combustor which shows that coal/RDF co-firing can significantly lower PCDD and PCDF formation.

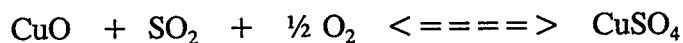
PCDD and PCDF formation mechanisms have been reviewed in detail by Addink and Olie.³ Measured yields can be affected by the combustion quality, levels of chlorine and catalyst species, residual carbon on the fly ash, and process parameters such as temperature and residence time. Two candidate mechanisms have been established for the inhibition of PCDD and PCDF formation by sulfur species:

1) Gas-phase reaction where SO₂ converts chlorine (Cl₂) to hydrogen chloride (HCl), a less-likely chlorinating agent^{4,2}:



Our recent work² appears to confirm this mechanism as a possibility.

2) Poisoning of copper catalysts by SO₂¹:



It has been shown that copper sulfate (CuSO₄) is a less active catalyst for the production of Cl₂ through the Deacon process, as well as for the biaryl synthesis step of PCDD and PCDF formation.¹

Lindbauer et al.⁵ have reported that co-firing coal in a municipal solid waste (MSW) incinerator leads to appreciably lower PCDD and PCDF levels. Recently, Ogawa et al.⁶ compared the effect of adding pure SO₂ versus generating SO₂ through coal addition, and found the latter to be more effective. Thus, there may be other benefits with coal co-firing than simply being a source of SO₂.

In this work, experiments were conducted in a large, pilot-scale unit which is a state-of-the-art facility with fuel handling and combustion release rates representative of large field units. The effect of coal co-firing was studied for two types of municipal-waste-based solid fuels. Tests were conducted over a range of process variables (e.g., calcium hydroxide [Ca(OH)₂] injection, HCl concentration, flue gas temperature, quench, and residence time) so that the results could have implications for a wide variety of waste combustors.

EXPERIMENTAL FACILITY AND PROCEDURES

The newly constructed, EPA Multi-Fuel Combustor (MFC) facility was used for conducting tests for this project. The MFC is rated at 0.6 MW (2x10⁶ Btu/hr) thermal output and is capable of burning a wide variety of solid fuels including MSW, RDF, biomass, and coal. The modular design of the

facility provides flexibility for studies on various pollutant emissions and control and for solid fuels with unknown firing and handling characteristics.

A schematic and a layout view of the MFC facility are shown in Figures 1 and 2, respectively. The MFC consists of a waste feeding system, a coal feeder, a lower combustion chamber containing a stoker, a radiant section, a convective flue gas passage, a baghouse, and a scrubber system. In addition, there is a separate fuel preparation system for shredding, screening, and mixing of the fuel. A large loading hopper conveys the processed fuel to the fuel silo.

As indicated in Figure 2, there are several ports for flue gas sampling and temperature measurements along the convective section and the duct. The convective section is equipped with cooling coils with high-pressure water circulation. The cooling coil originally present in location B was removed for this project, to accommodate PCDD/PCDF sampling. A typical temperature drop across the convective section is from 600 to 150°C which includes the PCDD/PCDF formation temperature "window" (200 to 500°C). Residence time/quench across this window is known to be an important parameter, and it can be varied in our tests by changing the temperature set point of the cooling water. From the convective section, flue gas was sampled through continuous emission monitors (CEMs) for recording the oxygen (O₂), carbon dioxide (CO₂), carbon monoxide (CO), HCl, and SO₂ concentrations.

The test program involved two major phases: In Phase I, the waste-derived fuel used was commercial RDF from municipal waste. The as-received RDF did contain some larger pieces and had to be run through the shredder in order to avoid clogging of the feed system. With this shredded fuel (simply referred to as "RDF" in this paper), the feed and burn could not be controlled sufficiently and the temperatures were lower than that observed in typical waste combustor operation. As a result, the flue gas O₂ and CO levels were higher than desired. Therefore, only a few tests were run with the RDF. To alleviate this problem, a commercial, densified refuse-derived fuel (dRDF), again from municipal waste, was acquired for subsequent testing under Phase II. The combustor operation was much improved with more uniform fuel feed and lower CO levels. In both phases, the coal used was an Illinois #6 coal, donated by Monterey Coal Company, Carlinville, IL, for this project. The coal was ground and classified to an average size of about 1 mm. The coal was fed using a screw feeder and entered the burner at the same location as the RDF/dRDF. Analyses of the dRDF and coal are shown in Table 1.

For Phase I, tests included separate RDF and coal baseline tests and a RDF/coal co-fired test. Under Phase II (dRDF), the experiments were structured to provide information on all two-factor interactions among the parameters of coal feed, dRDF feed rate, quench, sorbent injection, and HCl addition. During each test, the fuel feed rate was adjusted, whenever necessary, to maintain a constant flue gas temperature. Nearly the same firing rate was maintained between tests, again, by matching the flue gas temperature reading. For low fuel feed runs, natural gas was co-fired to compensate for the decrease in heat release and maintain similar temperature ranges between runs. Quench was varied by varying the temperature set point of the cooling water used in the convective section of the furnace. For runs with HCl addition, there was about a 100 ppm increase in HCl concentration. The sorbent used was a commercial hydrated lime, fed as a slurry at a Ca/Cl ratio of about 1.5. The sorbent injection temperature was approximately 700°C. Under Phase II, a total of 30 tests, including blanks, were run for various parameter settings.

For most of the runs, flue gas was sampled from two locations (A and B in Figure 2) for PCDD/PCDF according to EPA Method 23.⁷ For selected runs, dioxin samples were drawn from an additional sampling port, just before the convective section (location D). Before and after running Method 23 trains, a velocity traverse of the duct was carried out to measure the flue gas flow rate. The samples were analyzed in EPA's in-house Organics Support Laboratory (OSL), via procedures described elsewhere.² Recently, the OSL has expanded its capability to include quantification of mono-tri PCDD and PCDF congener class mass as well. Thus, the results obtained are levels of each mono-octa PCDD and PCDF congener class in the sample. However, since mono-tri PCDD and PCDF are not subject to regulation, most of the following discussions are based on the tetra-octa PCDD/PCDF yields.

RESULTS AND DISCUSSION

Phase I tests with the RDF

The run conditions and sampling data are provided in Table 2. For the trial RDF burn (run 1), the temperatures were lower, resulting in high CO formation. Runs 2 and 4 involved better combustion conditions, although there were CO excursions exceeding 2000 ppm. Run 3 was a natural gas blank between runs 2 and 4, with no RDF or coal feed. Run 5 was a coal baseline and run 6 the coal/RDF co-fired test. Results from the above tests are shown in Figure 3 as tetra-octa total PCDD+PCDF yield.

Substantial levels of PCDD and PCDF are measured at both sampling locations (A, B) for the RDF combustion. In fact, the difference in yields between the two locations is small. Thus, much of the formation takes place in-flight, within seconds from the burner. It is clear that an effective control technology should discourage this formation, before the flue gas and particles reach the particulate control device. Combustion quality appears to play an important role in PCDD and PCDF formation: run 1 (high CO and lower temperature) yields are much higher than those from run 2 or run 4. Given the variations in the run conditions and the nature of PCDD/PCDF formation, the difference between the two RDF baseline run (runs 2 and 4) yields is small, rendering credibility to the data obtained. Also, as with field units, yields of PCDF are higher than those of PCDD in these tests. However, the CO levels in our RDF baseline tests are higher than in typical municipal waste combustors (MWCs).

Contrary to the RDF, no PCDD or PCDF was detected from coal burning (run 5). Even the natural gas blank test (run 3) yielded PCDD/PCDF, although at much lower levels compared to RDF. Although the system was blown with a high flow of air prior to each test, some particle deposition on the system walls from earlier testing is inevitable, and could cause measurable yields even with natural gas. However, the coal baseline test showed no such residual or hysteresis effect. It appears that flue gas from coal burning, presumably SO₂, strongly inhibits formation.

The addition of coal to RDF in the co-fired test provided better burn conditions -- increased temperatures and lower CO. In this test (run 6), the resulting sulfur-to-chlorine (S/Cl) ratio was about 1.5. Under these conditions, the PCDD and PCDF yields decreased sharply from the RDF baseline levels. Past work at the EPA facilities² had suggested a S/Cl ratio of above 1.2 for effective PCDD/PCDF emission control. Thus, Phase I tests indicate that co-firing RDF with high-sulfur coal is an effective option for MWCs to inhibit PCDD and PCDF formation.

Phase II tests with the dRDF

For each test, temperature and flue gas composition data were stored in the data acquisition system. Run averages of these data were calculated for the duration of PCDD/PCDF sampling so that these values correspond to the measured yields. With the total flue gas flow rate known from the velocity traverse data, the average flue gas temperature profile data were used to determine the flue gas residence times at various locations in the MFC. In the temperature profiles, the residence time variable, t_R , is set to zero at 650°C. The choice of 650°C stems from the fact that most of PCDD/PCDF formation is known to take place below this temperature. In this project, for three runs, PCDD/PCDF levels were measured for the high-temperature ($\sim 600^\circ\text{C}$) dioxin sampling port (Port D), and the yields were relatively small.

Ranges of measured/estimated parameter values for Phase II tests are given in Table 3. The gas composition data show low CO levels from dRDF burning, indicating good combustion quality. In general, yields from dRDF combustion were lower compared to RDF combustion. The possible reasons are that, with the former, the HCl concentration in the flue gas is lower and the combustion quality is better (lower CO).

For one of the dRDF baseline tests (without coal), PCDD/PCDF levels were measured at three different sampling ports and the results are shown in Figure 4. The figure shows the total PCDD and PCDF yields for tetra-octa as well as for mono-octa congener classes. The PCDD/PCDF levels measured at the high-temperature port are relatively low, and the majority of the formation takes place between Ports D and B, in less than 0.5 sec. An examination of the temperature profile, shown in the same figure, indicates that in this region, the temperature decreases sharply. A more gradual temperature decline would result in larger residence times in this temperature window, possibly allowing more PCDD and PCDF formation. After Port B, the change in PCDD and PCDF levels is small. The figure also shows that the yields of mono-tetra PCDD and PCDF are significant, and it is possible that under different process conditions some of them might shift to the toxic, higher chlorinated congeners.

An average analysis of all the experimental data has been performed. The data are divided into three groups, dRDF alone, dRDF with coal co-firing, and dRDF with sorbent injection, although within a group other parameters such as HCl concentration and quench may vary. For each group, average PCDD and PCDF yield is computed for each congener class. Results are plotted for mono-octa PCDD and PCDF congener classes in Figure 5. Both coal co-firing and sorbent injection decrease PCDD and PCDF formation significantly; the congener class pattern is similar to that of the base dRDF case and, therefore, the reduction is not congener-class-specific. The total tetra-octa PCDD and PCDF yields for the three groups are plotted in Figure 6. The results clearly indicate that coal/dRDF co-firing as well as calcium-based sorbent injection reduces PCDD and PCDF formation.

Experimental results have been analyzed statistically for Port A and Port B data separately. The model results for both cases are similar and the model R^2 for the data for each port is 0.76. Among the five exogenous variables (labeled COAL, RDF, QUENCH, SORBENT, and HCL), four 2-factor interactions involving all five variables were found to be significant: COAL-HCL, RDF-QUENCH, QUENCH-SORBENT, and SORBENT-HCL. Thus, model predictions for coal co-firing are available. Model predictions are shown in Figure 7 for Port A data, and similar results are obtained (but not shown) for Port B data. The model predicts that an increase in HCl concentration increases

the PCDD and PCDF yield for dRDF combustion. More importantly, at both low and high HCl levels, the model indicates that coal co-firing reduces PCDD and PCDF formation significantly. More detailed modeling efforts are in progress, and the results will be available later.

CONCLUSIONS AND RECOMMENDATIONS

For commercial dRDF combusted in our 0.6 MW stoker combustor, a majority of the PCDD and PCDF formation took place between 600 and 300°C within about 0.5 sec.

Based on Phase I tests, improving the combustion quality appears to lower PCDD and PCDF yields.

Co-firing Illinois #6 coal with both the RDF and dRDF reduced PCDD and PCDF formation substantially. This reduction appears to be uniform across the entire congener range. Injection of Ca(OH)_2 injection is nearly as effective as coal co-firing.

Co-firing coal with waste-derived fuel is a candidate technology for reducing PCDD and PCDF emissions in commercial waste burning facilities. Further development on a full-scale facility is needed to demonstrate field applicability.

ACKNOWLEDGMENTS

This work was also co-sponsored by Illinois Clean Coal Institute (ICCI) (Project Manager: Ken Ho) and the National Renewable Energy Laboratory (NREL) (Project Monitor: Phil Shepherd). Logistical support from Richard Valentine (U.S. EPA/APPCD) is greatly appreciated. Suh Lee, Joey Valenti, Russell Logan, Scott Moore, John Foley, Dennis Tabor, and Ann Preston (Acurex Environmental Corporation), and Jeff Ryan (U.S. EPA/APPCD) provided extensive technical, sampling, and analytical assistance.

DISCLAIMER STATEMENT

This work was sponsored in part by the Illinois Department of Energy and Natural Resources (IDENR) through its Coal Development Board and Illinois Clean Coal Institute (ICCI). However, any opinions, findings, conclusions, or recommendations expressed herein do not necessarily reflect the view of IDENR and the ICCI.

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Table 1. Analyses of the densified refuse-derived fuel (dRDF) and Illinois #6 coal

	dRDF	coal
Proximate analysis (%)		
Moisture	7.83	14.96
Ash	8.71	8.32
Volatile matter	70.62	33.51
Fixed Carbon	12.84	43.21
Ultimate analysis (%)		
Moisture	7.83	14.96
Carbon	41.70	60.25
Hydrogen	5.58	4.22
Nitrogen	0.80	1.09
Sulfur	0.09	3.36
Ash	8.71	8.32
Oxygen (by difference)	35.29	7.80
Chlorine	0.14	0.09
Calcium	1.35	n.m.
Copper	0.002	n.m.
 kJ/kg (Btu/lb)	 16,408 (7,059)	 25,257 (10,866)

n.m. not measured

Table 2. Multi-Fuel Combustor test conditions for Phase I tests with the RDF

Run No.	fuel	run type	flue gas conditions					Port B (conv. section)		Port A (pre-baghouse)	
			O ₂ %	CO ₂ %	CO ppm	HCl ppm	SO ₂ ppm	Ts °C	D+F ¹	Ts °C	D+F ¹
1	RDF	trial burn	16.5	3.6	1345	n.m.	n.m.	250	1253	134	1340
2	RDF	baseline	14.8	5.3	201	n.m.	n.m.	302	716	153	798
3	natural gas	blank	13.7	2.7	3	n.m.	n.m.	260	46	117	95
4	RDF	baseline	12.8	6.2	690	n.m.	n.m.	239	497	124	630
5	coal	baseline	17.8	2.3	86	n.m.	n.m.	285	n.d.	151	n.d.
6	RDF & coal	co-fired	17.1	3.9	41	321	492	341	180	180	26

¹tetra-octa PCDD+PCDF (ng/dscm)

All concentrations are dry and not corrected to 7% O₂

Ts sampling temperature

n.m. not measured

n.d. none detected

Table 3. Ranges of test conditions and results for the Phase II MFC tests

Parameter	parameter range	
	dRDF runs	coal/dRDF runs
O ₂ (%)	11.5 - 14.4	9.3 - 16.9
CO ₂ (%)	4.5 - 8.1	4.8 - 10.0
CO (ppm)	0 - 28	2 - 97
HCl (ppm)	11 - 224	21 - 193
SO ₂ (ppm)	3 - 17	136 - 427
Port A		
t _R (sec)	1.90 - 3.06	0.43 - 1.58
T _s (°C)	151 - 192	146 - 196
tetra-octa PCDD + PCDF (ng/dscm)	1 - 1369 ¹	4 - 57
Port B		
t _R (sec)	1.66 - 3.69	0.37 - 1.94
T _s (°C)	296 - 380	299 - 370
tetra-octa PCDD + PCDF (ng/dscm)	9 - 1910 ¹	2 - 104

¹not including sorbent injection runs

All concentrations are dry, not corrected to 7% O₂.

Residence time t_R based on t=0 at 650°C.

T_s=Sampling port temperature.

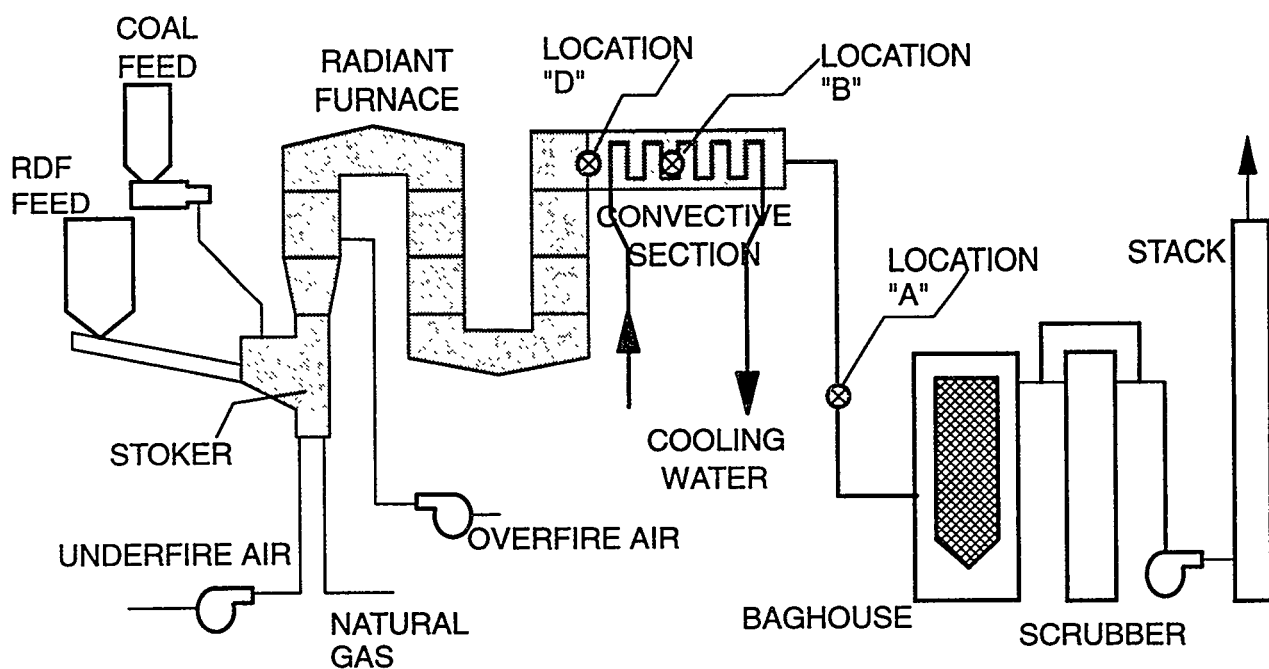


Figure 1. Schematic of the Multi-Fuel Combustor (MFC)

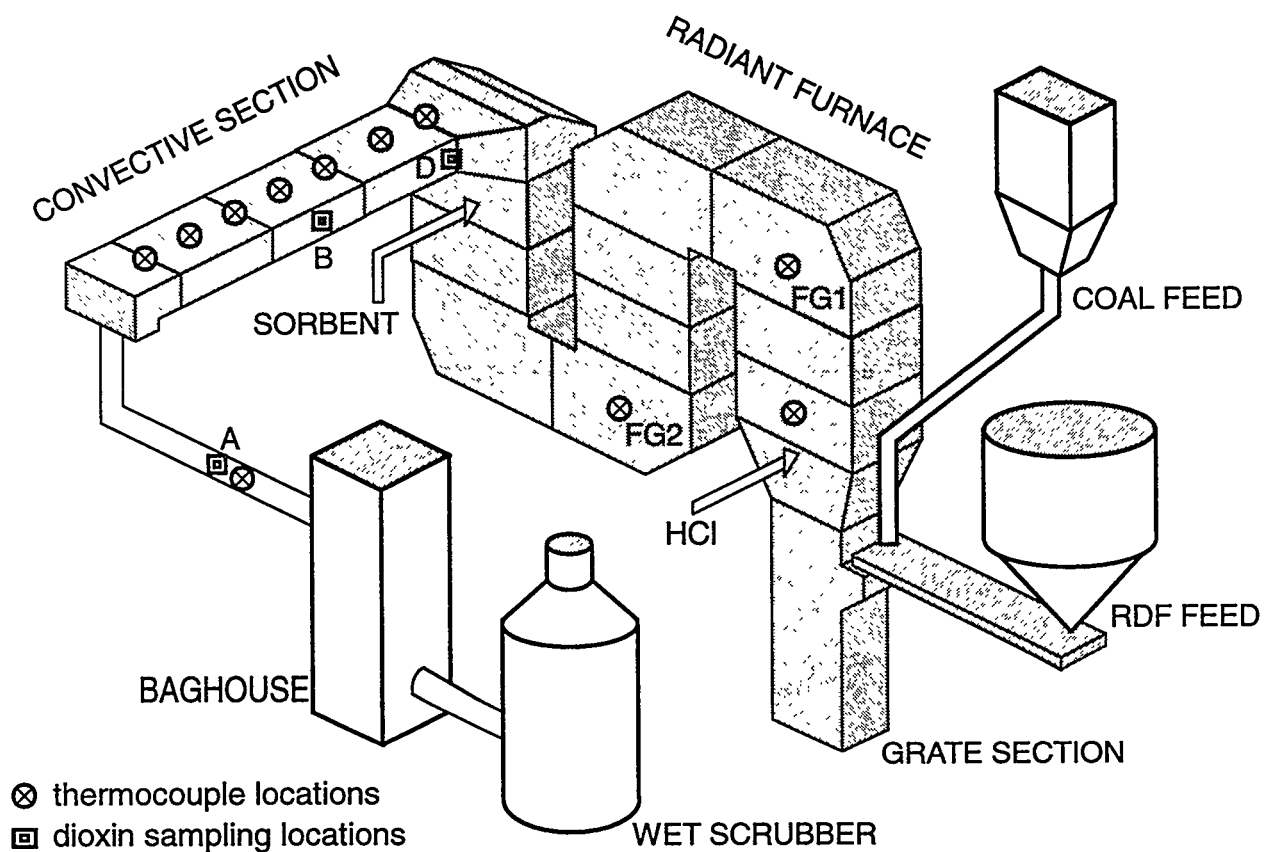


Figure 2. A view of the Multi-Fuel Combustor

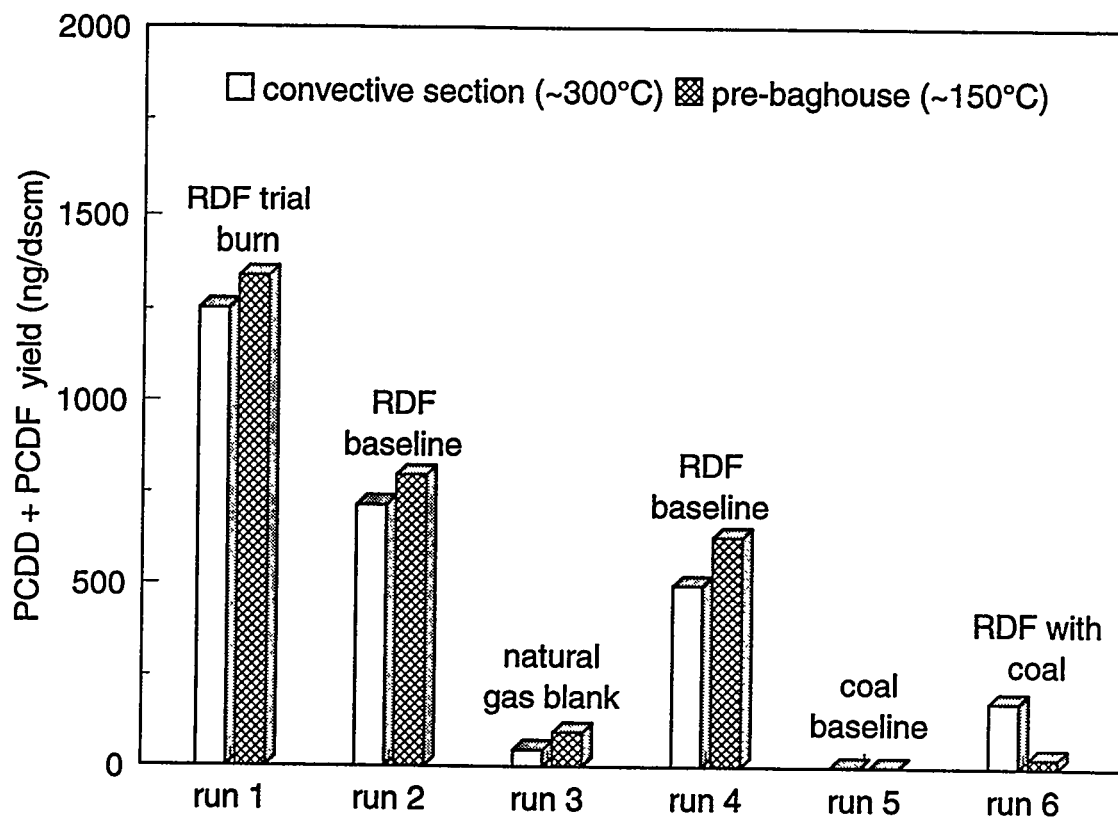
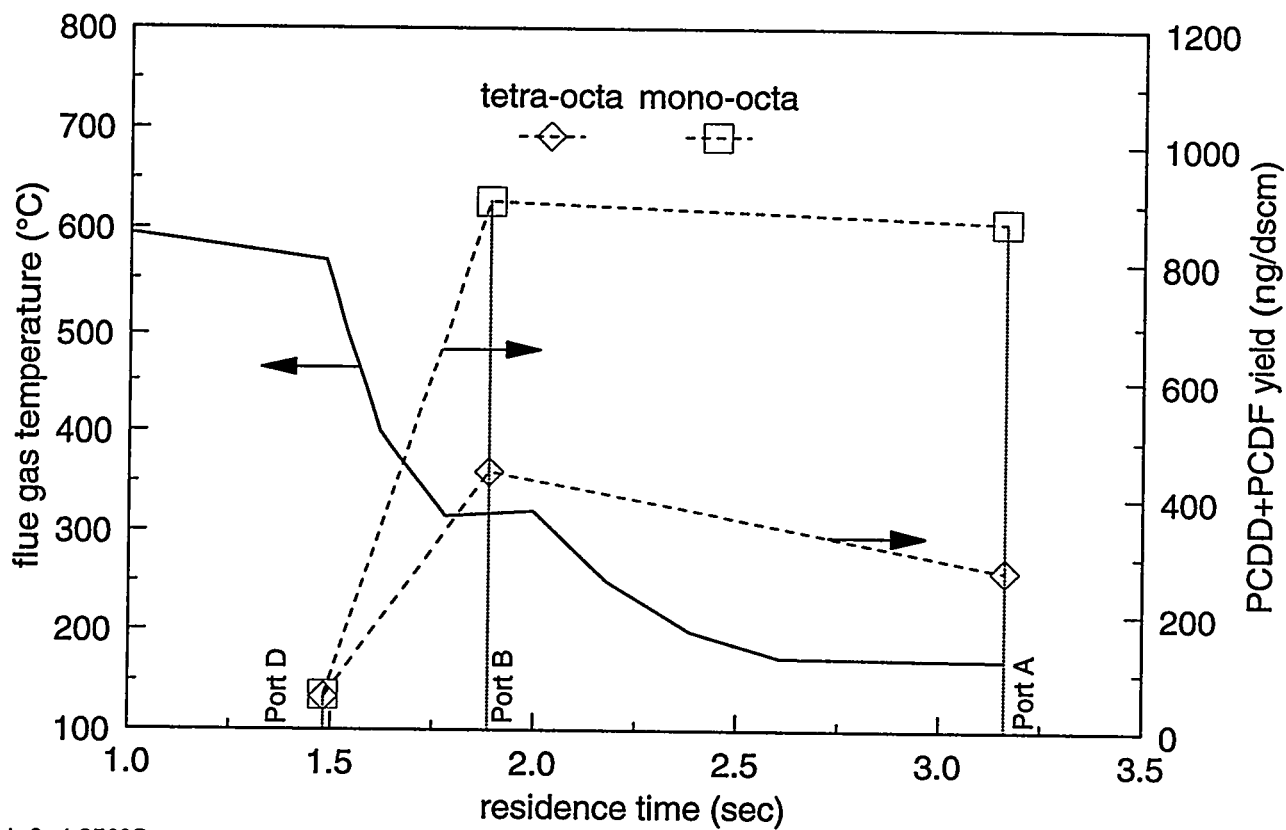


Figure 3. Total PCDD and PCDF (tetra-octa) yields from Phase I RDF tests



t=0 at 650°C

Figure 4. PCDD and PCDF yields from dRDF combustion measured at the three sampling ports

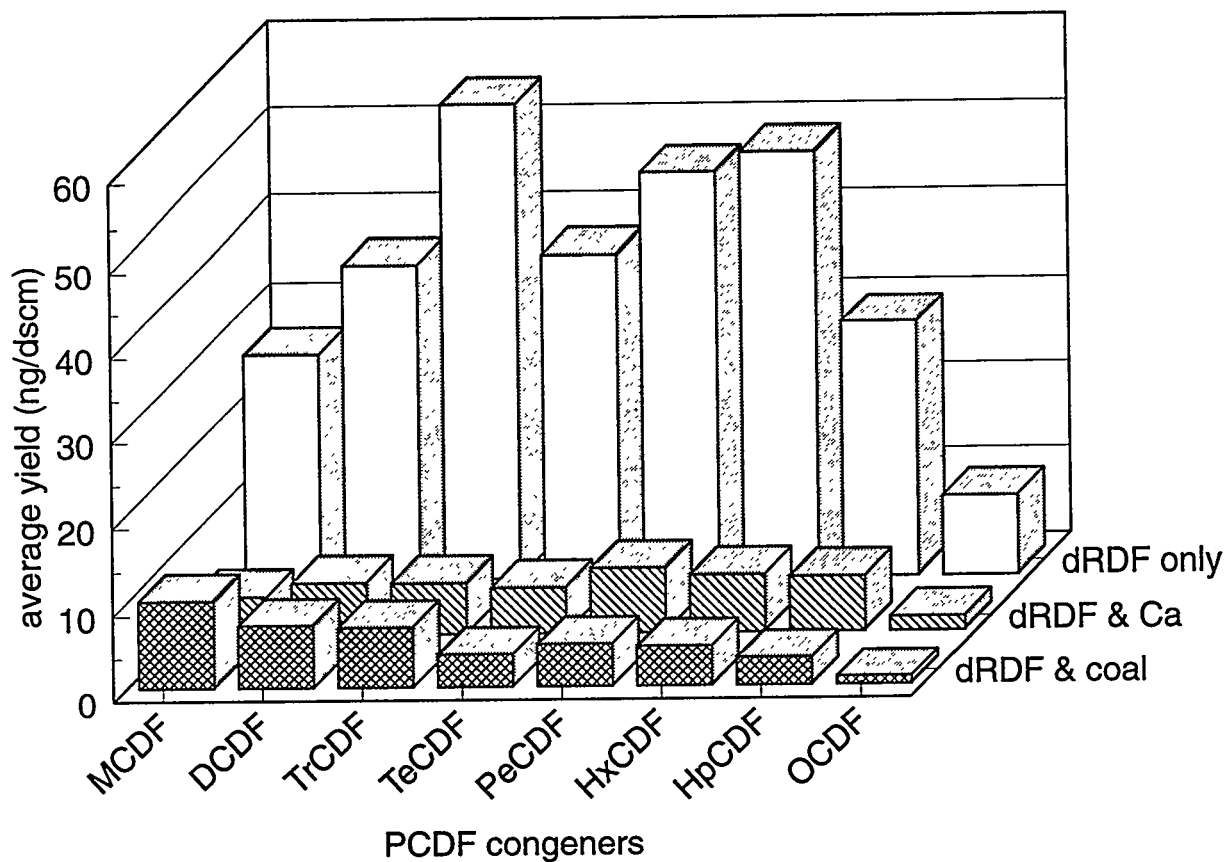
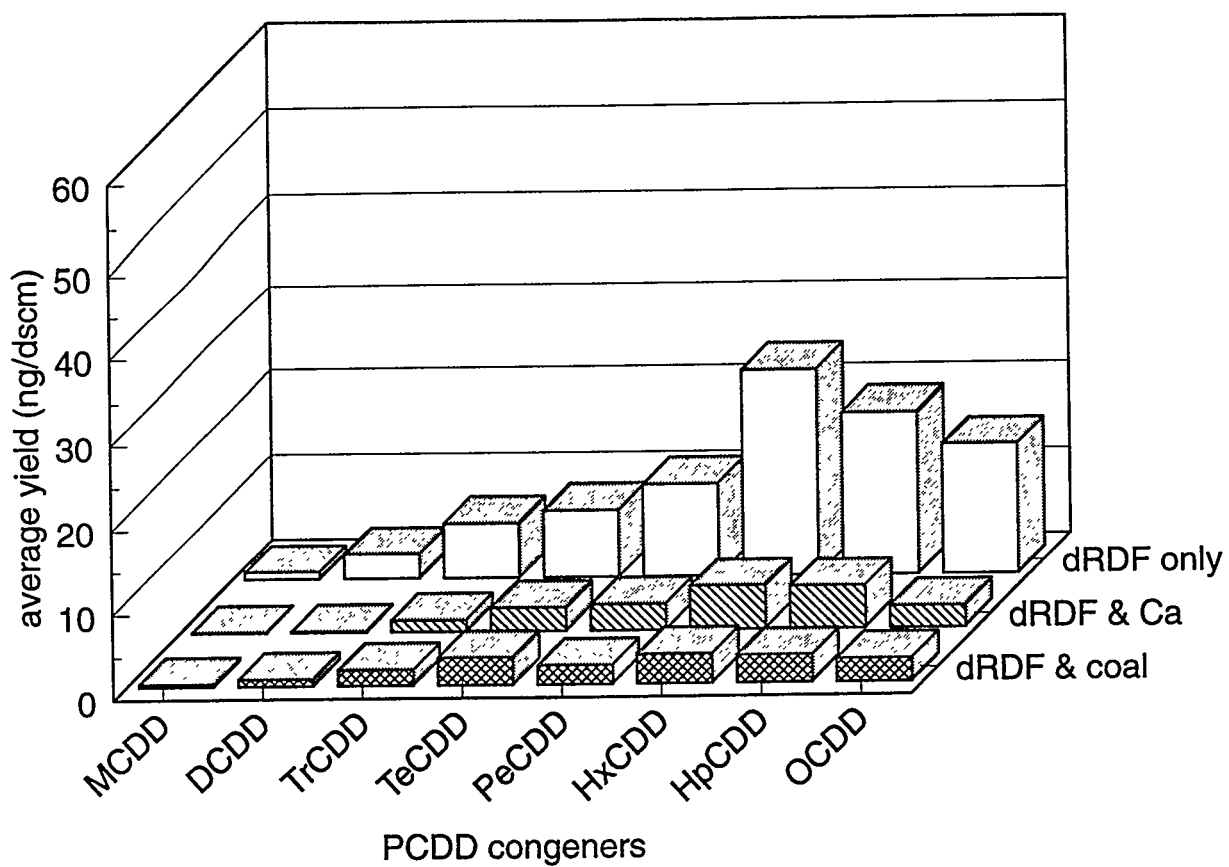


Figure 5. Effects of coal co-firing and sorbent injection on PCDD and PCDF congener yield.

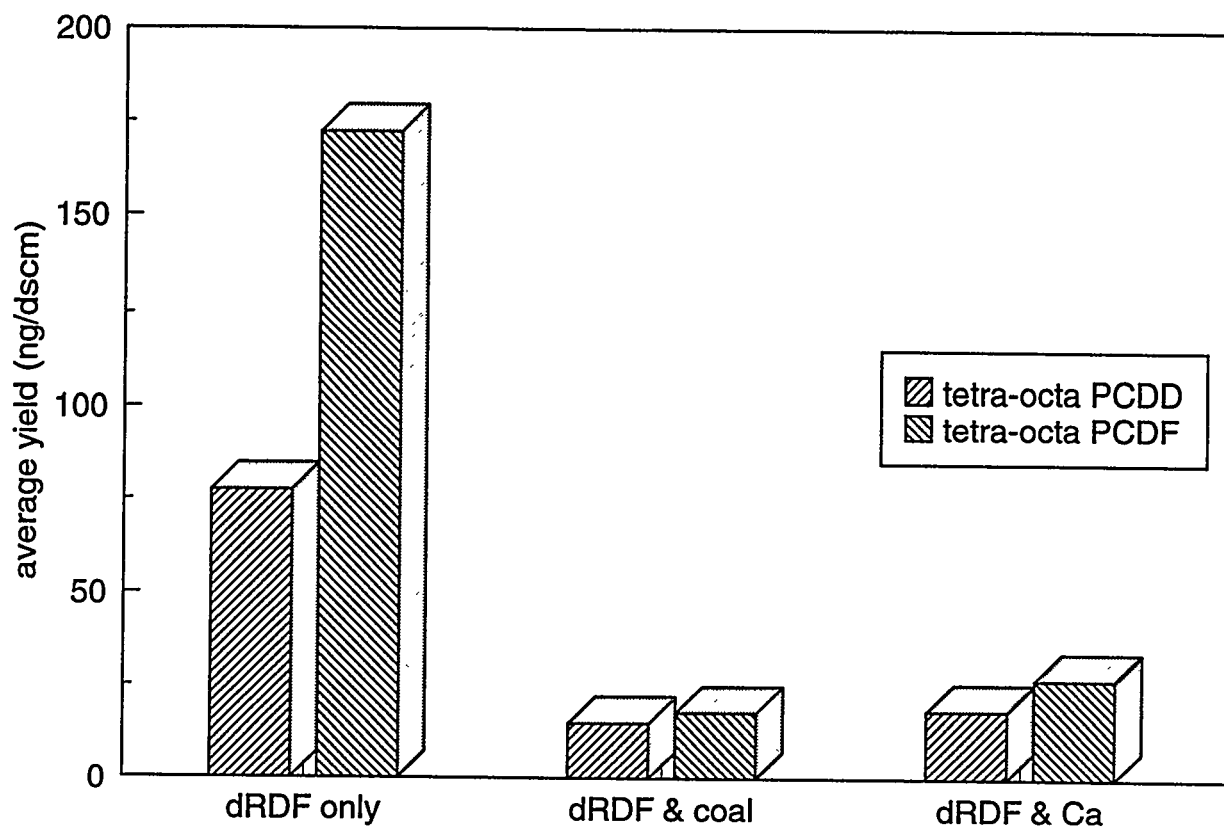


Figure 6. Effects of coal co-firing and sorbent injection on total PCDD and PCDF yield.

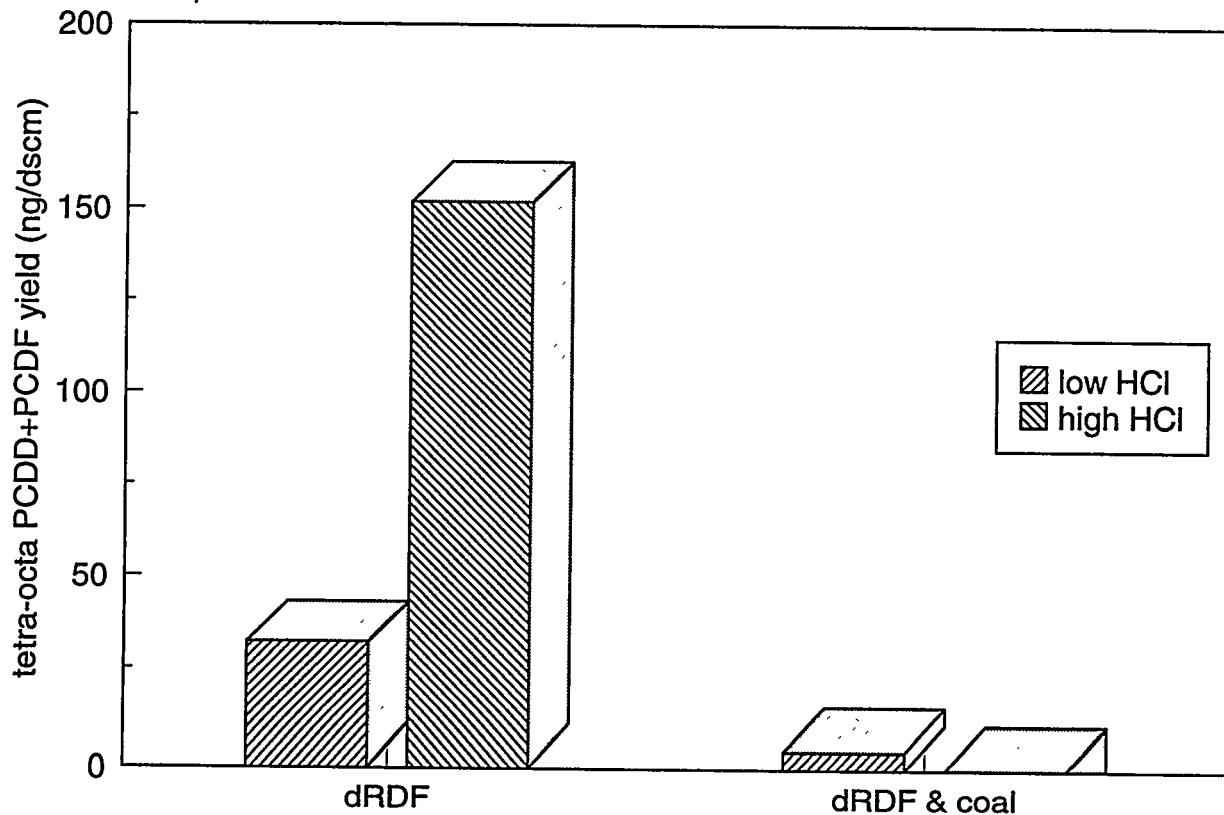


Figure 7. Effect of coal co-firing on PCDD+PCDF yield from the model for Port A

**An Experimental Study on Mercury Sorption by
Activated Carbons and Calcium Hydroxide**

**Behrooz Ghorishi
Acurex Environmental Corporation
4915 Prospectus Drive
Durham, NC 27713**

**Brian K. Gullett
U.S. Environmental Protection Agency
Air Pollution Prevention and Control Division (MD-65)
Research Triangle Park, NC 27711**

INTRODUCTION

Title III of the 1990 Clean Air Act Amendments (CAAA) requires the U.S. Environmental Protection Agency (EPA) to submit a study on 189 hazardous air pollutants (HAPs) from industrial sources. This study will include an emission and risk (to public health) assessment of the HAPs. Among the 189 HAPs, mercury has drawn special attention due to its increased levels in the environment and well-documented food chain transport and bioaccumulation.^{1,2}

Mercury, present in hazardous/municipal wastes and in coal³, is readily volatilized during combustion and incineration processes.⁴ Mercury is the most volatile among various trace metals, and major portions of it can pass through existing particulate control devices.⁴ A sorbent that can react with mercury can effectively shift this metal from the vapor phase to the particulate (sorbent) phase, facilitating its removal. Mercury control processes which use adsorption on dry sorbents do not pose the problem of treatment and stabilization of the waste liquid stream and, therefore, seem very attractive for coal combustors and hazardous/municipal waste incinerators. The need to develop mercury control technologies and the attractive features of adsorption processes on dry sorbents led researchers to focus their efforts on the evaluation of the adsorption kinetics and sorbent capacity of many different solid sorbents. Past research has identified two different classes of sorbents to be effective in mercury removal: activated carbons and calcium-based sorbents.⁵⁻⁷

An important scientific issue that needs to be addressed is the chemical form in which mercury is released from combustion systems. Previous investigations conducted in EPA laboratories^{6,7} have indicated that mercury control strategies are dependent upon the type of mercury species that exist in the coal/waste combustion flue gases. These studies have shown the relative ease of controlling oxidized mercury (specifically mercuric chloride, HgCl_2) as opposed to elemental mercury (Hg^0). Hall et al.⁸ showed that, in a simulated municipal waste combustor (MWC), flue gas mercury is mainly found as HgCl_2 . They postulated that HgCl_2 is the most favorable mercury species due to relatively high hydrogen chloride (HCl) concentration in MWCs. On the other hand, Hg^0 is the prevailing form of mercury in emissions from coal combustion processes.⁹ However, recent pilot-scale coal combustion test results have indicated that combustion of certain types of coal (Blacksville, a bituminous coal from the Pittsburgh No. 8 seam) can lead to a flue gas mercury species profile dominated by oxidized mercury (most probably HgCl_2).¹⁰ Research in this area is on-going to determine the conditions that favor formation of oxidized mercury in coal combustion processes.

The presence of both Hg^0 and HgCl_2 in combustion flue gases justifies a comprehensive research study on the adsorption of both these species by solid sorbents. As mentioned, preliminary investigations found activated carbons to be efficient Hg^0 sorbents,⁶ and calcium-based compounds to be effective HgCl_2 sorbents.⁷ The activated carbon studies⁶ were focused on determining the effect of temperature (23 vs. 140°C) on the adsorption of Hg^0 on two different kinds of thermally activated carbons (FGD and PC-100, Norit Americas Inc.) in a fixed-bed reactor system. It was concluded that surface area and temperature have a strong effect on the Hg^0 adsorption capacity of the activated carbons. PC-100, with twice the specific surface area compared to that of FGD, captured about four times the amount of Hg^0 captured by FGD. Both thermally activated carbons exhibited almost double the adsorption capacity at 23°C compared to that at 140°C. This study reports on the continuation of that investigation⁶ with emphasis on obtaining Hg^0 breakthrough sorption curves. Systematic tests were conducted in which the

effects of temperature, inlet Hg^0 concentration, and the presence or absence of sulfur dioxide (SO_2) were investigated. The adsorption of Hg^0 was studied by varying the temperature in the range of 60-140°C and the Hg^0 concentration in the gas stream in the range of 8-40 ppb (65-327 $\mu\text{g/dscm}$). The selected concentration range was higher than that observed in coal-fired units (1-20 $\mu\text{g/dscm}$).¹⁰ SO_2 is believed to be an important flue gas species influencing the capture of mercury compounds by activated carbons and calcium-based sorbents.⁷ The effect of this species was studied at a concentration of 1000 ppm (2.6 g/dscm).

A previous investigation⁷ illustrated the relative ease of removal of HgCl_2 as compared to Hg^0 . It was concluded that calcium-based sorbents --calcium hydroxide [$\text{Ca}(\text{OH})_2$] and mixtures of $\text{Ca}(\text{OH})_2$ and fly ash-- can potentially be very cost effective in adsorbing HgCl_2 from simulated flue gases. A comprehensive, systematic study on the control of HgCl_2 by activated carbons has been conducted by Karatza et al.¹¹, concluding that at a temperature of 150°C and gas-phase HgCl_2 concentration of 1000 $\mu\text{g/dscm}$ a thermally activated carbon can capture a mass of HgCl_2 greater than 1% of its weight. The investigation presented here reports on the continuation of a previous study⁷; it focuses on a systematic study on the effect of temperature (60-140°C), HgCl_2 concentration [11-73 ppb (122-809 $\mu\text{g/dscm}$)], and SO_2 (1000 ppm) on the HgCl_2 capture by $\text{Ca}(\text{OH})_2$.

In summary, the scope of the present work was to study adsorption of Hg^0 by thermally activated carbons and HgCl_2 by $\text{Ca}(\text{OH})_2$. While the focus of the previous investigations^{6,7} was mainly on a screening type of comparison between these sorbents, this work investigates the fundamental and quantitative dependence of the adsorption capacity of sorbents and mercury removal on sorption parameters such as temperature, gas-phase mercury species concentration, and flue gas species (SO_2). The experiments were performed in a laboratory-scale, fixed-bed apparatus, in which the inlet gas containing nitrogen, Hg^0 or HgCl_2 , and, on occasions, SO_2 were contacted with sorbents.

EXPERIMENTAL PROCEDURE

A schematic of the experimental apparatus used to study the capture of Hg^0 and HgCl_2 is shown in Figure 1. Pure HgCl_2 powder contained in a diffusion vial was the source of HgCl_2 vapor, and pure Hg^0 liquid in a permeation tube (VICI Metronics Inc.) was the source of Hg^0 vapor. The concentration of HgCl_2 or Hg^0 in the gas stream was controlled by adjusting the water bath temperature. A detailed description of the calibration of the mercury generation system and its quality control checks has been reported elsewhere.^{6,7} The mercury vapor generated was carried into a manifold by a nitrogen stream where it mixed with SO_2 (in the SO_2 studies only) at a constant total system gas flow rate of 350 cm^3/min (at standard temperature and pressure). A three-way valve placed before the manifold (Figure 1) diverted the mercury-laden nitrogen stream away from the manifold when desired. The first three-way valve placed after the manifold was used to direct flow to or away from the fixed-bed reactor. The sorbent to be studied (approximately 0.02 g diluted with 2 g inert glass beads; bed length of approximately 2 cm) was placed in the reactor which was maintained at the desired bed temperature by a temperature controller. A furnace kept at 850°C was placed downstream of the reactor to convert any oxidized mercury (Hg^{++} , as in HgCl_2) to Hg^0 . According to thermodynamic predictions, the only mercury species that exists at this temperature is Hg^0 .¹² The presence of the furnace enabled detection of non-adsorbed HgCl_2 as Hg^0 by the on-line ultraviolet (UV) Hg^0 analyzer, thus providing actual, continuous Hg^0 or HgCl_2 capture data by the fixed-bed of sorbent. The UV Hg^0 analyzer used in this study

responded to SO_2 as well as Hg^0 . For instance, a gas stream consisting of 1000 ppm SO_2 and 15 ppb Hg^0 produced a SO_2/Hg^0 signal ratio of 8/18. Contributions from SO_2 were corrected for by placing a SO_2 analyzer (UV) on-line downstream of the Hg^0 analyzer. The SO_2 analyzer was incapable of responding to mercury in the concentration range used in this study. By subtracting the SO_2 signal measured by the SO_2 analyzer from the total response of the mercury analyzer, the mercury concentration was obtained.

In each test, the fixed-bed was exposed to the mercury-laden flue gas for 24 hours or until 100% breakthrough (saturation) was achieved (whichever came first). During this period the exit concentration of mercury was continuously monitored. The percent removal of Hg^0 or HgCl_2 at any time was obtained as follows: percent removal = $100 * [(\text{mercury})_{\text{in}} - (\text{mercury})_{\text{out}}] / (\text{mercury})_{\text{in}}$. The amount of mercury species uptake at any time (q , weight mercury species/weight sorbent) was determined by integrating (in time) and evaluating the area under the removal curves. Selected experiments conducted during this test program were run in duplicates and indicated a variation of $\pm 10\%$ in the experimental results.

SORBENTS

The capture of Hg^0 was investigated using two different thermally activated carbons: FGD and PC-100. The capture of HgCl_2 was investigated using $\text{Ca}(\text{OH})_2$. FGD, manufactured by Norit Americas Inc., is a lignite-coal-based activated carbon with a bulk density of 0.51 g/cm^3 , ignition temperature of 450°C , and particle size greater than 400 mesh (less than $30 \mu\text{m}$). Information about the total surface area and average pore size diameter of FGD (and other sorbents) was obtained by using a Micromeritics ASAP 2600 based on nitrogen adsorption/desorption with the Brunauer-Emmett-Teller (BET) method. FGD has a total surface area of $500 \text{ m}^2/\text{g}$ and an average pore diameter of 3.2 nm . PC-100, manufactured by Norit Americas Inc., is a bituminous-coal-based activated carbon with a bulk density of 0.52 g/cm^3 , ignition temperature of 450°C , and a particle size greater than 400 mesh (less than $30 \mu\text{m}$). PC-100 has a total surface area of $900 \text{ m}^2/\text{g}$ and an average pore diameter of 1.8 nm . It has nearly twice the surface area of FGD; most of this surface area is due to its smaller pores than those of FGD as indicated by PC-100's smaller average pore diameter. The $\text{Ca}(\text{OH})_2$ used in the HgCl_2 removal studies was a reagent grade $\text{Ca}(\text{OH})_2$ (Sigma Inc.) containing 97.6% $\text{Ca}(\text{OH})_2$ and 1.8% calcium carbonate (CaCO_3). It has a total surface area of $13 \text{ m}^2/\text{g}$ and an average pore diameter of 33.4 nm .

EXPERIMENTAL RESULTS AND DISCUSSION

HgCl_2 Capture by $\text{Ca}(\text{OH})_2$

The effects of temperature and inlet concentration on the HgCl_2 uptake by $\text{Ca}(\text{OH})_2$, obtained under the baseline conditions (nitrogen and HgCl_2 only), are shown in Figure 2. During the 24 hours of exposure, HgCl_2 uptake (q) increased linearly as time of exposure progressed; $\text{Ca}(\text{OH})_2$ did not reach its saturation capacity under the baseline conditions. This observation may indicate an abundance of HgCl_2 adsorption sites on $\text{Ca}(\text{OH})_2$. Considering the acidic nature of gaseous HgCl_2 , these sites can be hypothesized to be alkaline. Note that, for the sake of comparison to the Hg^0 data, the results were truncated to show the first 5 hours of exposure; further uptakes up to 24 hours can be obtained by extending the lines.

The percent removals [constant during the exposure period; measured $(\text{HgCl}_2)_{\text{out}}$ was constant] of incoming HgCl_2 by the fixed-bed of $\text{Ca}(\text{OH})_2$ as a function of temperature and inlet concentration are shown in Figure 3. Increasing the HgCl_2 inlet concentration and decreasing the bed temperature

increased the percent removals. The bed temperature had a strong effect on the percent removals at the lowest concentration (11 ppb) tested, and the inlet concentration influenced percent removals more strongly at the highest temperature (140°C) tested.

In adsorption processes, a rise in partial pressure and a fall in temperature result in an increase in the amount of the material adsorbed (adsorbate). The temperature and the concentration (partial pressure) trends observed here suggest that the process is an adsorption (physical and/or chemical) controlled process and that the rate of HgCl_2 capture is determined by how fast molecules in the vicinity of the active sites are being adsorbed. This indicates that the capture process is not controlled by an external (boundary layer) mass transfer mechanism; boundary layer mass transfer is fast and the HgCl_2 concentration in the vicinity of the surface is very close to the bulk concentration. Moreover, the observed effect of temperature on the amount captured (or percent removed) does not support an external mass transfer hypothesis, since the mass transfer rate is proportional to the 1.5 power of absolute temperature.

The effect of SO_2 on HgCl_2 capture by Ca(OH)_2 was studied by adding 1000 ppm SO_2 to the nitrogen/ HgCl_2 stream, while keeping the total flow through the fixed-bed constant. The results are shown in Figure 4. This figure shows the effect of SO_2 at a constant inlet HgCl_2 concentration of 38 ppb for the three studied temperatures. At the low temperature (60°C), SO_2 had no effect. However, increasing the temperature drastically reduced the sorption capacity of Ca(OH)_2 in the presence of SO_2 . It appears that Ca(OH)_2 and SO_2 may react at higher temperatures, leading to the destruction of the available (alkaline) sites needed for HgCl_2 capture. In the presence of SO_2 and at 100°C, saturation capacity [0.7 mg HgCl_2 /g Ca(OH)_2] was achieved after 5 hours of exposure; at 140°C, saturation capacity [0.1 mg HgCl_2 /g Ca(OH)_2] was achieved after only 1 hour of exposure. Note that in the absence of SO_2 , saturation capacities were never achieved during the 24 hours of exposure.

Hg^0 Capture by Activated Carbons

The effects of temperature and inlet concentration on the Hg^0 uptake by activated carbon, FGD, under the baseline conditions, are shown in Figure 5. Unlike HgCl_2 capture by Ca(OH)_2 , during a typical 5-hour run the sorbent (FGD) reached its saturation capacity, indicating that the available active sites for capturing Hg^0 in the activated carbon are limited. The comparison between Hg^0 and HgCl_2 uptake results (Figures 2 and 5) suggests that it is more difficult to control Hg^0 emissions. It should be noted that in a previous investigation⁷, the baseline tests conducted using Ca(OH)_2 showed that no Hg^0 was captured, indicating the ineffectiveness of Ca(OH)_2 (lack of active sites) in capturing Hg^0 .

From Figure 5 it is apparent that the amount of Hg^0 captured is influenced more by the bed temperature than by the inlet concentration (note the ordinate scales). Increasing the temperature reduced the saturation capacity and the time needed to reach the saturation capacity. Increasing the inlet Hg^0 concentration increased the saturation capacity, and the initial rate of Hg^0 uptake (slope of tangent at the origin). Similar to the HgCl_2 case, the temperature and concentration trends suggest that the process is active site adsorption controlled.

The same set of tests were performed using PC-100 as the activated carbon sorbent. Results for PC-100 in comparison to FGD are presented in Figure 6 (bed temperature of 100°C). PC-100 also consistently exhibited higher saturation capacity than did FGD at temperatures of 60° and 140°C (not presented

here). It should be noted that PC-100 exhibited the same temperature and concentration trends as those of FGD: higher Hg^0 captures at lower temperatures and higher inlet concentrations.

The effect of SO_2 on Hg^0 capture by FGD was studied by adding 1000 ppm SO_2 to the nitrogen/ Hg^0 (40 ppb) stream while keeping the total gas flow through the fixed-bed constant. The highest inlet Hg^0 concentration was chosen to minimize the interference of SO_2 in the Hg^0 analyzer discussed previously. Figure 7 shows the effect of SO_2 on Hg^0 uptake at a constant inlet Hg^0 concentration of 40 ppb for the three studied temperatures. At the lowest temperature tested (60°C), SO_2 had essentially no effect on the Hg^0 uptake by the FGD; however, increasing the temperature increased the Hg^0 capture by the FGD. It appears that at higher temperatures, SO_2 might have reacted with the FGD and created active sulfur (S) sites, which are considered to be very active in capturing Hg^0 .⁶ The activity of FGD in the presence of SO_2 at higher temperatures resembled that of sulfur-impregnated (chemically impregnated) activated carbon studied by Krishnan et al.⁶ Based on these observations, one may consider injecting this activated carbon upstream of the acid gas removal devices of the full-scale combustion systems in order to take advantage of the enhancement effect of SO_2 on Hg^0 capture.

Unlike FGD, the presence of SO_2 did not have any effect on Hg^0 capture by PC-100. This may be due to the inability of PC-100 to form sulfur-activated sites. One may relate this observation to the differences in chemical structure and composition of these two thermally activated carbons. FGD and PC-100 are lignite-coal-based and bituminous-coal-based activated carbons, respectively. Future efforts will be directed toward a comprehensive understanding of the chemical nature (active sites) of these activated carbons and its influence on Hg^0 capture. These future studies will also help explain the observed higher activities of PC-100 as compared to FGD, since this may not be just a total surface area effect, as indicated by SO_2 studies.

CONCLUSION

The effects of bed temperature, mercury concentration, and the presence of SO_2 on the capture of Hg^0 and HgCl_2 , the mercury species identified in coal/waste combustion flue gases, by thermally activated carbons (FGD and PC-100, Norit Americas Inc.) and a calcium-based sorbent [$\text{Ca}(\text{OH})_2$] were examined in a fixed-bed, bench-scale system. Sorption studies indicated an abundance of HgCl_2 adsorption sites in $\text{Ca}(\text{OH})_2$. Considering the acidic nature of gaseous HgCl_2 , these sites can be assumed to be alkaline. Increasing the HgCl_2 inlet concentration increased its removal, and increasing the bed temperature decreased this removal. The observed temperature and concentration trends suggest that the process is adsorption controlled and that the rate of HgCl_2 capture is determined by how fast molecules in the vicinity of the active sites are being adsorbed. The presence of SO_2 drastically reduced the sorption capacity of $\text{Ca}(\text{OH})_2$ at a bed temperature range of $100\text{--}140^\circ\text{C}$. Sorption studies further indicated that the available active sites for capturing Hg^0 in the activated carbons are very limited, suggesting that it is more difficult to control Hg^0 emissions. Increasing the inlet Hg^0 concentration and decreasing the bed temperature increased the saturation capacities of the activated carbons, the time needed to reach this capacity, and the initial rate of Hg^0 uptake. PC-100, with twice the total surface area as that of FGD, consistently exhibited higher saturation capacity than that for FGD. The presence of SO_2 drastically increased the Hg^0 capture capabilities of FGD and had no influence on Hg^0 capture by PC-100. These observations may be due to the differences in chemical structure and composition of these two thermally activated carbons.

Based on these observations, the optimum region for control of HgCl_2 by calcium-based sorbents may be considered to be downstream from acid gas (SO_2) removal devices. One may also consider injecting activated carbon (FGD) upstream of the acid gas removal devices of the full-scale combustion systems in order to take advantage of the enhancement effect of higher SO_2 levels on Hg^0 capture.

ACKNOWLEDGMENTS

The authors acknowledge the logistical support of Richard Valentine (EPA/APPD), experimental assistance from Lisa Adams and Hamid Bakhteyar, and technical assistance from Wojciech Jozewicz (Acurex Environmental Corporation).

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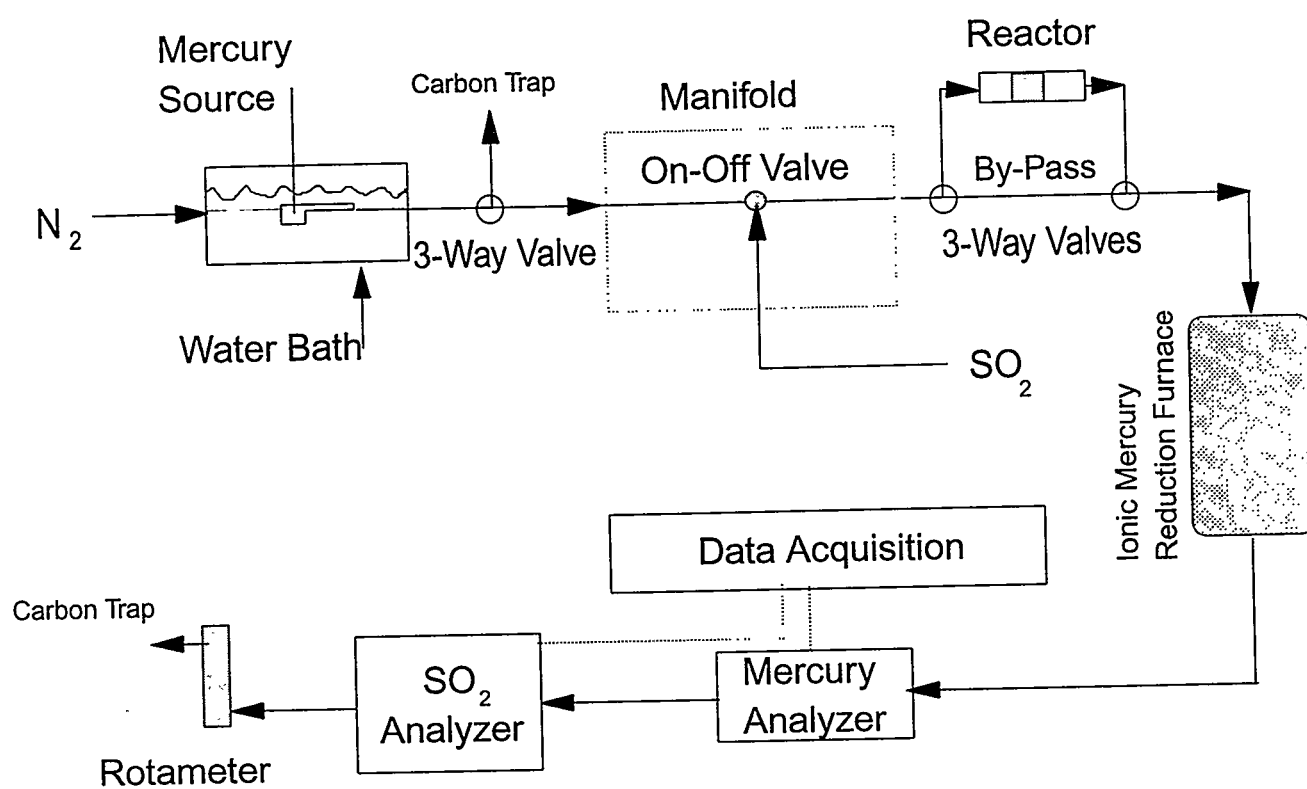


Figure 1. Schematic of the bench-scale, fixed-bed reactor setup.

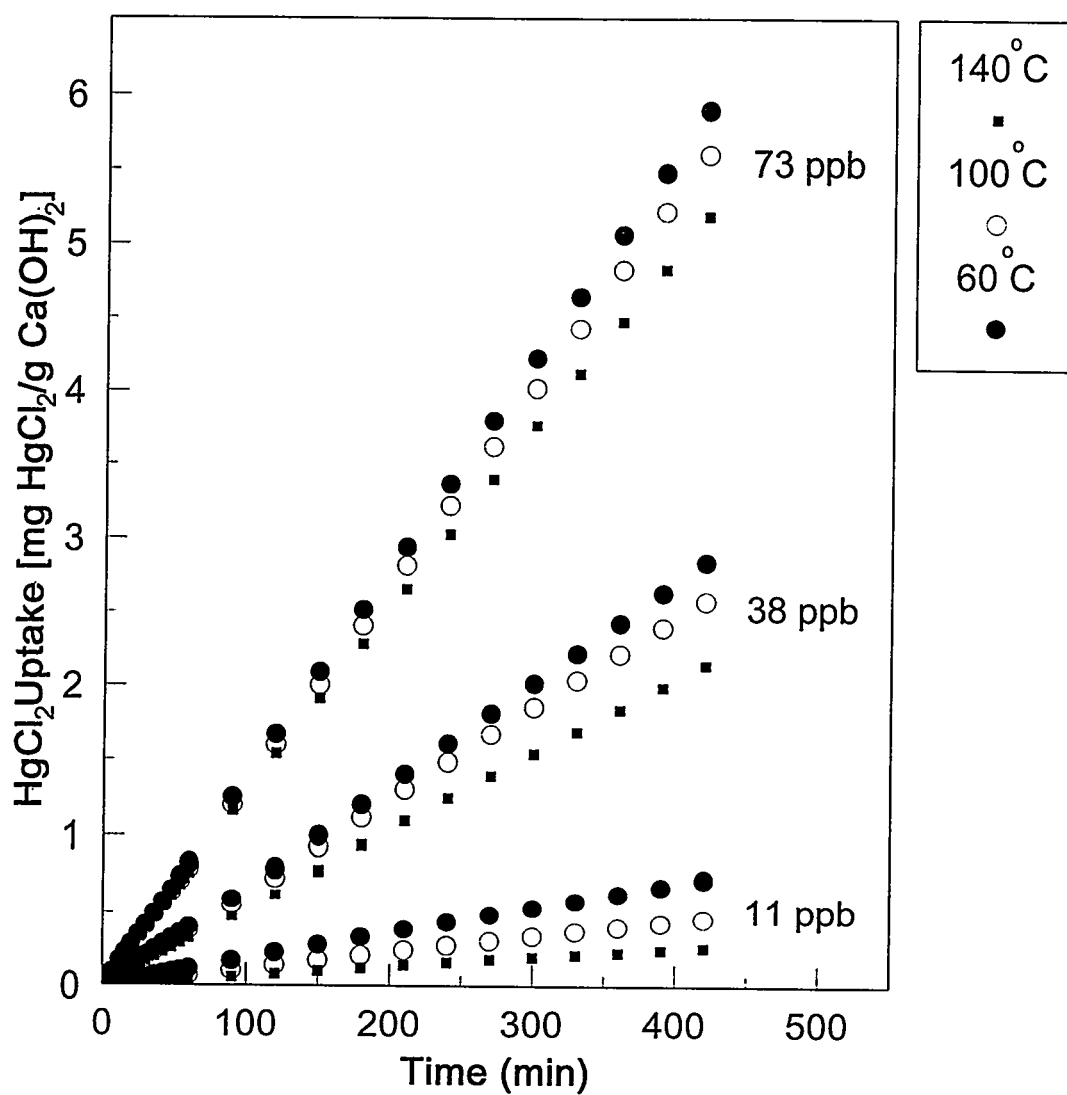


Figure 2. Effects of bed temperature and inlet HgCl₂ concentration on HgCl₂ uptake by Ca(OH)₂ (baseline conditions).

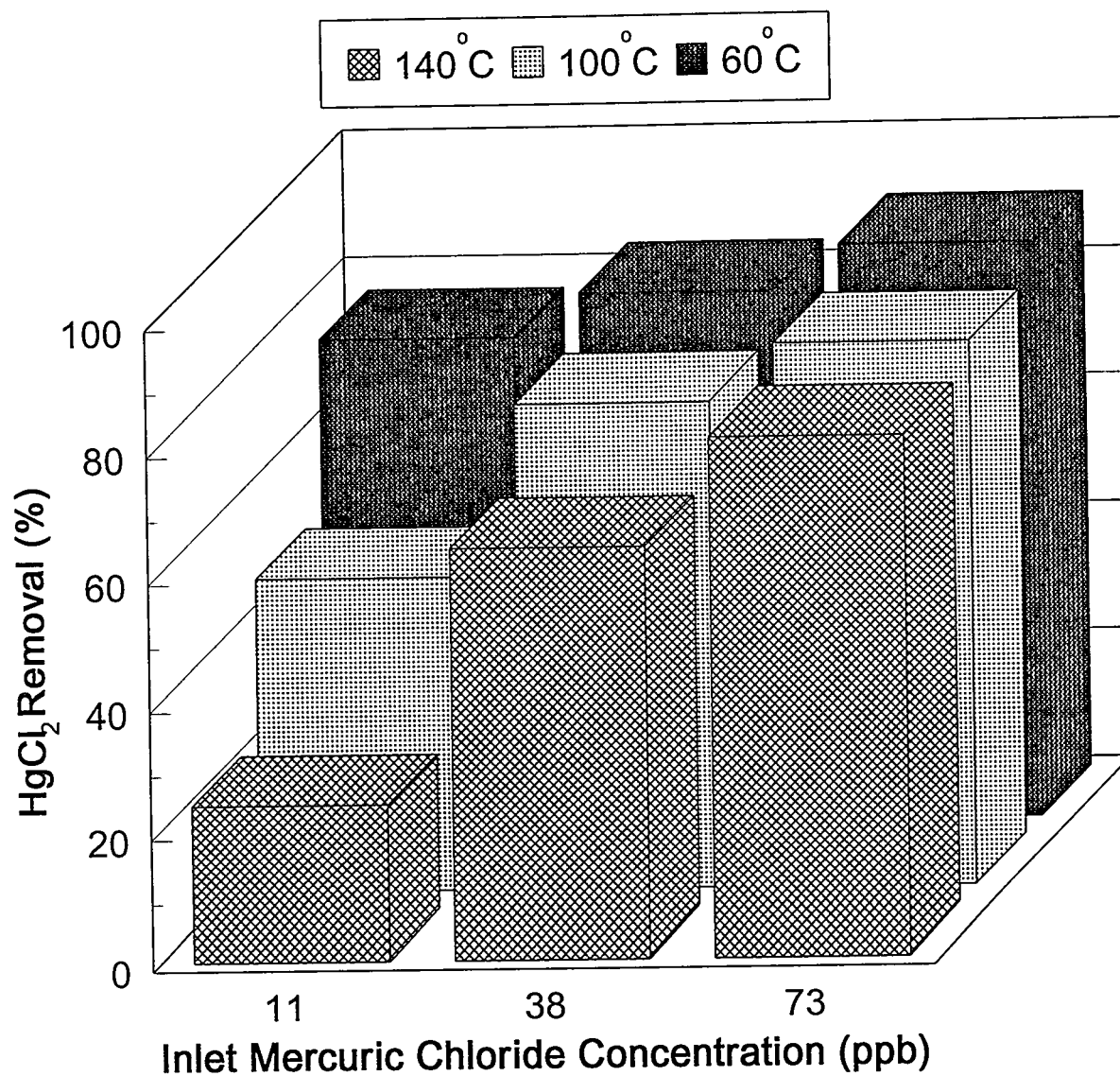


Figure 3. Effects of bed temperature and inlet HgCl_2 concentration on HgCl_2 removal by $\text{Ca}(\text{OH})_2$ (baseline conditions).

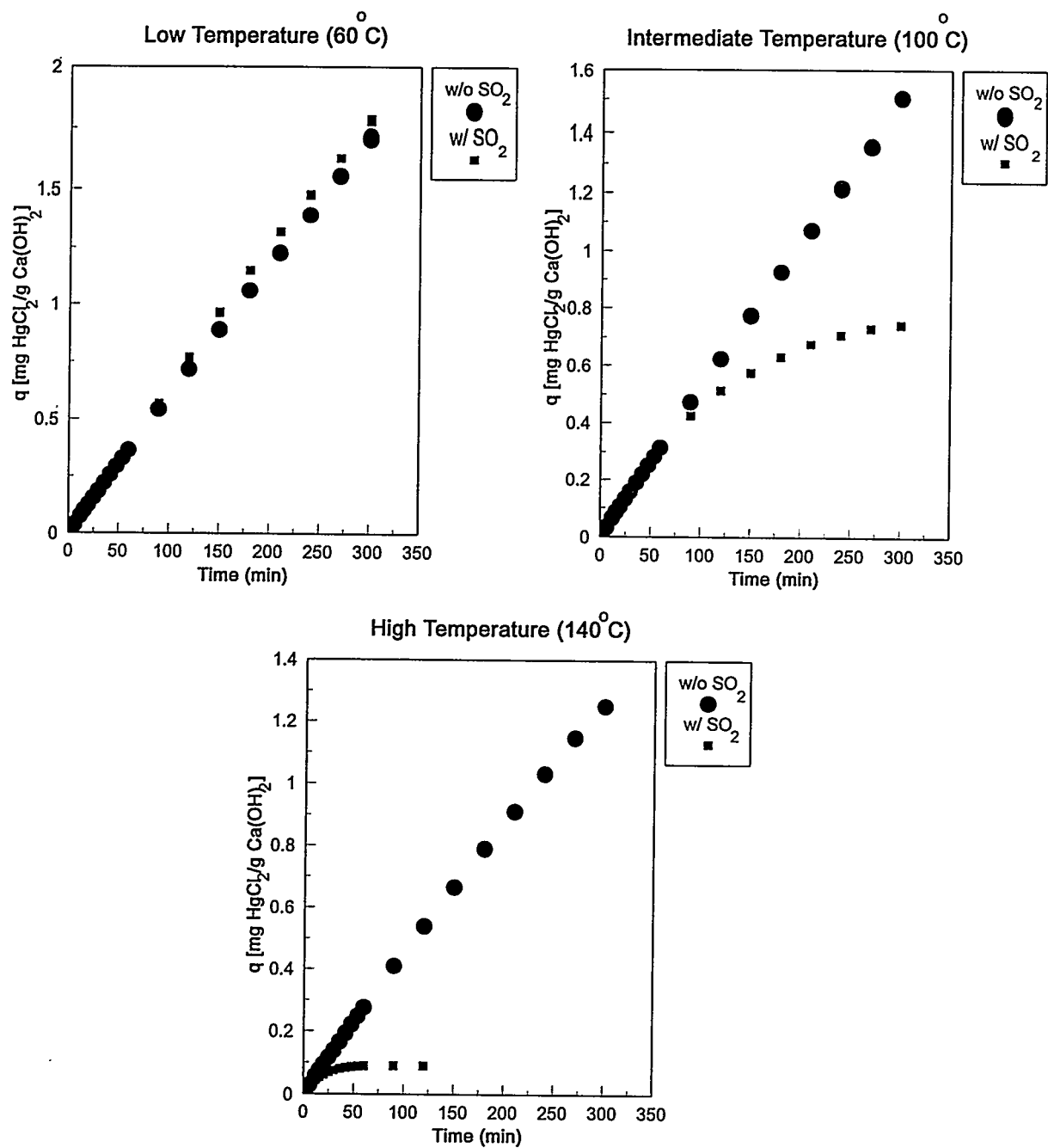


Figure 4. Effect of SO_2 (1000 ppm) on HgCl_2 uptake by Ca(OH)_2 (inlet HgCl_2 concentration of 38 ppb).

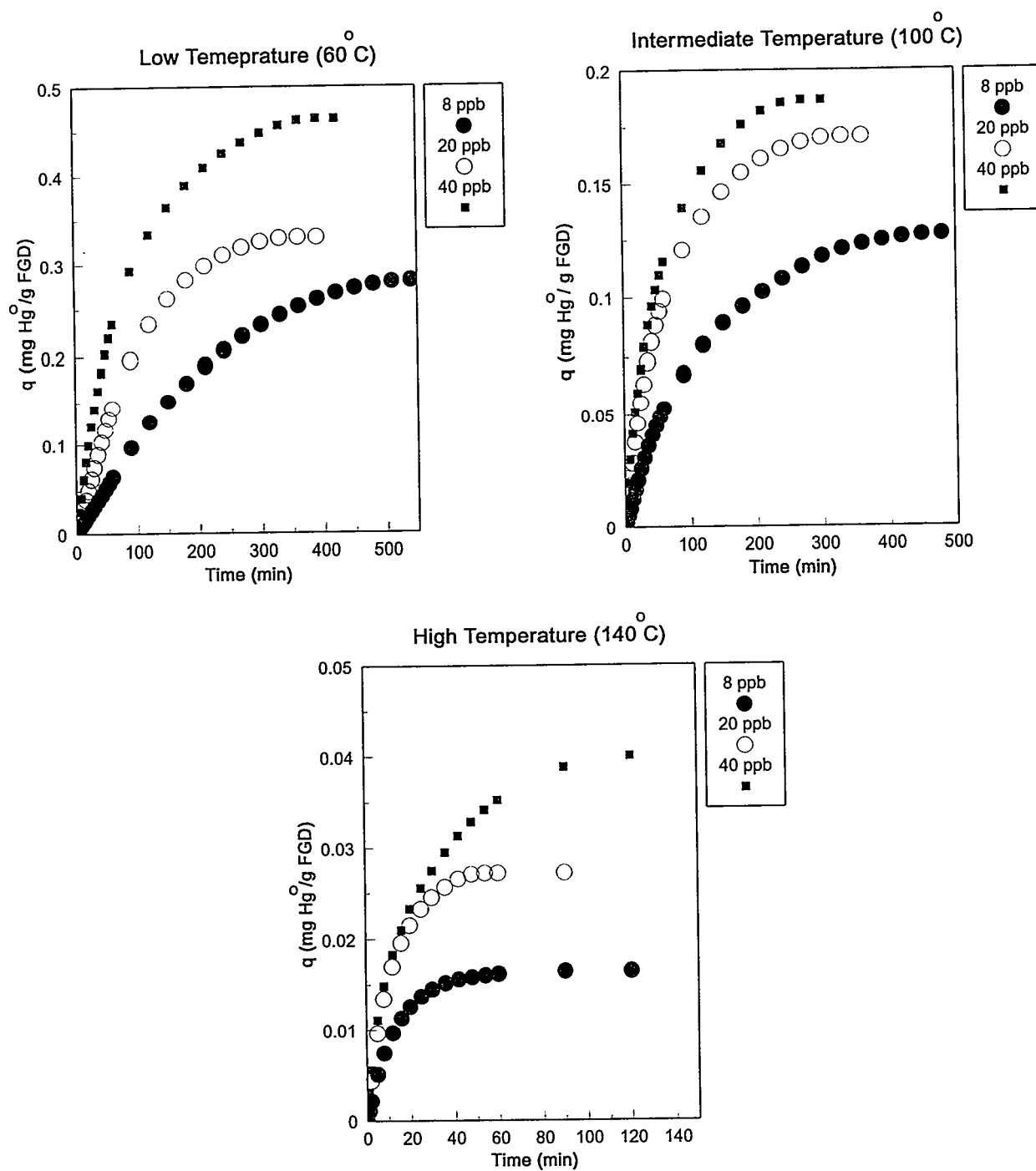


Figure 5. Effects of bed temperature and inlet Hg^0 concentration on Hg^0 uptake by activated carbon, FGD (baseline conditions).

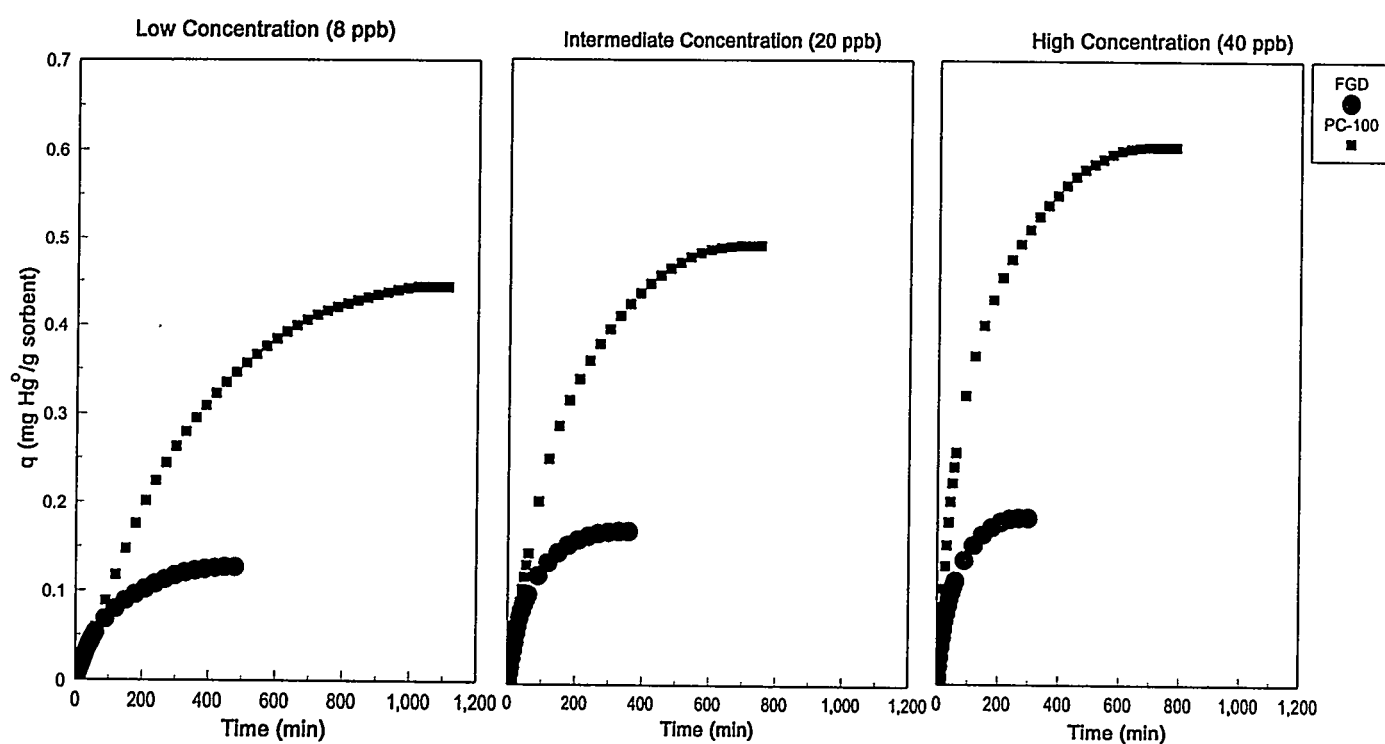


Figure 6. Uptake of Hg^0 by activated carbons, FGD and PC-100 (bed temperature of 100°C , baseline conditions).

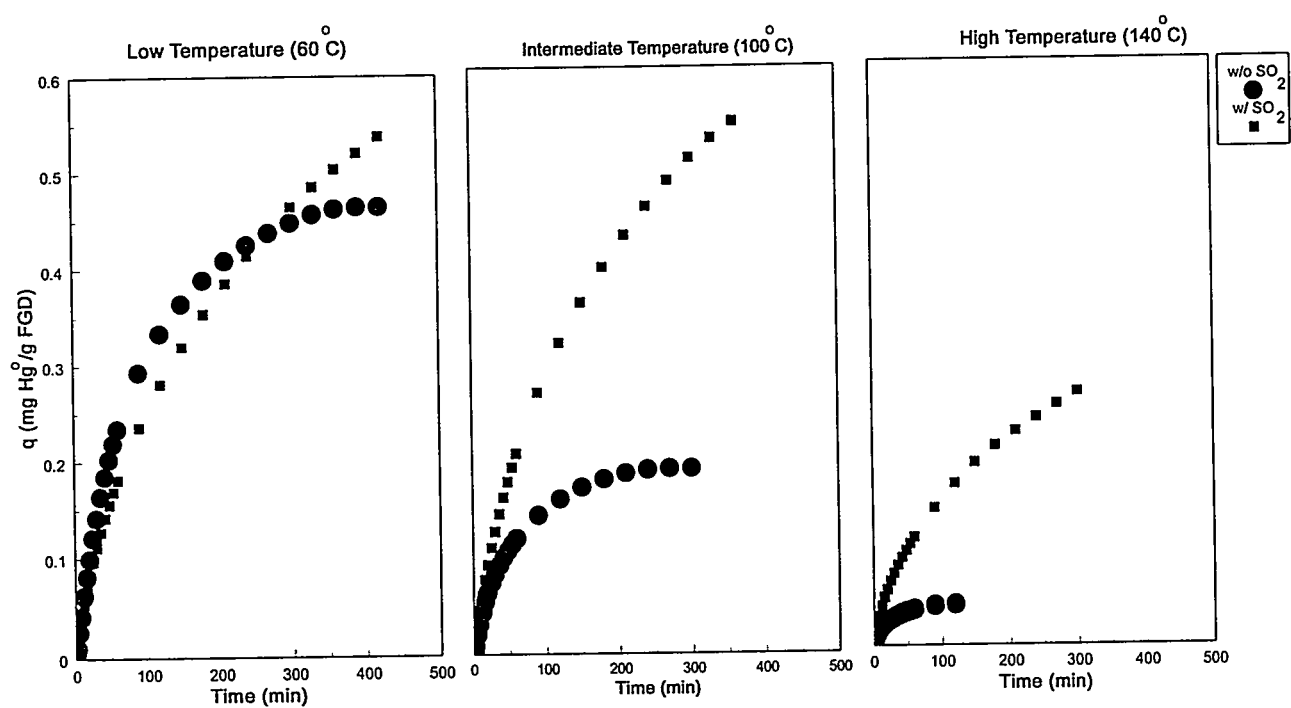


Figure 7. Effect of SO_2 (1000 ppm) on Hg^0 uptake by activated carbon, FGD (inlet Hg^0 concentration of 40 ppb).

Characterization of PIC Emissions from Combustion of Pentachlorophenol-Treated Wood Wastes

Suh Y. Lee, Joseph C. Valenti, and Dennis G. Tabor
Acurex Environmental Corporation
4915 Prospectus Drive
Durham, NC 27713

Robert V. Hendriks and C. W. Lee
Air Pollution Prevention and Control Division
National Risk Management Research Laboratory
U.S. Environmental Protection Agency
86 T.W. Alexander Drive
Research Triangle Park, NC 27711

INTRODUCTION

The use of waste wood as fuel for producing energy is a promising supplement to fossil fuels for many regions of the country. In addition to recovering energy and conserving landfill space, burning waste wood fuels also mitigates global warming created by fossil fuel combustion. However, the environmental consequences resulting from emissions generated by combustion of waste wood which contains paints, resins, or preservatives are not well understood. The combustion of waste wood treated with chemicals may produce potentially hazardous products of incomplete combustion (PIC) emissions such as dioxins.^{1,2}

Characterization of PIC emissions from the combustion of waste wood previously treated with pentachlorophenol is reported in this study. Utility poles and crossbars are typically treated with a preservative such as pentachlorophenol in order to prolong their service life. They are disposed of by landfilling after being taken out of service. Burning such wood waste in boilers for steam generation becomes an increasingly attractive waste management alternative as it contains substantial energy values and reduces landfilling costs. Pilot-scale combustion tests were conducted under well controlled conditions in a 0.58 MW (2 million Btu/hr) combustor to compare PIC emissions from burning untreated wood and pentachlorophenol-treated wood. Sampling and analyses for a wide variety of PICs, including volatile organic compounds (VOCs), semivolatile organic compounds (SVOCs), and dioxins and furans, were performed to assess the effect of pentachlorophenol preservative present in wood on PIC emissions.

EXPERIMENTAL

Test Facility

The combustion testing was conducted using a multifuel combustor (MFC) installed in the Environmental Protection Agency's research facility located at Research Triangle Park, North Carolina. The MFC, shown in Figure 1, is a pilot-scale stoker combustor with 0.58 MW (2 million Btu/hr) maximum thermal output which is sufficient for simulating the full range of conditions that might be encountered in practical systems. The MFC is capable of burning a wide variety of solid fuels including municipal solid waste, refuse derived fuel, biomass fuel, and coal singly or in combination. The combustor is constructed with modular sections, which provides maximum flexibility for modifying the combustor for research purposes. Access ports are installed throughout the entire combustor for sampling and visual observation.

The combustor was operated in a spreader stoker firing mode. Wood fuel was stored in a large roll-off container located near the building which houses the MFC. A tote bin filled with the wood fuel was transported to the MFC facility and the fuel was sequentially dumped into a loading hopper installed outside the facility building, using a forklift. An electric drive conveyor belt, installed under the loading hopper and penetrating through the facility building wall, moved the fuel to a vibrating active

storage silo installed inside the building. The silo is designed for a 2 hour turnover time using an average fuel density of 80 kg/m³ (5 lb/ft³) and a feed rate of 163 kg/hr (360 lb/hr). The silo is large enough to dampen out effects of spurious loading yet small enough to fit inside the facility building. A vibratory silo is designed to improve mixing and reduce wall sticking. The fuel was distributed from the silo onto an airtight horizontal vibratory feeder conveyor connecting the silo to the transition section of the spreader stoker. The mass flow of the conveyor was calibrated for control of the fuel feed rate. The fuel traveled horizontally along the conveyor and dropped through the transition section into the feed injection port of the spreader stoker. The vibratory transition section is designed with an inlet air plenum area and adjustable inlet angle plate to facilitate spreading fuel onto the 61 by 30 cm (2 by 1 ft) stoker grate where a burning fuel bed is formed.

Wood Fuel

Two different wood fuels, untreated wood and treated wood, were obtained from a plant where wood poles are treated with pentachlorophenol. The untreated wood was pine poles that are typically treated in the plant. The treated wood was a mixture of recently treated poles, mostly small pieces cut from the end to meet customers' length specifications and aged treated poles taken out of service. Both treated and untreated poles were ground into chips less than 7.6 cm (3 in.) in diameter. The two fuels were characterized by proximate, ultimate, and chlorine analyses: results are shown in Table 1. It can be seen that the treated wood fuel is drier with higher heating value as compared to the untreated wood. The chlorine content of the treated wood fuel is 10 times higher than that of the untreated wood.

Combustion Test Parameters

The only parameter investigated was the difference in emissions when burning treated vs. untreated wood fuels under similar combustion conditions; no attempt was made to conduct parametric tests for this study. In general, the operating conditions of the test were considered optimal when the fuel was burning at the designed heat release rate with nominally 160 % excess air and a low level (< 100 ppm) of carbon monoxide (CO) emissions in the flue gas.

The amount of fuel burned was not measured continuously during a test. It was estimated by weighing the fuel before it was dumped into the loading hopper of the MFC and measuring the time required for its complete consumption to calculate an average feed rate. The average feed rate was used to estimate the amount of fuel burned during a timed emissions sampling period. The MFC is equipped with continuous emission monitors (CEMs) -- for measuring oxygen (O₂), CO, carbon dioxide (CO₂), nitrogen oxide (NO), sulfur dioxide (SO₂), total hydrocarbon (THC), and hydrogen chloride (HCl) -- and equipment for continuously monitoring process temperatures and pressures.

Sampling and Analytical Procedures

The emissions sampling point for the present study was selected at the duct which connects the convective section of the furnace to the baghouse. The selection of a sampling point prior to any gas cleaning device was made to ensure that any difference in flue gas pollutant concentrations generated by combustion of treated and untreated wood fuels would be observed. Emission measurements made after the flue gas cleaning device would be expected to mask this difference and would be reflective of the effectiveness of the devices (i.e., baghouse and caustic scrubber) used.

The sampling program of the present study focused primarily on organic emissions, particularly those which are considered potentially hazardous, from the combustion of wood fuels. Sampling and analytical protocols used were based on existing EPA methods for measuring organic constituents in flue gases. Samples for measuring volatile organic PIC emissions were taken using EPA SW Method 0030, Volatile Organic Sampling Train (VOST), and the volatile PICs in the VOST samples were identified and quantified using SW Methods 5040 and 8240.³⁻⁵ Samples for measuring SVOC emissions were obtained using SW Method 0010, and SVOCs in the samples were analyzed using SW Method 8270B.⁶⁻⁷ Method 23 was used for measuring dioxin and furan emissions.⁸

RESULTS AND DISCUSSION

Test Conditions

Six combustion tests, three tests each for both the untreated and the treated wood fuels, were performed under similar combustor operating conditions. The untreated wood tests were performed first followed by the treated wood tests to avoid cross contamination. Triplicate runs were made to determine experimental repeatability. Since it was not practical to measure fuel feed rate continuously, the tests were performed under constant excess air level (nominally 160% excess air) and a constant combustion gas temperature (850° C) measured by a thermocouple located 152 cm (60 in) above the grate. The estimated heat release rates for all the tests are shown in Table 2 and the average CEMs-measured emission rates are shown in Table 3. The heat release rates are calculated based on the average fuel feed rate estimated by the amount of fuel consumed during the test period and the heating value of the fuel measured experimentally. It can be seen from Table 2 that the calculated heat release rates and the measured flue gas flow rates for Untreated Tests 2 and 3 are lower than those of the other tests. The lower flue gas flows for Untreated Tests 2 and 3 are consistent with their low fuel feed rates. The heat release rate was set at 80% of the maximum designed output of the MFC for the present study. The fuel feed rate was adjusted manually throughout all tests in order to maintain a constant temperature of 850° C above the stoker grate and keep CO emissions below 100 ppm, which were considered optimum conditions for the tests. The combustion gas temperature measured may not have been always truly representative. The tremendous turbulence generated above a burning hot fuel bed when the cold underfire air passing through the grate and the cold overfire air injected into the furnace above the grate may create a non-uniform gas temperature profile. Observations through installed viewing ports indicated that turbulent flow passed along the entire furnace during the tests. The heating values measured from the two fuel samples may not be truly representative due to the nonhomogeneous nature of the wood fuels. These two uncertainties may have contributed to the lower estimated heat release rates for the two tests.

It was difficult to produce exactly identical combustion conditions for all the tests, mainly due to the fact that the two wood fuels are not homogeneous. The treated wood fuel contains aged wood, which is drier, and has 30% higher heating value than the untreated wood fuel. Uneven fuel feed rates resulting from the fairly frequent manual adjustment of the fuel feeder could have caused fluctuations in air-to-fuel ratio and momentary excursions of CO emissions. CEM data for CO and CO₂ and visual observations of fuel flow into the stoker suggest that small excursions occurred during the tests. The nonhomogeneous nature of the fuels coupled with the practical difficulties to burn such fuels under well

defined conditions make the accurate estimation of heat release rates during tests impossible. The high CO emissions, shown in Table 3, calculated after the untreated wood tests, are another indication that combustion conditions were difficult to control when burning the untreated wood, which has low heating value and high moisture content.

Pentachlorophenol Destruction Efficiency

The concentration of pentachlorophenol in the treated wood fuel was analyzed to be 4,100 mg/kg (ppmw). For the six tests, pentachlorophenol was not detected in any of the semivolatile organic samples. The estimated pentachlorophenol destruction efficiency (DRE) for each test has been conservatively calculated based on the pentachlorophenol analysis practical quantitation limit (PQL). DRE results are presented in Table 4. The PQL is based on the lowest calibration concentration and does not include factors such as percent recovery or matrix effects. It is evident from these results that burning of the pentachlorophenol-treated waste wood in a stoker combustor destroys the pentachlorophenol efficiently with a DRE higher than that required for hazardous waste destruction (99.99%).

Volatile Organic Compound (VOC) Emissions

Analyses were performed for 50 VOCs in each of the test samples. The VOC emission results presented in Table 5 are the compounds found in concentrations higher than the analytical detection limit in at least one test. Higher levels of benzene were found in the untreated wood test samples, while bromomethane was found at higher levels in the treated wood test samples. Chloromethane, 1,3-butadiene, iodomethane, acetone, chloroform, and 1,2-dichloroethane were found in both untreated and treated wood test samples. The trace levels of chlorinated VOC emissions found in the untreated wood tests may possibly be caused by small amounts of naturally occurring chlorine in untreated woods. More chlorinated VOCs were found in the treated wood tests, probably as a result of higher chlorine content in the pentachlorophenol-treated wood.

SVOC Emissions

Of the 87 semivolatile organic compounds for which analyses were performed in the SVOC samples, only the following five targeted compounds were found to be above the analytical detection limits: phenol, acetophenone, naphthalene, 2-nitrophenol, and phenanthrene. The total SVOC emission rate for all six tests is calculated by adding all the quantifiable SVOC emissions in the test, and results are summarized in Table 6. The typically low SVOC emissions for both the untreated and treated wood tests are an indication that good combustion conditions were achieved during the tests. The slightly lower SVOC emissions for the treated wood tests compared to those for the untreated wood tests also suggest that the combustion of the drier treated wood fuel produced lower PICs. More moisture released during the combustion of the “green” untreated wood fuel may lower the localized combustion zone temperature and cause more PIC formation.

Dioxin/Furan (PCDD/PCDF) Emissions

The dioxin/furan samples measured by Method 23 were taken at the exit of the convective heat exchanger and before the baghouse. The temperature of the flue gas at the sampling point was between 150 and 160° C. It has been shown that the dioxin and furan formation “temperature window” in flue

gases is between 200 and 450° C.⁹ It is reasonable to expect that the formation of dioxins and furans has already been completed before the sampling location.

As shown in Table 7, total PCDD/PCDF emissions from the untreated wood tests [using the International Toxic Equivalency (I-TEQ) method of accounting for different toxicities of PCDD/PCDF congeners] averaged 0.274 ng I-TEQ/dscm and from treated wood tests 1.190 ng I-TEQ/dscm. These emission rates are prior to any control devices. Particulate control devices could potentially remove part of this material from the gas stream, depending on the fly ash collection efficiency, PCDD/PCDF formation, and solid-to-vapor-phase partition with the device. Since the temperature at the sampling point is below 160° C, it is likely that the rates of formation and desorption of fly-ash-associated PCDD/PCDF in a subsequent particulate collection device would be low.¹⁰ The PCDF emissions are significantly greater than PCDD emissions for both the untreated and treated wood tests, indicating de novo synthesis formation reactions rather than condensation reactions.¹¹ The PCDD/PCDF congener distributions for the treated and untreated tests also differ. In the untreated wood tests, the distribution is peaked at the the lower-chlorinated tetra-PCDD and di-PCDF congeners; in the treated wood tests, the distribution is shifted to the higher-chlorinated hexa-PCDD and penta-PCDF congeners. The PCDD/PCDF emission rates measured from both the untreated and treated wood tests are considered low when compared to the stack emissions from commercial municipal waste combustors, which range from 0.01 to 400 ng I-TEQ/dscm.¹² The low PCDD/PCDF emissions measured from the untreated wood tests are similar to those from burning natural wood, which range from 0.066 to 0.214 ng I-TEQ/dscm.¹ The PCDD/PCDF emissions from the treated wood tests are higher than those (0.0359 ng I-TEQ/dscm) from a waste-to-energy plant burning a mixture of clean wood and pentachlorophenol-treated waste wood.¹³

The higher PCDD/PCDF emissions from the treated wood tests compared to those from the untreated wood tests are consistent with their higher chlorinated VOC emissions. Approximately 200 ppm of HCl was measured in emissions from the treated wood tests, while HCl was not detected in the untreated wood tests. The PCDD/PCDF samples were collected into front half and back half of the sampling train and analyzed separately, which gives an indication of the PCDD/PCDF associated with the particulate material and as gaseous emissions. Table 8 shows that the percentage of PCDD/PCDF in the front half catch is greater in the treated wood tests than in the untreated wood tests. The treated wood tests had a higher flue gas flow rate (see Table 2) as a result of the higher heating value of the treated wood burned, which would enhance particulate load at the sampling point. This information suggests that particulate carryover may affect the total amount of PCDD/PCDF, especially in the treated wood samples where a larger percentage is in the front half catch. Combustor operating conditions in addition to the wood treatment may also contribute to higher measured PCDD/PCDF emissions for the treated wood tests.

CONCLUSIONS

This study was conducted to identify potential air emissions problems associated with the combustion of waste wood, primarily utility poles treated with pentachlorophenol preservative, as a fuel for energy production in a boiler. The emphasis of the study was placed on the characterization of the PIC emissions from combustion of pentachlorophenol-treated waste wood. The methodology used was a comparative test of emissions prior to the air pollution control device of a pilot-scale combustor burning

untreated wood and wood treated with pentachlorophenol preservative as a fuel. The tests showed that combustion of pentachlorophenol-treated wood is an effective method of destroying the pentachlorophenol contained in the wood, with destruction efficiencies higher than 99.99 %.

Differences in VOC, SVOC, and PCDD/PCDF emissions from the combustion of untreated and treated wood fuels have been noted. The data do not enable identification of the exact cause of these differences in emissions. These differences are possibly caused by the significantly different moisture content, heating value, and chlorine content of the two fuels. The difference in flue gas flow rate required for the combustion of these two fuels with different combustion characteristics (moisture content and heating value) may also cause the differences in PCDD/PCDF emissions. These emissions are representative only of this facility and configuration and may not be quantitatively comparable to other combustors.

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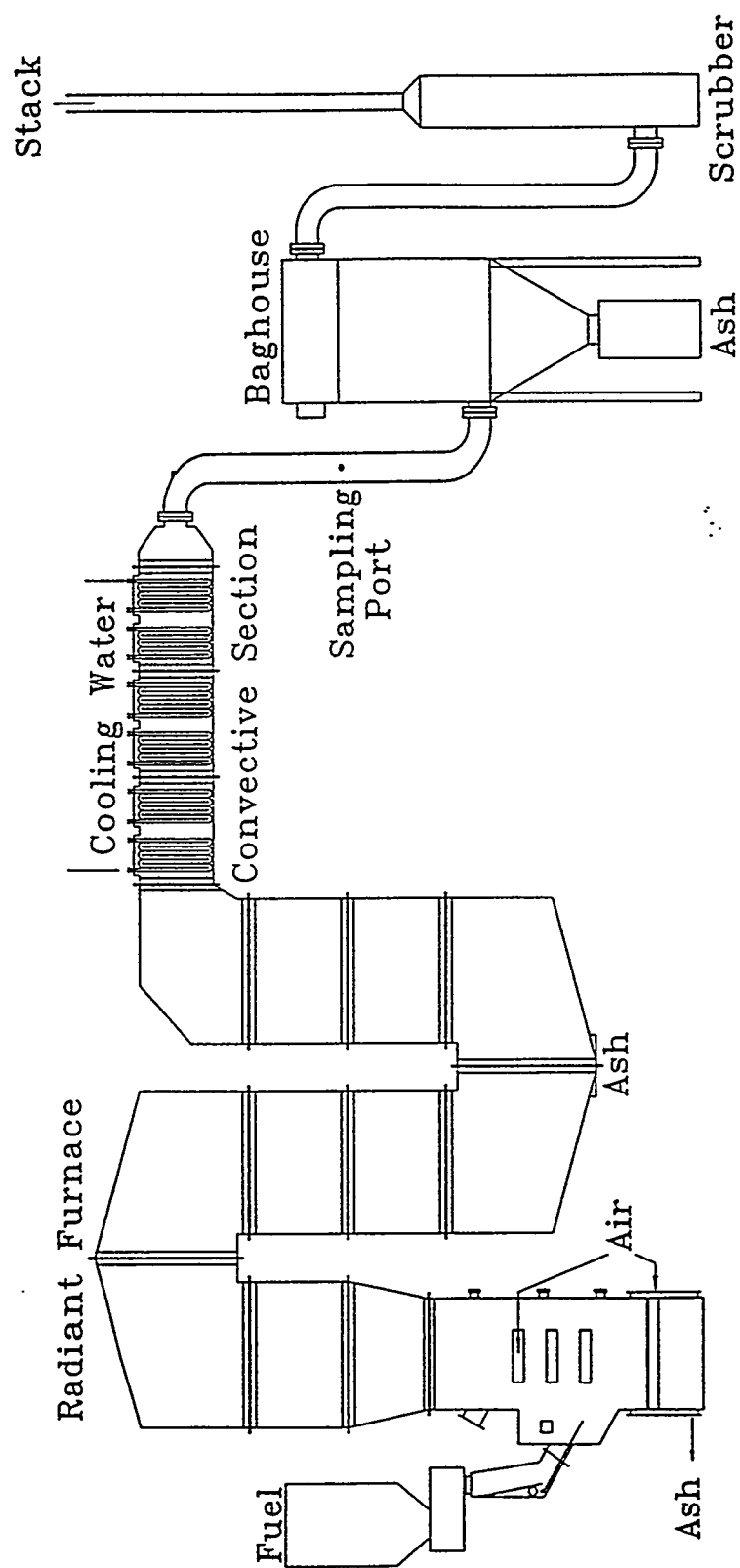


Figure 1. Schematic of the multifuel combustor.

Table 1. Characteristics of wood fuels.

Constituent	Content ^a	
	Untreated Wood	Treated Wood
<u>Proximate Analysis</u>		
Moisture, %	33.44	21.46
Ash, %	0.25	0.57
Volatile Matter, %	57.92	66.28
Fixed Carbon, %	8.39	11.69
Heating Value, kJ/g (Btu/lb)	12.953 (5,569)	16.833 (7,237)
<u>Ultimate Analysis</u>		
Carbon, %	33.83	43.24
Hydrogen, %	4.20	4.92
Nitrogen, %	0.28	0.28
Sulfur, %	0.01	0.05
Oxygen, %	27.99	29.48
<u>Chlorine Analysis</u>		
Pentachlorophenol, ppm	6.7	4,100
2,4-dichlorophenol, ppm	2.4	3.6
Chlorine, %	0.02	0.20

^a: Measured on an as-received basis

Table 2. Combustor operating conditions.

Test	Averaged Fuel Feed Rate, kg/hr (lb/hr)	Combustor Thermal Output, MW (million Btu/hr)	Flue Gas Flow, dscm
Untreated 1	134.4 (296.4)	0.48 (1.65)	19.4
Untreated 2	117.1 (258.1)	0.42 (1.44)	16.6
Untreated 3	114.1 (251.6)	0.41 (1.40)	17.9
Treated 1	100.6 (221.8)	0.47 (1.61)	25.0
Treated 2	102.3 (225.6)	0.48 (1.63)	21.0
Treated 3	102.5 (225.9)	0.48 (1.63)	25.8

Table 3. Summary of flue gas temperature and CEM data.

Location	Temperature, °C					
	Untreated Test 1	Untreated Test 2	Untreated Test 3	Treated Test 1	Treated Test 2	Treated Test 3
Stoker Section Exit	849	801	827	869	921	870
Sampling Port	152	153	153	155	160	160
Constituent	Concentration, %					
O ₂	12.5	13.2	12.9	13.1	13.3	13.3
CO ₂	7.5	7.2	7.1	6.7	6.5	6.5
H ₂ O	11.0	9.8	9.8	8.7	8.7	9.0
CO ^a	203	249	456	66	21	20
NO ^a	103	133	83	295	178	210
THC ^a	77	56	2	4	3	3
HCl ^a	<1	<1	<1	195	194	183
SO ₂ ^a	10	11	13	<1	<1	<1

a: in ppm @ 7% O₂

Table 4. Destruction efficiency for pentachlorophenol.

Test	DRE, %
Treated Test 1	>99.9974
Treated Test 2	>99.9976
Treated Test 3	>99.9975

Table 5. VOC emission rates.

VOCs	Emission Rate, $\mu\text{g/dscm}$ @ 7% O ₂					
	Untreated Test 1	Untreated Test 2	Untreated Test 3	Treated Test 1	Treated Test 2	Treated Test 3
Chloromethane	53.3	28.5	16.9	55.8	96.7	51.5
1,3-Butadiene	0.6	0.2	1.2	0.1	0.1	0.1
Bromomethane	1.7	1.4	2.1	15.4	33.9	70.5
Iodomethane	0.8	2.4	5.7	1.7	5.1	24.1
Acetone	11.6	7.2	7.5	4.5	11.7	14.3
Chloroform	0.9	0.3	0.3	2.6	1.8	3.9
1,2-Dichloroethane	1.3	5.2	0.1	1.6	0.7	2.9
Benzene	25.4	16.2	27.9	2.1	2.6	3.0

Table 6. SVOC emission rates.

Test	Total Emission Rate, $\mu\text{g/dscm}$ @ 7% O ₂
Untreated Test 1	10.1
Untreated Test 2	11.4
Untreated Test 3	11.7
Treated Test 1	7.0
Treated Test 2	7.7
Treated Test 3	5.9

Table 7. Total PCDD/PCDF emission rates.

Test	Emission Rate ^a			
	Total PCDD, ng/dscm	Total PCDF, ng/dscm	Total PCDD/PCDF, ng/dscm	Total PCDD/PCDF, ng I-TEQ/dscm
Untreated Test 1	8.4	22.3	30.7	0.5
Untreated Test 2	2.6	17.2	19.8	0.2
Untreated Test 3	1.0	11.1	12.1	0.1
Treated Test 1	15.0	42.2	57.2	1.3
Treated Test 2	20.9	56.5	77.4	1.2
Treated Test 3	18.7	45.0	63.7	1.1

a: @ 7% O₂

Table 8. Distribution of PCDD/PCDF in sampling train.

Test	% of PCDD I-TEQ in Front Half	% of PCDF I-TEQ in Front Half
Untreated Test 1	31.6	24.1
Untreated Test 2	53.0	40.1
Untreated Test 3	49.0	33.3
Treated Test 1	75.8	63.4
Treated Test 2	70.4	59.4
Treated Test 3	68.0	59.7

TECHNICAL SESSION IV

***Retrofits & Advanced
Technologies***

Retrofitting A Spray Dryer ESP-Equipped Facility

**Marty Suchan
American Ref-Fuel Company of Essex County
183 Raymond Boulevard
Newark, NJ 07105**

**Scott Zapf
American Ref-Fuel Company of Essex County
183 Raymond Boulevard
Newark, NJ 07105**

**Greg H. Gesell
American Ref-Fuel Company
777 N. Eldridge Parkway
Houston, TX 77079**

INTRODUCTION

During the development of the December 19, 1995 United States Environmental Protection Agency's (EPA) Emission Guidelines for Municipal Waste Combustors, much consideration was given to electrostatic precipitator (ESP) equipped facilities. The cost for replacement of well performing ESPs is prohibitive, especially if the facility is already equipped with a spray dryer absorber (SDA). EPA proposed and promulgated Emission Guidelines which were designed to allow facilities with modern well performing ESPs to comply without replacement of existing equipment.

The Essex County Resource Recovery Facility is one example of a facility equipped with a modern, well performing SDA/ESP combination. Due to actions taken by the State of New Jersey Department of Environmental Protection (DEP), the Essex County Facility has already been retrofitted and is in position to comply with the December, 1995 Emission Guidelines. This paper provides further discussion of the actions taken to retrofit the Essex County Facility and presents limited resultant emission data.

FACILITY DESCRIPTION

The Essex County Resource Recovery Facility is located in Newark, New Jersey and is owned and operated by American Ref-Fuel Company. Refer to Figure 1 for a site layout of the retrofitted facility. The facility processes approximately 2,500 tons of municipal solid waste per day. Operation began in November, 1990 with completion of performance and compliance testing in early 1991.

The facility is comprised of three independent mass-burn processing trains and two steam turbine generators. Each of the three processing trains is equipped with a Deutsche Babcock Anlagen (DBA) Roller Grate System and a four-pass boiler. The DBA Roller Grate System was designed and developed in Europe over 50 years ago and is exclusively licensed to American Ref-Fuel Company in North America.

Municipal solid waste is received on the tipping floor, where it is inspected with any unacceptable waste removed before being deposited into the 11,000 ton capacity refuse bunker. In the bunker, the refuse is mixed and usually inspected by one of two overhead refuse crane operators. The waste is stored in the bunker before being charged to one of the three boiler feed hoppers. Maintaining tight control over the waste before incineration and feeding a consistent mixture of refuse aids in good combustion and controlling emissions within state and federal requirements.

Refuse is charged to the furnace by a ram feeder located at the bottom of the feed chute. Waste slowly tumbles down the roller grates, passing through drying, combustion, and burnout zones before the remaining ash residue falls into the water filled quench tank of one of two ash extractors. Wetting the ash minimizes the potential for fugitive dust and facilitates safe handling. Ferrous metal is recovered from the facility residue stream.

Combustion is closely monitored by a Control Room Operator and is controlled by a computerized combustion system which adjusts the combustion parameters to maintain a constant boiler load and control emissions. Combustion air is provided by an under grate primary air fan and a secondary air fan.

Superheated steam is generated in the pendant superheater sections and tube bundles. An economizer section warms feedwater in the fourth pass resulting in a flue gas exit temperature of about 450-520 degrees F. Much of the ash carried with the flue gas from the furnace drops out as the gases turn between the second and third boiler pass. Superheated steam is collected in a common header from the

three boilers and is routed to two 35 megawatt turbine generators. Approximately 70 megawatts of electricity are produced with 12 percent used for in-house purposes. The steam is condensed in dual air-cooled condensers.

Facility Emission Control Equipment

The flue gas passes from the furnace section through the four pass boiler. After leaving the boiler and economizer, the flue gas is split and travels through one of two precyclones and spray dryer absorbers (SDA). Part of the remaining fly ash is removed in the precyclones. Lime slurry is injected in the dual fluid nozzle SDAs to facilitate removal of acid gases. Slurry injection rate is controlled by the SDA sulfur dioxide (SO₂) level. More lime slurry is injected as the SDA inlet SO₂ increases. In order to maintain a constant outlet temperature of 300 degrees F, additional temperature control water is atomized in the SDA's.

From the dual SDA's the flue gas passes through an electrostatic precipitator (ESP), induced draft fan and is discharged through a three flue stack. The ESP has three fields which remove remaining particulate and spent lime and salts of reaction from the SDAs. The ESPs have a duct spacing of about 12 inches and a design specific collection area of 575 ft per 1000 acfm. Gas velocity is slightly greater than two feet per second and the aspect ratio is less than 1. The total projected collecting area is almost 100,000 ft.

The fly ash and spent lime are collected and treated with a WES-PHIX® phosphoric acid conditioner and water in a pugmill before being combined with the bottom ash. The combined ash stream is stored in an enclosed bunker. A clam shell overhead crane is used to load trucks within the building. A tarping station completes the ash handling area and allows for controlled fugitive ash emissions.

The facility is equipped with a continuous emission monitoring system and continuous opacity monitoring system. These systems provide the facility feedback on SO₂ concentrations and reduction, carbon monoxide (CO), nitrogen oxide (NO_x) and opacity levels. This information allows rapid adjustment of the facility operation by the combustion control system and Control Room Operator to maintain in compliance.

FACILITY HISTORY

American Ref-Fuel Company of Essex County obtained an Air Permit to Construct a Municipal Solid Waste Resource Recovery Facility in December, 1985 from the New Jersey Department of Environmental Protection (NJDEP). The original air pollution control equipment included good combustion control, and a dual SDA/ESP. The dual SDA/ESP was selected based upon the recommendations of the project consulting engineer. At the time this selection was made, SDAs were not in common use. Thus, dual 60 percent capacity SDA's were selected to allow for additional redundancy and reliability. In addition, limited long term performance had been demonstrated for fabric filters (FF) and ESP's were the particulate collection device of choice for most existing waste-to-energy facilities and utility boilers.

NO_x CONTROL REQUIREMENTS

The facility permit, as issued, contained numerous emission requirements. For NO_x, two requirements were provided: (1) 95 pounds per hour (pph) per unit averaged over three successive test runs using USEPA Method 7; and (2) a one-hour average of not-to-exceed 300 parts per million on a dry basis corrected to seven percent oxygen (ppmdv @ 7% O₂). The 95 pph was derived by the use of an emission factor of three pounds of NO_x generated per ton of MSW. Prior to completion of the facility it was confirmed through testing at American Ref-Fuel's Hempstead, New York facility that the commonly used 3 lbs/ton emission factor was in error, based upon incomplete and inaccurate information available at that time, and was not achievable.

A BACT analysis concluded that combustion controls alone were not adequate to bring the facility into compliance with the 95 lb/hr requirement and that Selective Non-Catalytic Reduction (SNCR) was the appropriate add-on control system to be employed by the facility. The evaluation process resulted in the selection of the Thermal deNO_x aqueous ammonia technology offered by Exxon Corporation. After reviewing the process designed by Exxon, American Ref-Fuel purchased the technology agreement and modified the system to best fit the facility.

NO_x CONTROL RETROFIT

When it was determined that an SNCR system was required, the plant was too close to its startup date to effectively implement a redesign of the boiler to allow for an integrated NO_x control system. A retrofit strategy was developed by American Ref-Fuel corporate engineering to implement NO_x control according to a schedule imposed by the New Jersey DEP.

Technical grade aqueous ammonia (27.4 wt %) is utilized in the Essex thermal deNO_x process. Aqueous ammonia is stored onsite at atmospheric pressure in a 20,000 gallon tank and pumped to three identical vaporizer skids located in the boiler house. Steam is used to evaporate the aqueous ammonia. The ammonia vapor is mixed with steam prior to being injected into the furnace. This carrier steam aids the dispersion of the relatively small quantity of ammonia.

The ammonia vapor/steam mixture can be injected into the boiler through one of three available sets of injection nozzles located on the side walls of the upper first pass of the waterwall boiler. At each level nine nozzles are available on each side of the boiler. The nozzles vary in size and are arranged in a pattern of alternating relatively large and small nozzles at each level.

Because this project was an application of relatively new technology being applied in a retrofit manner on boilers with existing unique emission control technology, as much flexibility as possible was designed into the system to allow for variations in operation such as boiler load and fouling.

Several challenges occurred for this project. First, no provisions were made during the original boiler design for penetration at the required locations. Locating the storage tank, vaporizers and other required equipment was a challenge on the congested site. Routing of feed lines, electrical power supplies, and controls needed to conform to the existing layout. Installation was completed while the facility was operating with tie-in occurring during scheduled boiler outages.

NO_x CONTROL SYSTEM OPERATION

There were no comparable systems to use to predict performance, thus questions remained regarding the potential system capability. Testing flexibility was hampered by a requirement to remain within permit limits unless a specific variance was granted by NJDEP. American Ref-Fuel wanted to maintain its clear stack and thus did not want any ammonia slip reacting with HCl to form a visible ammonia chloride (NH₄Cl) plume. Concerns were also raised and addressed concerning public and employee safety due to a potential aqueous ammonia spill. Assurances had to be made that proper programs were in place to prevent spills and control them if necessary.

Several modifications were made to the initial design. Adjustments were made to the control logics, carrier steam supply and the nozzles used for injection. Only two problems were identified during startup. The first was a metallurgy compatibility concern which was quickly addressed. Secondly, the system vaporizers were and are an ongoing concern due to significant fouling. About once a month each system must be taken off-line for cleaning. This cleaning must be carefully prepared for to allow the system to return to service and maintain compliance under NJDEP's permit requirement of a three hour rolling average.

The thermal deNO_x system is controlled from the plant's distributed control system (DCS). The function of the control system is to maintain the target outlet NO_x concentration by regulating the aqueous ammonia flow rate. Changing of levels or zones is completed manually. Levels are changed infrequently as the boiler conditions change.

The SNCR system was installed in late 1994 and has worked well since. Compliance with the proposed MACT emission limit and averaging time is achievable. The system is routinely achieving an NJDEP requirement of 174 ppm_{dv} @ 7% O₂ on a 3-hour rolling average and 95 lb/hr. The outstanding concern of achieving the NJDEP NO_x emission requirement on a 3-hour rolling average basis during a required outage remains as a special challenge for the facility.

MERCURY CONTROL REQUIREMENTS

In addition to the SNCR system, the facility has also been retrofitted with an activated carbon injection (CI) system. The original permit requirement for mercury emissions was 0.053 lb/hr. This value was derived from early test data at other waste-to-energy facilities which later proved to be lower than typical emission rates. Although the Essex County Facility was burdened with an artificially low mercury emission requirement, the facility was fortunate to have had mercury emissions among the lowest of any waste-to-energy facility in New Jersey before activated carbon systems were installed. While mercury had always been an emission of concern under the existing permit, aggressive measures taken by the NJDEP and the facility were successful in minimizing mercury in the waste stream and allow the facility as initially equipped to comply with its permit limits.

The Essex Facility and American Ref-Fuel worked with several efforts to remove mercury from the waste stream. Recycling programs and information were communicated to the various regional hospitals and pharmacies. These sources were assumed to be the largest consumers and dispensers of mercury batteries and hearing aid batteries. American Ref-Fuel also actively participated on a New Jersey DEP task force commissioned to address mercury emissions and establish control requirements.

The revised New Jersey mercury emission requirements for all facilities are presently 65 µg/dscm corrected to 7% O₂ or 80 percent reduction. The concentration requirement is based upon an annual

average of four quarters where as the reduction requirement must be demonstrated every quarter. A further requirement will lower the allowable concentration to 28 µg/dscm or 80 percent removal in the year 2000. The new mercury regulations also required that the Essex County Facility install a system to control mercury.

MERCURY CONTROL RETROFIT

Various mercury control technologies were reviewed by all facility operators and the New Jersey DEP to determine which system granted the greatest potential for success. Any system would also need to be capable of increasing control at a future date. It was determined that this objective could best be achieved with a dry activated carbon system and the regulations therefore required that this type of system must be installed at all New Jersey facilities. Norit Americas Inc. was selected by the Essex County Facility as the vendor and design and construction proceeded as expeditiously as possible.

The Norit technology employed utilizes a dry carbon of lignite origin and injects the carbon into the flue gas ahead of the system precyclone and spray dryer absorber. The carbon is handled dry and is pneumatically conveyed to the injection points. Safety concerns of carbon powder were also considered and addressed with the facility design by installation of controls, blowout panels, fugitive dust control and operating procedures.

To provide some additional flexibility, two potential injection points were provided, upstream of the spray dryer atomizer and in the spray dryer vessel. The injection points are shown in the unit cross section in Figure 2. These points were suggested due to concerns about dropping out a significant quantity of carbon in the precyclone and for ease of installation. Early testing determined that the longer residence time and improved distribution of injecting upstream of the precyclones more than compensated for any loss of carbon in the precyclones.

Construction proceeded on a fast track to achieve the required completion date of before December 31, 1995. Several retrofit related modifications were made during this time slowing construction completion. Partially because all the facilities in New Jersey were installing systems, certain critical vendor capabilities were also in short supply.

Difficulties associated with most retrofit projects, including routing of carbon lines, power lines and controls, limited siting options and existing foundations also were incurred and addressed. As previously noted, the Essex site is very congested and locating a carbon silo and blower building was not easy. Penetrations to the existing units only involved penetrating through plate steel, however, access to the chosen injection locations is very restrictive. Work proceeded while the facility was on line.

MERCURY CONTROL SYSTEM OPERATION

Experience with carbon injection on SDA/ESP equipped facilities was very limited, consisting largely of the Warren County EPA carbon injection study. No long term reliable data was available for any similar systems. Concerns were raised over possible reduction in the particulate control performance of the ESPs. Carbon can demonstrate the ability to rapidly lose an electrical charge and thus lose its attraction with an ESP and "skip" through the ESP fields without being captured.

The activated carbon injection system installation was completed in late December, 1995 and the system has been in operation since. The ability of the facility to achieve the December, 1995 Emission Guideline requirements has been demonstrated. The NJDEP emission requirements of 65 µg/dscm corrected to 7%

O₂ or 80 percent reduction, has also been demonstrated to be achievable. Accurate measurement of carbon injection rates are completed by measuring usage on a shift basis and verifying this value on a plant-wide basis by using the truck scales and silo measurements on a monthly basis.

FACILITY PERFORMANCE

Limited emissions data is available for the retrofitted Essex County Facility. The facility has demonstrated exceptional emission results for all testing completed since the retrofits were completed. The emission results are compared to the Emission Guidelines promulgated on December 19, 1995 in Table 1 and show favorable results for all parameters impacted by the retrofit. An added benefit of the mercury control system is the excellent dioxin control achieved. If significant revisions are made to the Emission Guidelines in the process of any legal proceeding or if the interpretation or application of the Guidelines by NJDEP were to significantly revise the Guidelines for the State of New Jersey, meeting the revised requirements may be substantially more difficult. For example, if the NO_x emission requirement is applied on a 3-hour rolling average as opposed to a 24-hour block basis, even though the concentration requirement is not adjusted, the emission requirement is substantially more difficult.

CONCLUSION

The Essex County Resource Recovery Facility has been retrofitted and has the emission control configuration of Good Combustion Control/SDA/ESP/SNCR/CI. This configuration is capable of achieving the emission performance requirements of the 1995 EPA Emission Guidelines. This project demonstrates that the emission requirements of the Guidelines as promulgated can be achieved by some facilities equipped with well performing ESPs.

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Table 1. Essex County Emission Comparison of Selected Parameters Post-Retrofit.

Parameter	Facility Unit 1	Average Unit 2	Corrected to 7% O ₂ Unit 3	December 19, 1995 Emission Guideline
Particulate, gr/dscf	0.0025	0.0010	0.0010	0.012
NO _x , ppm _{dv}	less than 180	less than 180	less than 180	200
Mercury, µg/dscm	27	22	27	80 or
percent reduction	81%	85%	80%	85%
Total Dioxins ^① , ng/dscm	3.0	1.5	2.0	60

① Total dioxins is reported as tetra-octa polychlorinated dibenzo-p-dioxin and tetra-octa polychlorinated dibenzo furans reported on a total basis.

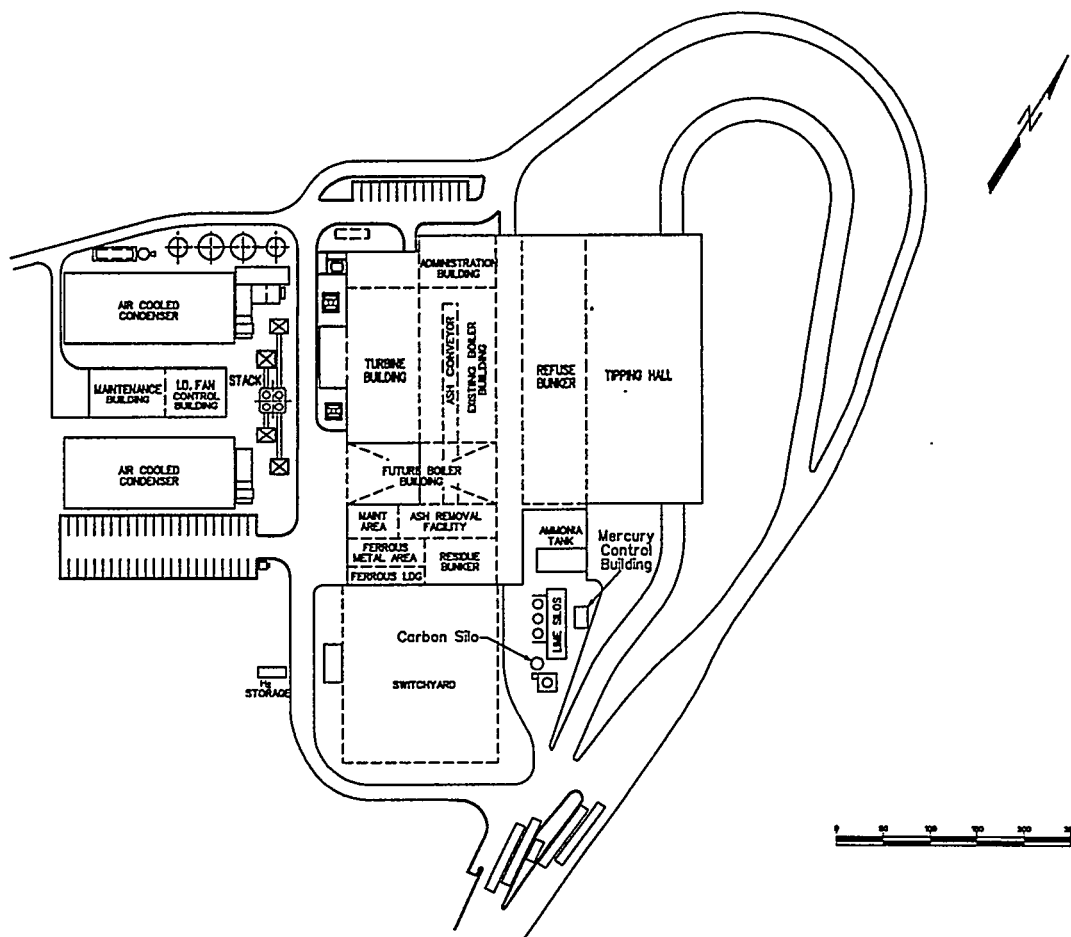


Figure 1 Essex County Resource Recovery Facility Site

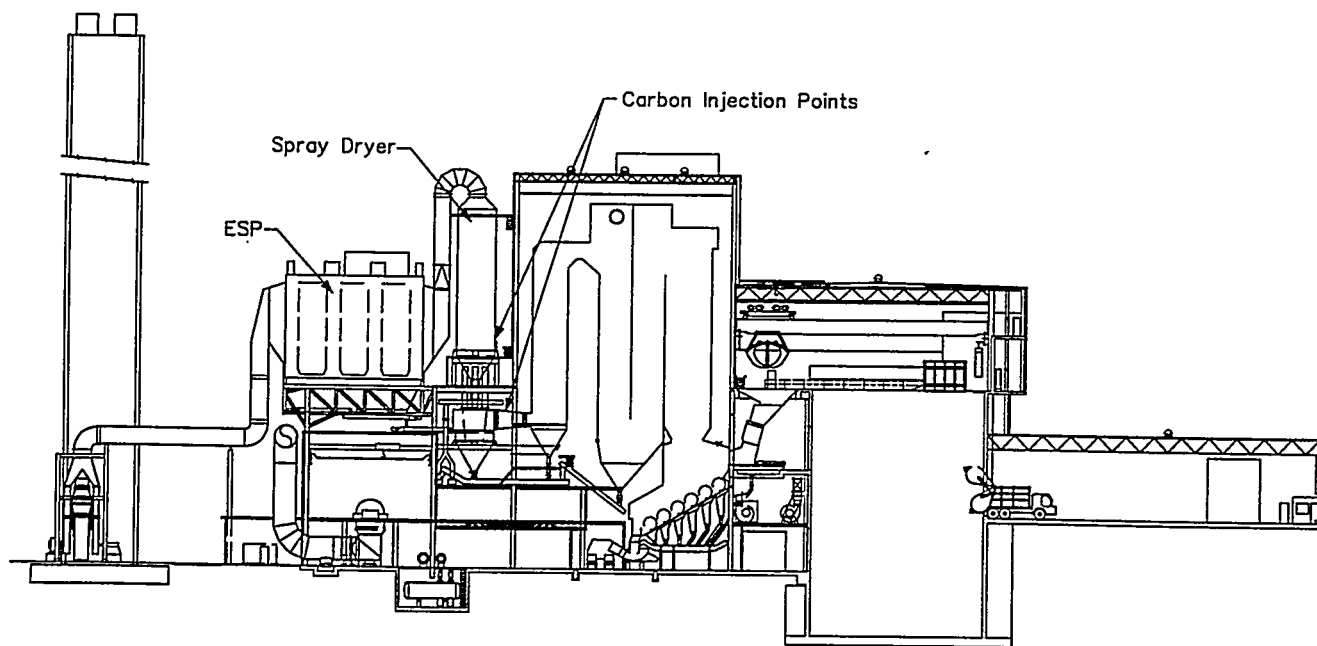


Figure 2. Essex County Resource Recovery Facility
Cross-Section showing Carbon Injection Location

**Combined Heat Recovery and Dry Scrubbing for MWCs
To Meet the New EPA Guidelines**

**Peter J. Finnis. P. Eng.
Procedair Industries Corp.,
12700 Shelbyville Road
Louisville, KY 40243
Ph: (502) 254-6130, Fax: (502) 254-6132**

**Brian M. Heap, Managing Director
Procedair Limited
Wombourne, UK**

INTRODUCTION

Both the UK and US Municipal Waste Combuster (MWC) markets have undergone upgraded regulatory control. In the UK, the government's Integrated Pollution Control (IPC) regime, enforced by the 1990 Environmental Protection Act (EPA) Standard IPR5/3 moved control of emissions of MWCs from local councils to the government Environmental Authority (EA). Existing MWCs had until December 1, 1996 to complete environmental upgrades. Simultaneously, the European Community (EC) was finalizing more stringent legislation to take place in the year 2001.

In the US, the 1990 Clean Air Act amendments required the Environmental Protection Agency (EPA) to issue emission guidelines for new and existing facilities. Existing facilities are likely to have only until the end of 1999 to complete upgrades.

In the UK, retrofits had considerable incentive to maximize energy recovery because of government incentives for energy production from renewable resources. Four facilities with a total capacity of 900,000 tpy opted for energy recovery and air pollution control. Our company in the UK received contracts, which included energy recovery equipment as part of Air Pollution Control (APC) contracts at:

1. Coventry and Solihull Waste Disposal Company(CSWDC), originally with a capacity of 175,000 tpy but upgraded to 260,000 tpy.
2. London Waste Company, Edmonton, with a capacity of 690,000 tpy.

In North America, our company had received contracts from Kvaerner EnviroPower AB, for APC systems on four new Refuse Derived Fuel (RDF) fluid bed boilers that incorporated low outlet temperature economizers as part of the original boiler equipment. The Fayetteville, North Carolina facility was designed for 200,000 tpy.

What all these facilities have in common is low economizer outlet temperatures of 285°F coupled with our Total Dry Scrubbing Systems. MWC or RDF facilities using conventional spray dryer/fabric filter combinations have to have economizer gas outlet temperatures about 430°F to allow for evaporation of the lime slurry in the spray dryer without the likelihood of wall build up or moisture carry over. Since the Totally Dry Scrubbing System can operate with economizer gas outlet temperatures about 285°F, the added energy available for sale from adding low outlet temperature economizer heat recovery can be considerable.(Figure 1). This paper focuses on Procedair's new plant and retrofit experience using "Dry Venturi Reactor/Fabric Filter combination with this lower inlet temperature operating conditions.

SYSTEM COMPONENTS

The principal components in designing a high heat recovery/dry scrubber system are:

1. Heat recovery economizer designed for low outlet temperature (less than 290°F).
2. Dry venturi reactor for hydrated lime and powdered activated carbon injection and primary gas reaction with the boiler flue gases.
3. Fabric filter dust collector for particulate collection and secondary gas reaction.
4. Material handling for recycle of partially reacted and unreacted reagent and waste disposal.

Heat Recovery Economizer

Gas temperature has a major effect on the performance of any dry-scrubbing system, particularly the SO₂ removal efficiencies as shown in (Figure 2). The designs utilized for the enhanced heat recovery for the Coventry and Edmonton retrofits utilized finned tubes to provide heat recovery in minimal space. Figure 3 shows typical designs of a single and double finned tube for economizers. Finned tube economizers have been used in Europe for this application for some time as shown in (Table 1). The Uppsala economizer is installed after the primary electrostatic precipitators and therefore sees relatively little dust (about .02 gr/dscf). The SYSAV economizer is located after a primary cyclone separator, and therefore, sees only about 1.0 gr/dscf dust load. The economizers installed on the Coventry and Edmonton retrofits have no pre-cleaners ahead of them. They therefore see the total flyash load. They are also installed before the acid gases are removed from the gas.

The Coventry economizers have three banks of finned tubes. The first two banks have carbon steel fins and the third or outlet bank has cast iron fins. The Edmonton retrofit used a first-stage bare tube section followed two carbon steel finned tube sections. Design details from the Coventry economizer is shown in Table 2. Both systems were integrated into the existing boiler heat cycle. The economizer subcontractors undertook extensive studies of the existing economizers and boiler steam drum designs to insure the added steam production could be handled by the existing boiler design. Both systems feature water recirculation systems to control the exit flue gas temperatures between 275°F and 285°F. The first of the two economizers for London Waste was put on line in June, 1995 with subsequent units being added about every three months. The three economizers at Coventry were put on line between twelve to fifteen months ago. To date, no cleaning other than normal soot blowing has been required for any of the units at Edmonton or Coventry. The units have been inspected every boiler outage (between eight to ten weeks). However, there is no sign of dust build up or corrosion.

Dry Venturi Reactor

Our vertical dry venturi reactor shown in Figure 4 has been developed over more than 20 years. The gases pass through a convergent zone into the reaction throat where hydrated lime and powdered activated carbon are injected into the flue gas. The reactor tower is basically a vertical double annulus, which provides for both the homogenous mixing of totally dry reagents with the flue gas constituents and also insures the necessary residence time (contact time) for the reagent in the gas stream. This use of a vertical arrangement insures that there is minimal stratification with resultant uneven or poor neutralization. The injection of the reagents into the gas stream through a venturi insures complete distribution of the reagent in this turbulent flow section. Pressure drop across the Venturi Reactor is only 2" H₂O, compared to 10" H₂O for conventional fluid bed reactors and 2 ½" H₂O for spray dryer type absorbers.

Fabric Filter Dust Collector

Both the Coventry and Edmonton installations are equipped with our TGT pulse jet fabric filter units for the final cleaning stage. This is a modern state-of-the-art pulse jet fabric filters utilizes low pressure compressed air (25 to 45 psig), injected by means of our proprietary Integrated Action Piston (IAP) valve for high-volume low-pressure cleaning. The IAP valve replaces the conventional diaphragm valve and overcomes many of the disadvantages of this type of valve. Due to its large open section and piston operation, the pressure drop across the IAP valve is extremely low compared to a conventional diaphragm valve, with significant energy savings. The principal advantage, however, of the IAP valve is

that unlike the diaphragm valve, which both snaps open and snaps shut rapidly, it permits a rapid opening with a slow controlled closing sequence. The snapping shut of the diaphragm valve causes the fabric to slap back onto the cage creating bag to cage wear, shock wave problems and thus dust carry through. With the IAP valve, the bag is rapidly inflated for maximum cleaning efficiency, but is deflated slowly. Reducing the pressure within the bag progressively permits it to regain its normal filtration position in a slow and controlled manner and to obtain for the fabric what is termed as a "soft landing." The use of soft landing reduces the wear of the fabric caused by the fibers rubbing against each other and also the shock of the fabric returning to the support cage. This translates into longer bag life and lower emission levels. Prior to the development of the IAP valve, the only method by which filter bag could be cleaned in a similar manner was to isolate individual cells from the main gas flow and to clean the bags in that cell of line. This however, frequently requires the use of an additional compartment to allow for off-line cleaning. This method of cleaning not only does away with the need for the additional compartments, but also enables longer filter bags (greater than 16 ft) to be cleaned by the pulse jet method. At both Coventry and Edmonton, the bags are 23 ft long. By using long bags, and on-line cleaning, the footprint of the filter unit is minimized, which can be a very important consideration when retrofitting, especially in cases like Coventry, where the majority of equipment had to be installed inside the existing glass-walled building.

The TGT dust collector makes use of a proprietary baffled inlet (Figure 5), that provides the following benefits:

1. Directs the gases upwards and across the bags reducing greatly the interstitial ("can velocity") velocity.
2. Deflects a large part of the dust directly into the hopper to reduce the dust load on the bags.
3. Allows units to operate with on-line cleaning at high filtering velocities of 4 fpm, which again reduces the equipment footprint:

Powdered Activated Carbon Injection

Increasingly, emphasis is being given by the Regulatory authorities to the emission of mercury and Dioxin/furans (PCDD/PCDF). Considerable work has been done on the removal of mercury and PCDD/PCDF from flue gas streams. With the Dry System, the Powdered Activated Carbon (PAC) is injected separately into the Venturi reactor. Procedair has considerable experience in the removal of polyhydrocarbons using dry injection of powdered coke or carbon products in to venturi reactors. This is derived from more than fifteen years of supplying APC equipment to control the hydrocarbon emissions from green anode plants in the primary aluminum industry.

Material Handling for the Recycling of the Partially Reacted Reagent

The fabric filter separates the flyash/acid salts and unused lime. These dry solid particles are constantly evacuated from the baghouse hoppers and, in the Procedair Dry System, are in the main recycled. Without recycling, it is a fact that even with a good reactor tower design and secondary neutralization in the filter cake in the bag house, there will be over 60% of the lime unreacted and going to waste. This has a major impact on operational costs due to the need for high stoichiometric ratios to achieve regulatory emission control levels. By using reactor product recirculation, there is a five-fold benefit created by the "apparent stoichiometric ratio" at the Venturi Reactor (Figure 6).

1. Unreacted lime will be afforded further opportunity to be used, lowering fresh stoichiometric ratios and operating costs.
2. Recirculation, at rates of between 30 and 50 times the fresh lime feed rate, means the mass of reagent within the gas stream increases the probability of contact by pollutant molecules with reagent, thus increasing removal efficiency.
3. The multiple handling and passage of the particulates due to recirculation causes a particle size reduction, partially through attrition, and partially due to reacted surface material breaking away exposing unreacted material.
4. The continuous mass of material recirculating throughout the process acts as a buffer dampening peak pollution production levels and compensates for any reduction or interruption in fresh reagent flow.
5. The high recirculation rate also provides for recirculation of the activated carbon. Without recirculation, activated carbon would have to work on a once-through basis. Recycling reduces the usage of activated carbon at the same time minimizing PCDD/PCDF and mercury emissions.

These aspects are demonstrated in Figure 7, which is a comparison of systems with and without recirculation. Consistent higher removal efficiencies are obtained at lower fresh lime stoichiometric ratios with recirculation. Higher predictability is gained with recirculation. With the commercial necessity to guarantee consistently low emission levels at minimized stoichiometric ratios, these advantages are very important.

OPERATIONAL FACILITIES

Dry scrubbing of MWC five gases has gone through three phases which are shown on Table 3. The first phase is dry-scrubbing from earlier installations, at temperatures of 400-450°F. Here emission levels were not as strictly regulated and the control of SO₂ frequently not required. The second is where the dry system is modified by the addition of an evaporative cooling tower between the boiler and the dry-scrubbing system. This permitted capture of SO₂ and consistent operation with the higher efficiencies required by earlier updates of regulations. The two reasons for this improvement over a dry-system are:

1. Inlet temperature to the scrubbing system can be very precisely controlled and for optimum performance lowered to 285°F without increasing corrosion risks in heat recovery equipment.
2. The relative humidity of the flue gas increased by the water which contributes to improved scrubbing performance.

The third, our present generation operating systems utilizing low outlet temperature economizers with totally dry-scrubbing systems to achieve the latest regulatory emission control levels.

BCH Energy, Fayetteville, NC.

The BCH Energy facility comprised two Kvaerner bubbling fluid bed combustors burning RDF. Each combustor was rated at 300 tpd. Economizers, provided for the boilers by Kvaerner, cool the gases

below 290°F. It was felt that the use of the bubbling fluid bed would lead to higher flyash production due to the carryover of bed sand particles with the RDF flyash. For this reason the APC equipment starts with a cyclonic precleaner to reduce the dust load to the APC system. The design conditions for the BCH Energy project are shown in Table 4. The scope of supply for the equipment for the APC equipment is shown on Table 5. Results of the emission tests performed on the two boilers in 1996. Shown in Table 6, indicates that the APC equipment performance was better than that required by the permit.

Coventry and Solihull Waste Disposal Company (CSWDC)

At the time of tendering, the CSWDC facility comprised three mass burn water wall incinerators utilizing Martin grate technology with a unit capacity of 320 tpd of MSW. The original operating permit for the facility was based on any two furnaces operating at one time; therefore, the existing air pollution control equipment consisted of only two lines of electrostatic precipitators for flyash removal through a manifold system at the outlet of the three boilers.

The CSWDC facility added an electrical generating steam turbine in 1991 to take advantage of the revenue available from electricity generation. The retrofit contract called for three sets of air pollution control equipment to allow the facility to operate all three at a time. This increased both the waste throughput revenue and the electrical generation revenue.

During the bidding process, extensive visits were made to other facilities in Europe and North America by the Coventry operational personnel. After talking directly to the operational staff at these facilities, two opinions were formed.

1. Despite having demonstrated its ability to meet the required emission standards, the semi-dry process (spray-dryer with lime slurry with fabric filter) in its various forms had the considerable disadvantages of requiring the preparation and handling of lime slurry and its atomization into the flue gas stream in a spray dryer.
2. The totally dry-scrubbing technology was seen to offer the potential to meet the new required standards with fewer potential operational difficulties and maintenance requirements. It was realized also that this system would allow the recovery of additional energy using an extended economizer rather than wasting energy by spraying water into the spray dryers.

The scope of work for the CWSDC retrofit is shown in Table 7 and the design criteria for the CWSDC system in Table 8. The Coventry facility has been tested and the test results are shown in Table 9.

London Waste Limited

The London Waste Limited, Edmonton facility was originally owned and operated by five London Boroughs. These formed a joint venture with SITA (GB) Limited, to form a company called London Waste Limited (LWL). The facility consists of five, 450 tpd mass burn grates and boilers, giving a

capacity of 690,000 tones/year. Each boiler was equipped with an economizer for heat recovery and electrostatic precipitator for dust removal. At the LWL facility, a decision was made during the bidding stage that the upgraded facility would be capable of meeting the more stringent European Community (EC) legislation for 2001. This meant that the outlet HCl emission had to be guaranteed at 10 mg/Nm³ (6 ppm_{dv}) against a high potential inlet condition of 2,000 mg/Nm³ (1230 ppm_{dv}). At the time, it was thought necessary to combine the precise temperature control and added humidification from a conditioned dry system with the heat recovery/dry system in order to have no risks on the guarantees. As a result, the LWL facility decided to upgrade the performance of the economizer but only to reduce the flue gas outlet temperature down to 330°F and install an evaporative cooling tower, to further cool the gases to 285°F. This condition would insure compliance with the UK standard IPR 5/3. To meet the more stringent EC standards, the economizer outlet temperature could be raised to 365°F allowing for increased humidification of the flue gas. It should be noted that CWSDC decided to take the maximum heat recovery during the early stages of the operation so increasing the energy income until 2001. Space, however, has been left in the facility building to allow the retrofitting of evaporative conditioning towers to provide conditioned dry systems should CWSDC need this in order to meet the EC 2001 regulations.

The design conditions and scope of supply for Edmonton are shown in Tables 10-11. The facility has undergone performance tests and the results are shown in Table 12. These show that the units can practically meet the more stringent EC 2001 when operated at the lower economizer outlet temperature.

CONCLUSIONS

The use of a Heat Recovery/Dry-Scrubbing System for retrofit MSW installations provides the following:

1. Increased energy recovery from an existing facility is possible within the existing boiler design parameters. The finned tube economizers can reduce the gas outlet temperatures to below 285°F and control the outlet temperature at this level when combined with a temperature control system.
2. The capital costs for the Heat Recovery/Dry-Scrubbing System is competitive with conventional spray-dryer/fabric filter combinations. The facility gains the extra benefit of the added revenue from increased energy production.
3. The Heat Recovery/Dry Scrubbing System can provide performance levels that exceed those currently envisaged by the most recent EPA regulations for MWCs.
4. The footprint for the Heat Recovery/Dry-Scrubbing System is generally smaller than that required for the spray dryer/fabric filter combination.
5. The total gas volume to be handled by the dry scrubber is reduced by heat recovery instead of humidification, resulting in less fan horsepower. The pressure drop for the enlarged economizer/venturi reactor is approximately the same as for a spray dryer.
6. The use of powdered activated carbon (PAC) within the dry-scrubbing system is highly effective for the removal of mercury and PCDD/PCDF compounds. This removal is achieved at low consumption rates for PAC due to the recycling of the PAC with the other reagent compounds.
7. Finned tube economizers can operate with dirty gas and low outlet temperatures for extended periods without plugging and corrosion.

The heat recovery/dry scrubbing system has particular application to those facilities selling electricity or steam. The additional steam raised can be turned into useful energy, generally within the capability of the

existing boiler/turbine combination. This extra energy will supply the parasitic power needed for the APC equipment, and will allow additional export of power for revenue purposes.

Acknowledgements

The authors wish to Acknowledgments the assistance given by CSWDC and LWL personnel in providing information for this paper. They also wish to thank Kvaerner and BCH Energy for their help with test data.

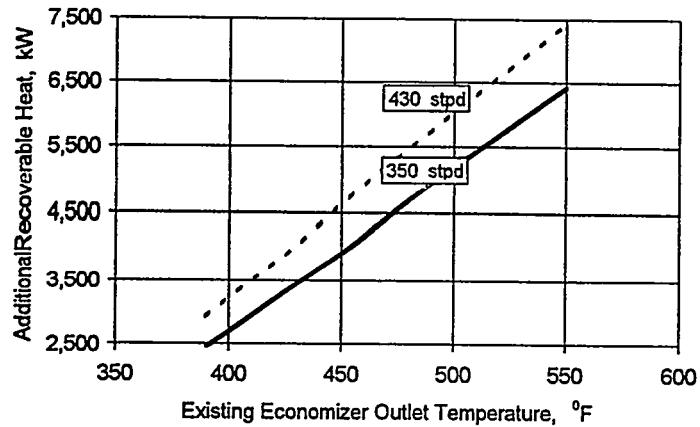


Figure 1. Additional Heat Recovery from Municipal Waste Boilers assuming 290 °F from New Economizer Section

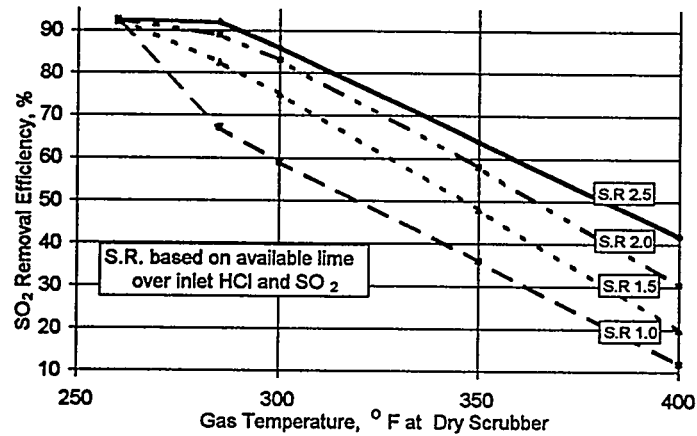


Figure 2. SO₂ Removal Efficiency by Dry Scrubbing at Various Gas Temperatures and Stoichiometric Ratios (S.R.)

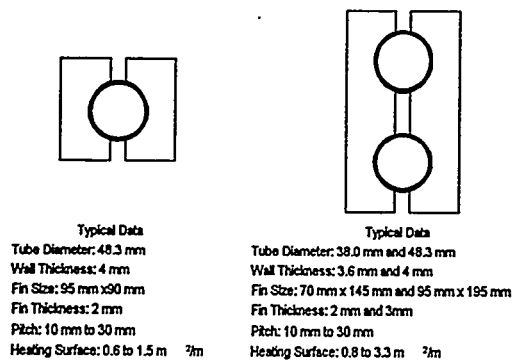


Figure 3. Typical Specifications for Single and Double Finned Tubes for Economizers for MSW Boilers

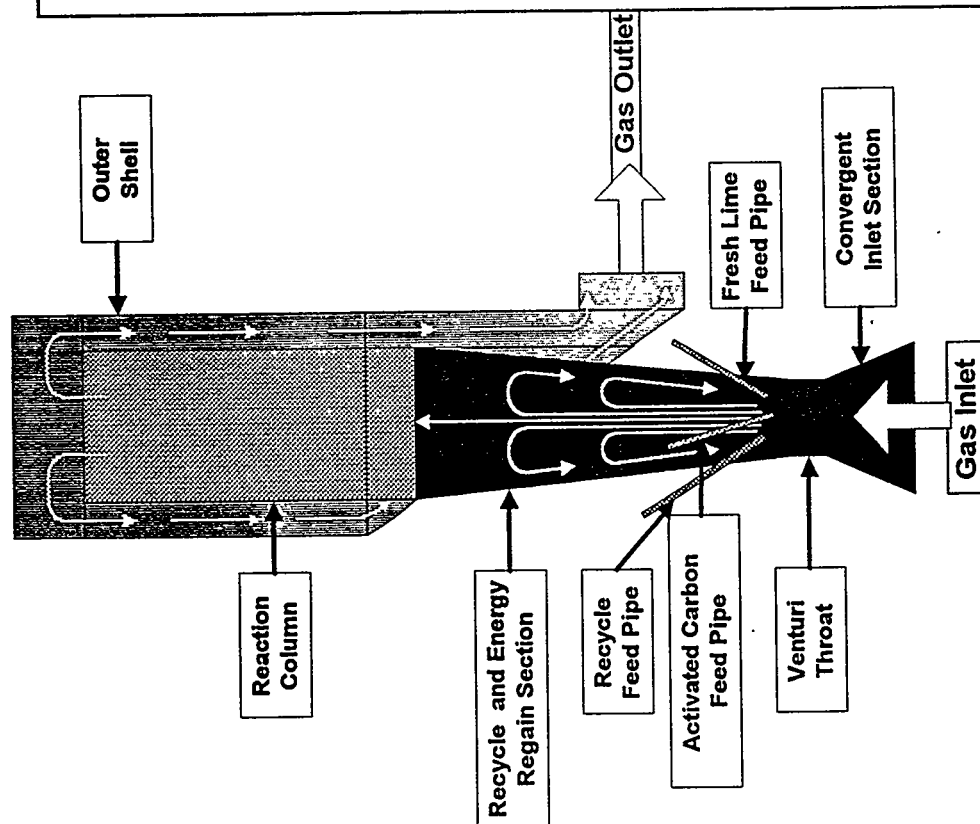


Figure 4. Dry Vertical Venturi Reactor

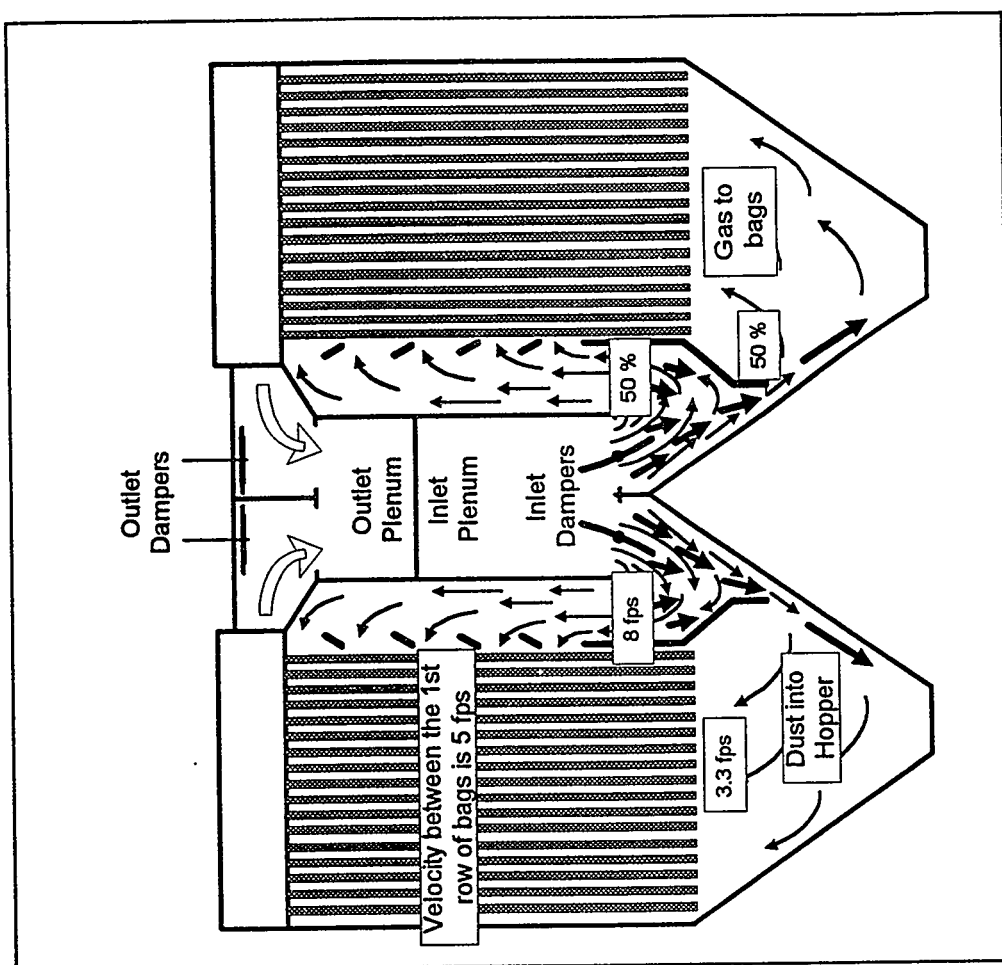


Figure 5. Baffled Inlet Design for
TGT low pressure jet filters

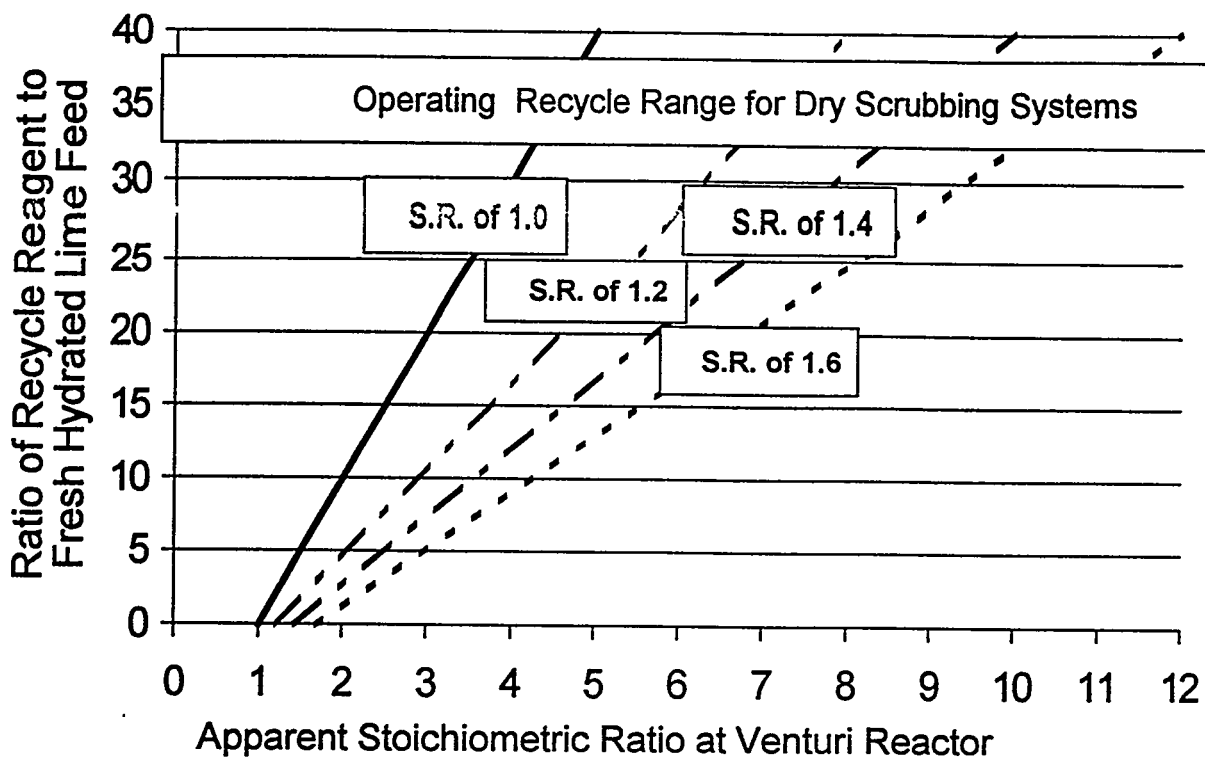


Figure 6. Effect of Recycle Rate on Apparent Stoichiometric Ratio at Venturi Reactor

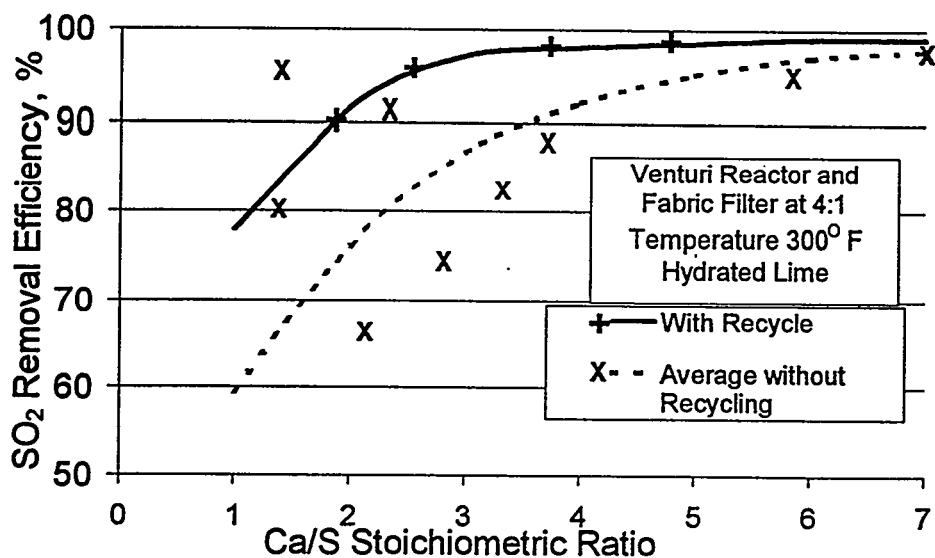


Figure 7. Pilot Plant Dry Scrubber System SO₂ Removal Capabilities

Flue Gas Flow: 45,000 SCFM

Feed Water Flow: 119,000 lb/hr
(includes 20,000 lb/hr recirculation)

Feed Water / Hotwell
Temperature: 194 ° F

Delivery Date	SYSAV	Upsala	London Waste	Coventry
No. Units	1994	1991	1995	1996
Dust Load	One	One	Five	Three
Gas Flow	0.8740	0.0218	1	4.0
Inlet Temperature	97,347	236,789	120,950	92,628
Outlet Temperature	572	482	550	626
Water Flow	354	284	331	284
Inlet Temperature	22,046	855,385	110,340	146,826
Outlet Temperature	275	248	248	266
Tube Type	333	284	370	388
Material	Double	Double	Bare & Double	Double
Tube Diameter	Carbon Steel	Carbon Steel	Carbon Steel	Carbon Steel
Tube Length	1.50	1.50	1.50	1.50
No. Finned Tubes	8.5	20	19	15
Fin Pitch	630	660	1584	1584
Cleaning Method	Shot Cleaning	Shot Cleaning	Steam Blower	Steam Blower

Table 1. Typical Finned Tube
Economizers

Gas		Water		LMTD	Heat Transfer	Boiler
Inlet, ° F	Outlet, ° F	Inlet, ° F	Outlet, ° F	° F	MW	Cleanliness
Economizer outlet gas temperature controlled to 284 ° F						
536	284	257	365	109	3.6	Clean
626	284	257	342	126	5.0	Average
698	284	257	374	136	6.0	Fouled
Economizer outlet gas temperature controlled to 428 ° F						
536	428	257	302	232	1.6	Clean
626	428	257	342	255	3.0	Average
698	428	257	374	271	4.0	Fouled

Table 2. Coventry and Solihull Waste
Disposal Company
Economizer Heat Transfer Data

Dry Process	Year	Size	Gas Volume- acfm
Roselare, France	1987	2 X 100 tpd	2 X 30,400 at 482 ° F
Edegem, Belgium	1987	2 X 50 tpd	2 X 15,800 at 482 ° F
U.I. O. M., France	1988	2 X 100 tpd, Von Roll	2 X 22,300 at 464 ° F

Conditioned Dry Process			
Community of Quebec, Canada	1988	4 X 250 tpd, Von Roll	4 X 105,000 at 480 ° F
City of Windham, USA	1989	1 X 200 tpd	1 X 71,700 at 518 ° F
Peel Resource Recovery, Canada	1992	4 X 100 tpd, Consumat	2 X 103,400 at 500 ° F
Heat Recovery /Dry Process			
Kvaerner EnviroPower, USA	1994	2 X 300 tpd, Fluid Bed	2 X 63,500 at 290 ° F
CSWDC, UK	1995	3 X 320 tpd, Martin	3 X 64,210 at 285 ° F
LWL, UK	1995	5 X 450 tpd	4 X 110,000 at 285 ° F
Kvaerner EnviroPower, USA	1997	1 X 600 tpd, Fluid Bed	1 X 95,000 at 290 ° F

Table 3. Progression of Dry Scrubbing from Dry-Dry at High Temperature to Conditioned Dry to Heat Recovery and Total Dry

● Gas Flow	62,400 ACFM	● One (1) Hydrated Lime Handling System
● Temperature	293° F	● with Redundant Feeders
● Gas Analysis	H ₂ O 13.1 to 17.3	● Procedair Activated Carbon Storage and Metered Feed System
● % by vol	CO ₂ 11.0	● Two (2) Procedair Duplex Cyclones
	O ₂ 6.1	● Two (2) Procedair Dry Venturi Reactors
	N ₂ 69.7	● Two (2) Procedair Pulse jet Baghouses,
● SO ₂ Concentration	240 ppm dv	● Reagent Recycling and Dust Handling System
● at 7% O ₂		● Controls and Instrumentation
● HCl Concentration	761 ppm dv	
● at 7% O ₂		
● HF Concentration	35 ppm dv	
● at 7% O ₂		
● Dust Concentration	4.5	
● gr/dscf at 7% O ₂		

Table 4. BCH Energy Design Inlet Conditions

Table 5. Equipment Supplied to Kvaerner for BCH Energy, Fayetteville. NC.

Stack Emission		Heavy Metal	mg/dscm @ 7% O ₂	Unit No 1	Unit No 2
Particulate	< 0.002 gr/dscf				
SO ₂	< 0.25 ppm _{dv}	Arsenic		<0.0003	<0.0004
HCl	< 1.5 ppm _{dv}	Beryllium		ND < 0.0001	ND < 0.0001
Opacity	0	Cadmium		<0.001	<0.0004
Mercury	< 1.0 µg/dscm	Chromium 6		ND < 0.0001	
		Lead		<0.015	<0.002
PCDD/PCDF	< 3.0 ng/dscm	Mercury		<0.001	<.002

Table 6. BCH Energy, Stack Emissions
Averaged from Performance Test Data

- One (1) Hydrated Lime Handling System
- Three (3) Vertical Counterflow Economizers
- Three (3) Proceadair Venturi Reactors
- Three (3) TGT Low Pressure Pulse Baghouses
- Recycling, Waste Handling and Ash Silos
- Controls and Instrumentation and CEMs
- Activated Carbon Injection System
- Three (3) new Induced Draft Fans and Motors
- Three (3) pair of oil-fired Auxilliary Burners

Table 7. APC Equipment supplied and installed under the Contract with CSWDC

● Gas Flow	94,000 ACFM
● Temperature	630 °F
● Gas Analysis	
● % by vol	H ₂ O 11.0
	CO ₂ 11.0
	O ₂ 10.0
	N ₂ 68.0
● SO ₂ Concentration	195
	ppmdv at 7% O ₂
● HCl Concentration	950
	ppmdv at 7% O ₂
● Dust Concentration	4.0
	gr/dscf at 7% O ₂

Table 8. Unit Design Inlet Conditions for CSWDC

	Inlet Levels		Outlet Levels	
	g/Nm ³ @ 11% O ₂	ppmdv @ 7% O ₂	g/Nm ³ @ 11% O ₂	ppmdv @ 7% O ₂
Dioxins TEQ			0.025	
HCl	423	365	4.9	4.2
HF	1.8	2.8	0.1	0.16
SO ₂	165.6	81.3	0.5	0.25
	g/Nm ³ @ 11% O ₂	gr/dscf @ 7% O ₂	mg/Nm ³ @ 11% O ₂	gr/dscf @ 7% O ₂
Particulate	2.46	1.40	3.2	0.002
Total Metals	0.021	0.012	1.4	0.0008

Tin	mg/dscm @ 7% O ₂ .07	Chromium	mg/dscm @ 7% O ₂ .07
Cadmium	.01	Copper	.11
Lead	.07	Mercury	.81
Nickel	1.6	Arsenic	.01

Period- 1996	HCl			SO ₂			Hydrated Lime		Gas	
	Inlet	Outlet	Efficiency	Inlet	Outlet	Efficiency	lb/hr	S.R.	Volume	Temperature
	ppmdv	ppmdv	%	ppmdv	ppmdv	%			acfm	° F
Aug 7 to 10	551	15	97.35	120	14	88.55	242	1.92	62,536	284
Aug 18 to 21	537	12	97.84	131	12	91.23	271	2.04	46,986	280
Aug 23 to 26	492	14	97.17	128	20	84.66	239	2.10	55,579	286
Aug 31 to Sep 2	501	10	98.05	147	10	93.34	235	1.61	44,714	271

Table 9, CSWDC Emission Summary Line 1
Independent Performance Tests performed 7/8/96

● Gas Flow	208,000 ACFM
● Temperature	930 °F
● Gas Analysis	
● % by vol	H ₂ O 10.0
	CO ₂ 9.0
	O ₂ 9.4
	N ₂ 71.6
● SO ₂ Concentration	180 ppm _{dv} at 7% O ₂
● HCl Concentration	1720 ppm _{dv} at 7% O ₂
● Dust Concentration	0.4 gr/dscf at 7% O ₂

Table 10. London Waste Limited, Edmonton
Design Inlet Conditions

- One (1) Hydrated Lime Handling System
- Five (5) Economizers
- Four (4) Evaporative Conditioning Towers
- Four (4) Proceair Venturi Reactors
- Four (4) TGT Low Pressure Pulse Baghouses
- Recycling, Waste Handling and Ash Silos
- Controls and Instrumentation and CEMs
- Activated Carbon Injection System
- New Induced Draft Fans and Motors

Table 11. APC Equipment supplied and installed under
the Contract with LWL

Test to IPR 5/3			HCl Emissions			SO ₂ Emissions			Hydrated Lime	
Date	Test	Start	Limit	Actual	% of Limit	Limit	Actual	% of Limit	Actual	Actual
			ppmdv	ppmdv	%	ppmdv	ppmdv	%	lb/hr	S.R.
2/9/97	1	11:00	25.9	8.5	33.0	147.3	6.0	4.1	420.6	1.73
	2	12:00	25.9	5.8	22.3	147.3	3.3	2.3	419.1	1.86
	3	13:00	25.9	3.5	13.3	147.3	3.1	2.1	416.7	1.52
	4	14:00	25.9	7.8	30.0	147.3	6.8	4.6	412.9	1.29
2/11/97	1	10:00	25.9	3.9	15.0	147.3	2.7	1.8	447.8	1.47
	2	11:00	25.9	3.7	14.3	147.3	4.5	3.0	445.5	1.44
	3	12:00	25.9	7.0	27.0	147.3	4.2	2.9	448.4	1.57
	4	13:00	25.9	6.8	26.3	147.3	4.9	3.3	446.4	1.81
2/11/97	1	14:00	25.9	7.9	30.7	147.3	6.1	4.1	451.1	1.85
	2	15:00	25.9	7.2	28.0	147.3	4.3	2.9	443.3	1.75
	3	16:00	25.9	11.2	43.3	147.3	11.8	8.0	442.7	1.41
	4	17:00	25.9	13.7	53.0	147.3	12.0	8.1	446.7	1.56
2/14/97	1	13:00	25.9	6.7	26.0	147.3	11.2	7.6	361.8	2.52
	2	14:00	25.9	5.1	19.7	147.3	5.4	3.6	358.9	2.03
	3	15:00	25.9	2.6	10.0	147.3	4.4	3.0	358.5	1.8
	4	16:00	25.9	3.2	12.3	147.3	3.1	2.1	360.2	3.12
2/15/97	1	12:00	25.9	4.7	18.0	147.3	6.9	4.7	438.7	1.69
	2	13:00	25.9	4.4	17.0	147.3	6.4	4.4	433.4	1.78
	3	14:00	25.9	4.9	19.0	147.3	7.8	5.3	436.3	1.89
	4	15:00	25.9	4.3	16.7	147.3	7.2	4.9	435.4	1.7
Mean			25.9	6.1	23.8	147.3	6.1	4.1	421.2	1.79

Table 12. Performance Test Results to IPR 5/3 for London Waste Limited, Edmonton

Retrofitting ESP Equipped MWCs to Meet the 1995 Emission Guidelines
Using Sensible Heat Exchanger Cooling and Dry Reagent Injection

H. Gregor Rigo
Rigo & Rigo Associates, Inc.
1 Berea Commons, Suite 211
Berea, Ohio 44017
and
A. John Chandler
A. J. Chandler & Associates Ltd.
12 Urbandale Avenue
Willowdale, Ontario, Canada M2M 2H1

INTRODUCTION

Many municipal waste combustion (MWC) facilities are equipped with electrostatic precipitators (ESPs) and have no acid gas controls. Latent heat of vaporization (water spray) temperature control combined with Trona (sodium based acid gas control reagent) and powdered activated carbon (PAC) injection¹ met EPA's December 19, 1995 Emissions Guidelines for small plants². A follow-up study to demonstrate similar performance using sensible heat removal (heat exchangers) for enhanced energy recovery along with powdered hydrated lime and activated carbon injection at an ESP equipped MWC was conducted to provide maximum flexibility to facilities needing to come into compliance with these regulations.

In 1995, the authors performed a proof-of-concept testing program at the Davis County Energy Recovery Facility in Layton, Utah under a subcontract from the National Renewable Energy Laboratory (NREL), a U. S. Department of Energy national laboratory to the American Society of Mechanical Engineers. That testing demonstrated that small MWCs equipped with ESPs could meet the EPA's small facility MWC emissions guidelines if the ESP inlet temperature was controlled and dry acid gas reagents and powdered activated carbon were added to the gas stream. Temperature control at the Davis County facility was accomplished by injecting water into the gas stream ahead of the ESP. This method of temperature control produced some operational problems, including particulate deposition in the gas ducts. Another test was conducted in 1996 in which temperature control was accomplished in a facility using extra heat exchangers to reduce the ESP inlet temperature to nearly 300°F from the 425°F traditionally found at MWCs. This testing was accomplished under an extension of the original arrangement with NREL.

Demonstration testing was conducted from December 1-11, 1996 at the 2x120 TPD, ESP equipped MWC at Energy Answers Corporation's Resource Recovery Facility in Pittsfield, MA (EAC/Pittsfield). The test plan was expanded to obtain duplicate metals (Cd, Pb and Hg), particulates, dioxin and acid gas runs at each condition.

Nine distinct emissions control conditions (two ESP operating temperatures, three levels of activated carbon addition and three levels of powdered hydrated lime acid gas control reagent) were planned to be tested during normal plant operations. The no acid gas reagent, no activated carbon (baseline) condition was replicated to provide a measure of reproducibility and experimental error.

During testing, selected plant operations, furnace conditions and Continuous Emissions Monitoring System (CEMS) data were continuously recorded by a digital data acquisition system. CEMS emissions data included NO_x, SO₂, CO, and O₂ both at the stack downstream of a tail-end wet scrubber and immediately after the electrostatic precipitator (ESP) as well as Continuous Opacity Monitoring System (COMS) data at the ESP outlet. The data covers periods of operation before, after testing and during each test run. It was used to demonstrate that the facility was operating normally during the proof-of-concept demonstration testing.

The operating conditions for each test day were established during the previous evening after all testing was completed. Testing activities commenced at dawn each day with sampling starting 3 to 4 hours later. The following emissions were measured at the ESP outlet:

- Front-half particulate matter, metals & mercury — Method 29
- Acid gas (HCl) — Method 26

- Dioxins and Furans (PCDD/F — 2,3,7,8 substituted isomers (congeners) plus homologue totals — Method 23
- Other combustion gases (CO, NO_x, and SO₂) — Methods 6c, 7 and 10 (CEMS)

To obtain replicates in the small rectangular duct leaving the ESP each day, a dual- or quad-probe sampling system had to be used. Duplicate Method 23 and 29 samples were obtained. The average of the duplicate results is used to characterize emissions for each test series. Method 26 used another port as did the Method 7 (CEMS) extractive probe.

For about six hours prior to and throughout sampling, the tested incinerator was run at its rated capacity of 30,000 lb/hr of 500 psig, 515°F steam. The specified ESP temperature (nominally 325 or 350°F) and targeted acid gas reagent (0, 12, 160 and 180 lb/hr of powdered hydrated lime —equivalent to stoichiometric ratios of 0:1, 2:1, 2.5:1 and 3:1) and activated carbon feed rates (0, 4 and 8 lb/hr — equivalent to 0, 100 mg/dsm³ and 200 mg/dsm³ were also maintained.

SITE SELECTION CRITERIA

While there is considerable evidence that reducing ESP operating temperature and adding reasonable amounts of acid gas sorbent and activated carbon to incinerator flue gas can theoretically allow existing ESP equipped MWCs to economically meet proposed guidelines; field experience has shown that it is difficult to reliably reduce ESP temperatures using evaporative (water spray) cooling techniques. Phase I testing under this program at Davis County, Utah Energy Recovery Facility demonstrated that dry acid gas sorbent and powdered activated carbon injection resulted in satisfactory performance of existing APCS. It was also demonstrated that the air or steam atomization system had to be carefully designed, located and operated to achieve reliable operation. The question remained, however, if similar emissions control performance could be achieved while recovering additional heat using heat exchangers without water sprays.

HOST FACILITY DESCRIPTION

Although built with three pre-engineered, refractory wall, excess air furnaces of the Enercon design, rated at 120 tons/day each, EAC/Pittsfield is only permitted to run with two of the furnaces on-line. Each furnace includes controlled overfire and underfire airflow, a large loading ram and water cooling of steel components. Dual fuel burners, gas or oil, located in the primary chambers provide initial ignition of refuse and at the exit of the trim economizer preheats the air pollution control system (APCS). These burners are turned off after the MSW fire is established. Primary chamber outlet and waste heat boiler (WHB) inlet temperatures are normally controlled using recirculated flue gas (RFG).

The manifold or tertiary chamber transports the hot gases from the furnaces to the WHBs. The normal gas flow is from both on-line furnaces to both Bigelow WHBs. Each WHB is rated at 30,000 lb/hr at 250 psi and 515°F. Flue gas temperature entering the boiler is maintained in the tertiary chamber with recirculated flue gas to 1,500°F. Boiling and trim economizers serve to heat boiler feed water before it enters the boilers, while reducing flue gas temperature to 350°F at the ESP inlet. Downstream of the ESP, a condensing heat exchanger is used to preheat the 100% boiler make-up and reduce the flue gas temperature below the acid gas saturation point before final flue gas cleaning in a packed bed scrubber.

The facility is equipped with a 4-field ESP designed to achieve particulate levels of 0.015 gr/dsft^3 @ 12% CO_2 . Acid gas control is provided by a wet scrubber using a sodium carbonate scrubbing solution located downstream of the ESP and condensing heat exchanger (also called a "raining economizer"). Sampling access exists between the ESP outlet and raining economizer inlet. This is where most of the testing was conducted. Limited simultaneous sampling was conducted in the stack, after the wet scrubber, to provide an indication of the benefits of using a tail-end scrubber.

Figure 1 is a process flowchart of the facility. Table 1 is a heat balance for an individual combustion unit when the facility is burning 4,500 Btu/lb MSW at maximum continuous rating (MCR) conditions, or 120 TPD of MSW burned. The stoichiometric powdered hydrated lime addition rate (based on the plant's historical uncontrolled HCl and SO_2 concentrations) is 64 lb/hr.

Dry hydrated lime (Graybec Calc Inc.) and Powdered Activated Carbon (PAC) (Norit's FGD grade) were delivered to the site in nominal 1,000 kg supersacks. They were out-loaded using calibrated metering screws to a common eductor. The original temporary installation used compressed ambient air and a small commercial eductor. The system plugged rapidly when lime was added even though it was more than satisfactory for PAC-only injection. Air dryers were added and plant air was used on the system, but operating time only increased from 1 to 2 hours. The eductor was replaced by an entrainment device fabricated out of a 2", Schedule 40 cross connection (reagent falls into the top, pipe plug in the bottom to facilitate cleaning, $\frac{1}{2}$ " pipe nozzle in one side supplying nominal 10 psig dry air and a 2" pipe connected for exhaust flow from the other side of the entrainment box). This very inexpensive eductor substitute performed without difficulty throughout the balance of the test program.

PROGRAM OBJECTIVE

The objective of this program was to determine the emissions performance level achievable by a combination of ESP inlet temperature control, acid gas reagent injection and activated carbon addition. The target was to meet the emissions guideline requirements for small facilities and to determine if large facility guidelines can be met for particulates, dioxins, SO_2 , HCl and mercury using dry sorbent injection technology in conjunction with sensible heat removal temperature control. The emitted concentrations and removal efficiencies are the numeric objectives shown in Table 2.

EXPERIMENTAL DESIGN

To accomplish the program objectives, a fractional $2 \times 3 \times 3$ factorial test plan with one replicated test condition was developed. The order of testing was randomized using a $2 \times 2 \times 3$ test matrix, but the no acid gas reagent condition was excluded from the overall randomization. To minimize the chance of lime carry-over effects from controlled test conditions to baseline, the baseline runs were scheduled to be conducted the day after a PAC-only run. Due to field exigencies, baseline testing was conducted at the beginning of the test program between the PAC-only and lime plus PAC test conditions to both maximize the applicability of baseline testing to other tests and to accommodate start-up difficulties with the dry powdered hydrated lime handling system.

The unbalanced experimental design provided in Table 3 makes maximum use of the available test runs. Data reduction is slightly complicated by this experimental design since traditional fractional factorial designs do not include partial replicates and utilize a different pattern. Mathematical tools do exist to interpret this data. The selected pattern enabled the fitting of a theoretically based predictive equation for

dioxin and mercury control to the data so that interpolation (and limited extrapolation) to other conditions can be performed and the expected performance of a retrofit application determined.

RESULTS

The test matrix is provided in Table 3. The majority of the baseline runs were done under normal operating conditions where the flue gas temperature entering the ESP is less than 330°F. One high temperature run was performed with 4 lb/hr of PAC addition. Acid gas reagent (powdered hydrated lime obtained from Graybec Calc, Inc., Marbleton, Canada) was tested at three nominal temperatures in combination with two different PAC addition rates. A zero PAC, acid gas reagent test was not conducted because this condition provides neither baseline information nor was likely to produce operating conditions in compliance with EPA's December 19, 1995 Emission Guidelines for Existing Facilities.

The first question addressed was how much PAC and lime can be injected before the ESP and still maintain current emissions control performance.

Table 4 is a summary of the particulate and trace metal emissions test results. The particulate concentrations measured at the ESP outlet, the emissions likely to be seen by a MWC equipped with only this emissions control device, are unchanged regardless of the amount of lime or PAC injected. This is not particularly unusual given the comparatively large size of the dry sorbents being injected. Particles larger than 44 μm , those that pass a 325 mesh sieve are visually very fine, but are actually very coarse as far as an ESP designed to control sub-micron particles is concerned. Unfortunately, due to their large size and relative abundance compared to normal particulate loadings from the furnace, the residue take-away conveyors under the first hopper overfilled and plugged. Design modifications to overcome this problem are needed for a successful commercial installation.

As with the particulate results, lead and cadmium are unaffected by the dry injection of lime or PAC. This is the expected behavior since these pollutants are associated with the front-half particulates. Mercury was substantially reduced by the addition of PAC. Lime injection had a negligible effect on mercury emissions. Inspection of the data provides a strong indication that there is a temperature effect with lower temperatures enhancing mercury removal. The nominal 4 lb/h PAC injection rate is equivalent to 100 mg/dsm³ 7% O₂. Three-run average mercury emissions below 50 $\mu\text{g/dsm}^3$ @ 7% O₂ can be expected with this injection rate over the temperature range tested. This is as predicted by the extrapolated Davis County³ results.

Dioxin concentrations shown in Table 5 are comparatively low at the ESP outlet due to the low flue gas temperature. With PAC addition, a factor of four reduction in dioxin emissions was observed. It is important to realize that the dioxin concentrations leaving the ESP were already in compliance with EPA's December 19, 1995 Emissions Guidelines for existing ESP equipped facilities. Simple inspection of the table indicates that the reduction is larger with lime injection. This could be real or simply a data artifact since the emitted concentrations are less than the Reference Method Practical Quantification Limit for Total and International Toxic Equivalent (ITEQ) dioxins established by the supplemental simultaneous results performed during this effort.

Other combustion condition related pollutant emissions (CO and NO_x) were unaffected by the addition of PAC.

Dry hydrated lime injection is expected to reduce sulfur dioxide and hydrogen chloride emissions. Reductions were observed in the data displayed in Table 6. Comparison of the results with and without lime injected indicates that using the calculation procedures in Method 19, better than the 50 percent HCl and SO_x removal needed to meet the 1995 Emissions Guidelines for Small Facilities was achieved.

The data in Table 7 include the results of three HCl tests conducted between the boiler and boiling economizer on the last day of testing (e.g. 301-3). This location is upstream of the lime/PAC injection point and represents uncontrolled emissions. Comparing these values to those obtained at the ESP outlet during conditions when no lime was being added to the system suggests that there is either a problem with Method 26 or relatively significant removal, on the order of 30 percent, is occurring across the economizer and ESP as a result of native alkalinity in the fly ash.

CONCLUSIONS

This performance demonstration test was successful. Dry acid gas and mercury reagent injection combined with ESP inlet temperature control are capable of bringing existing ESP equipped MWCs into compliance with EPA's December 19, 1995 Emissions Guidelines for small facilities. Large facility guidelines can be met for all pollutants except acid gases (SO₂ and HCl). Given the amount of acid gas reagent injected during some tests (almost a stoichiometric ratio of 3:1) and the results obtained, it is questionable if sufficient reagent could be injected to achieve the 95 percent HCl removal required by the large plant guidelines without causing particulate emissions exceedances.

Most importantly, ESP performance, while unchanged by dry injection, was not improved. This indicates that the addition of heat exchangers to reduce flue gas temperature while recovering more energy; hence, cover some of the costs of additional pollution control is prudent. However, using water sprays to accomplish part of the temperature reduction also improved ESP performance sufficiently that this effect might justify dealing with the difficulties described in the Davis County report.

Injection of either dry hydrated lime or Trona in combination with powdered activated carbon is capable of meeting the 1995 Small Plant Emissions Guidelines and all but the acid gas reduction requirements for large plants. Dry reagent injection in combination with temperature control is a viable method of extending the life of existing facilities at reasonable cost and seriously considered for plants that must be modified to comply with small plant standards.

Acknowledgments

The American Society of Mechanical Engineers' (ASME) Center for Research and Technology Development (CRTD) awarded a lower tier subcontract under a subcontract with the Department of Energy's National Renewable Energy Laboratory (NREL) to demonstrate the technical performance and viability of heat exchanger flue gas temperature in combination with dry acid gas reagent and activated carbon injection at an existing electrostatic precipitator (ESP) equipped municipal waste combustor (MWC). The effort was directed by a Subcommittee of the ASME Research Committee on Industrial and Municipal Wastes (RCIMW) chaired by Dave Hoecke with John Norton as the ASME/RCIMW on-site representative. Mr. Greg Barthold of ASME/CRTD is the Project Manager.

Site modifications, routine operations and acquisition of facility data were performed by EAC/Pittsfield personnel under the direction of Dr. Lew Clark, Special Consultant and Dave Consalvo, Plant Manager. Emissions sampling was done by Bovar Environmental, Toronto, under the direction of David Law, and

analytic laboratory support was provided by Zenon Laboratories, Burlington, Ontario, under the direction of Dr. Ron McCleod. TCLP analyses were performed by Inchscape Laboratories. The contribution of each organization and individuals involved contributed to the successful conclusion of this demonstration program. The efforts of everyone involved are gratefully acknowledged.

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1. H.G. Rigo and A.J. Chandler, "Retrofit of Waste-to-Energy Facilities Equipped with Electrostatic Precipitators," (Davis County), an ASME Research Report, CRTD-Vol. 39, April 1996.
2. USEPA, Proposed Standards of Performance for Municipal Waste Combustors and Emission Guidelines for Existing Sources, 60 Fed. Reg. 65,387, December 19, 1995.
3. Op. Cit. Ref. 1, Figure 3.3.

Table 1. Boiler heat balance for EAC/Pittsfield (4,500 Btu/lb reference fuel).

[illegible]

Table 2. Target emissions control objectives for ESP equipped MWCs.

	Small Plant Guideline	Large Plant Guideline
Dioxins	125 ng/dsm ³	60 ng/dsm ³
Particulates	0.030 gr/dsft ³	0.012 gr/dsft ³
Mercury	80 mg/dsm ³ or 85% removal	80 mg/dsm ³ or 85% removal
SO _x	80 ppm or 50% removal	31 ppm or 75% removal
HCl	250 ppm or 50% removal	31 ppm or 95% removal

All emitted concentrations at 7% O₂, dry, standard conditions (68°F, 760 mm_{Hg}).

Table 3. Overall test matrix -- allocation runs conducted.

ALLOCATION OF TEST RUN CONDITIONS				
REAGENT FLOW		ELECTROSTATIC PRECIPITATOR TEMPERATURE		
LIME lb/hr	PAC lb/hr	<330°F	330-340°F	>340°F
0	0	T07 T08 T09 T10		
0	4	T01		T02
0	8	T03 T04 T05 T06		
120	4	T11	T17	
120	8		T18	T16
160	4		T12	T13
160	8			T14 T15
180	8	T19		

Table 4. Particulate, lead, and cadmium test results.

PARTICULATE CONCENTRATION gr/dsm ³ @ 7% O ₂				
REAGENT FLOW LIME lb/hr		ELECTROSTATIC PRECIPITATOR TEMPERATURE		
PAC lb/hr		<330°F	330-340°F	>340°F
0	0	0.032 0.021 0.016 0.025		
0	4	0.030		0.024
0	8	0.017 0.025 0.015 0.011		
120	4	0.038	0.053	
120	8		0.031	0.032
160	4		0.018	0.024
160	8			0.021 0.033
180	8	0.027		

LEAD CONCENTRATION µg/dsm ³ @ 7% O ₂				
REAGENT FLOW LIME lb/hr		ELECTROSTATIC PRECIPITATOR TEMPERATURE		
PAC lb/hr		<330°F	330-340°F	>340°F
0	0	1,591 1,718 1,161 2,108		
0	4	2,490		2,346
0	8	1,697 2,034 1,244 1,202		
120	4	2,515	2,456	
120	8		1,430	1,351
160	4		946	1,461
160	8			1,438 1,805
180	8	703		

CADMIUM CONCENTRATION µg/dsm ³ @ 7% O ₂				
REAGENT FLOW LIME lb/hr		ELECTROSTATIC PRECIPITATOR TEMPERATURE		
PAC lb/hr		<330°F	330-340°F	>340°F
0	0	70 86 51 64		
0	4	73		60
0	8	50 54 48 58		
120	4	86	74	
120	8		51	40
160	4		28	42
160	8			37 59
180	8	32		

Table 5. Mercury test results and estimated removal efficiency.

MERCURY CONCENTRATION µg/dsm ³ @ 7% O ₂				
REAGENT FLOW LIME lb/hr		ELECTROSTATIC PRECIPITATOR TEMPERATURE		
PAC lb/hr		<330°F	330-340°F	>340°F
0	0	13 239 240 151		
0	4	93		13
0	8	16 6 7 11		
120	4	45	26	
120	8		21	17
160	4		31	89
160	8			22 25
180	8	15		

MERCURY REMOVAL EFFICIENCY				
REAGENT FLOW LIME lb/hr		ELECTROSTATIC PRECIPITATOR TEMPERATURE		
PAC lb/hr		<330°F	330-340°F	>340°F
0	0			
0	4	65%		95%
0	8	94% 98% 97% 96%		
120	4	83%	90%	
120	8		92%	93%
160	4		88%	66%
160	8			92% 91%
180	8	94%		

Table 6. Dioxin, oxides of nitrogen and carbon monoxide test results.

TOTAL DIOXIN CONCENTRATION ng/dsm ³ @ 7% O ₂				
REAGENT FLOW LIME lb/hr		ELECTROSTATIC PRECIPITATOR TEMPERATURE		
PAC lb/hr		<330°F	330-340°F	>340°F
0	0	20.9 36.6 22.2 17.6		
0	4	10.3		4.4
0	8	6.0 3.6 5.2 4.8		
120	4	42.0	3.3	
120	8		1.5	1.9
160	4		2.5	2.7
160	8			1.6 2.0
180	8	1.2		

TOTAL DIOXIN REMOVAL EFFICIENCY				
REAGENT FLOW LIME lb/hr		ELECTROSTATIC PRECIPITATOR TEMPERATURE		
PAC lb/hr		<330°F	330-340°F	>340°F
0	0			
0	4	68%		87%
0	8	81% 89% 84% 94%		
120	4	62%	90%	
120	8		95%	94%
160	4		92%	92%
160	8			95% 94%
180	8	96%		

OXIDES OF NITROGEN CONCENTRATION ppm _{av} @ 7% O ₂				
REAGENT FLOW LIME lb/hr		ELECTROSTATIC PRECIPITATOR TEMPERATURE		
PAC lb/hr		<330°F	330-340°F	>340°F
0	0	98 165		
0	4	152		100
0	8	162 90 99 86		
120	4	90	98	
120	8		91	93
160	4		89	86
160	8			94 98
180	8	157		

CARBON MONOXIDE CONCENTRATION ppm _{av} @ 7% O ₂				
REAGENT FLOW LIME lb/hr		ELECTROSTATIC PRECIPITATOR TEMPERATURE		
PAC lb/hr		<330°F	330-340°F	>340°F
0	0	9.7 7.1		
0	4			8.9
0	8	5.2 3.1 7.5 2.2		
120	4	4.9	3.8	
120	8		7.6	6.9
160	4		3.2	6.9
160	8			5.3 4.0
180	8	6.4		

Table 7. Sulfur dioxide and hydrogen chloride test results.

SULFUR DIOXIDE CONCENTRATION ppm _v @ 7% O ₂				
REAGENT FLOW		ELECTROSTATIC PRECIPITATOR TEMPERATURE		
LIME lb/hr	PAC lb/hr	<330°F	330-340°F	>340°F
0	0	101 121		
0	4	237		154
0	8	201 122 67 100		
120	4	101	57	
120	8		83	97
160	4		80	99
160	8			75 76
180	8	84		

SULFUR DIOXIDE REMOVAL EFFICIENCY				
REAGENT FLOW		ELECTROSTATIC PRECIPITATOR TEMPERATURE		
LIME lb/hr	PAC lb/hr	<330°F	330-340°F	>340°F
0	0			
0	4			
0	8			
120	4	48%	70%	
120	8		57%	50%
160	4		59%	49%
160	8			61% 61%
180	8	56%		

HYDROGEN CHLORIDE CONCENTRATION ppm _v @ 7% O ₂				
REAGENT FLOW		ELECTROSTATIC PRECIPITATOR TEMPERATURE		
LIME lb/hr	PAC lb/hr	<330°F	330-340°F	>340°F
0	0	448 580 636 485		
0	4	402		463
0	8	285 398 420 457		
120	4	333	403	
120	8		259	502
160	4		118	165
160	8			124 151
180	8	237		

HYDROGEN CHLORIDE REMOVAL EFFICIENCY				
REAGENT FLOW		ELECTROSTATIC PRECIPITATOR TEMPERATURE		
LIME lb/hr	PAC lb/hr	<330°F	330-340°F	>340°F
0	0			
0	4			
0	8			
120	4	39%	26%	
120	8		53%	8%
160	4		78%	70%
160	8			77% 72%
180	8	57%		

Table 8. Test results data tabulation.

Test Date YYMMDD	Run Identifica tion	lb/h		mg/dsm ³		°F Stack Temp.	Flue Gas			%	Opacity	--@7% O ₂ --							Total Dioxin
		LIME	PAC	LIME	PAC		Flow	Moisture	Oxygen			Carbon Monoxide	Sulfur Dioxide	Oxides of Nitrogen	Hydrogen Chloride	Front-Half Particulates	Lead	Cadmium	
961201	T01	0	4	0	94	328	18,685	12.1	12.4	3.5		237	152	402	0.030	2,490	72.7	93.9	10.3
961201	T02	0	4	0	91	345	17,803	12.1	11.7	3.6	8.9	154	100	463	0.024	2,346	59.7	42.5	4.4
961202	T03	0	8	0	205	318	18,598	11.3	13.1	2.6	5.2	204	162	285	0.017	1,697	49.9	16.5	6.0
961202	T04	0	8	0	199	326	18,532	12.8	12.8	3.1	3.1	122	90	398	0.025	2,034	54.2	6.7	3.6
961203	T05	0	8	0	175	326	18,870	12.9	11.9	3.7	7.5	67	99	420	0.015	1,244	48.1	6.8	5.2
961203	T06	0	8	0	195	327	19,601	10.8	13.1	4.5	2.2	100	86	457	0.011	1,202	57.8	11.5	1.8
961204	T07	0	0	0	0	324	18,922	11.9	12.0	4.0	9.7	101	98	448	0.032	1,591	70.3	43.9	20.9
961204	T08	0	0	0	0	328	18,999	11.7	13.0	5.1	7.1	121	165	580	0.021	1,718	85.9	238.7	36.6
961205	T09	0	0	0	0	314	20,028	12.0	14.7	3.8				636	0.016	1,161	51.5	239.6	22.2
961205	T10	0	0	0	0	328	19,626	10.8	13.9	5.8				485	0.025	2,108	64.3	151.3	17.6
961206	T11	120	4	3,358	112	323	19,073	10.5	13.9	1.1	4.9	101	90	333	0.038	2,515	85.6	44.8	42.9
961207	T12	160	4	3,298	82	339	19,571	12.2	11.7	1.2	3.2	80	89	118	0.018	946	27.8	30.6	2.5
961207	T13	160	4	3,772	94	348	18,465	11.1	12.4	1.6	6.9	99	86	165	0.024	1,461	42.5	88.9	2.7
961208	T14	160	8	3,765	188	353	18,607	11.8	12.4	2.8	5.3	75	94	124	0.021	1,438	36.8	21.9	1.6
961208	T15	160	8	3,850	192	351	19,394	10.5	12.9	2.5	4.0	76	98	151	0.033	1,805	59.4	24.8	2.0
961209	T16	120	8	2,913	194	351	18,529	11.8	12.7	4.2	6.9	97	93	502	0.032	1,351	39.8	17.2	1.9
961209	T17	120	4	2,996	100	340	18,994	11.5	13.1	3.5	3.8	57	98	403	0.053	2,456	73.9	26.2	3.3
961210	T18	120	8	2,859	191	335	19,288	11.4	12.8	3.0	7.6	83	91	259	0.031	1,430	50.6	20.5	1.5
961210	T19	180	8	4,252	189	327	19,215	12.5	12.7	2.9	6.4	84	157	237	0.027	703	32.3	15.0	1.2
961211	BO1	180	12	5,190	346		18,989	13.4	14.1					705					
961211	BO2	180	12	4,383	292		18,989	11.0	12.9					821					
961211	BO3	240	25	6,469	674		18,989	12.1	13.7					638					

Note: Lined through data points are statistical outliers; outlying individual data points are excluded from displayed pair averages displayed.

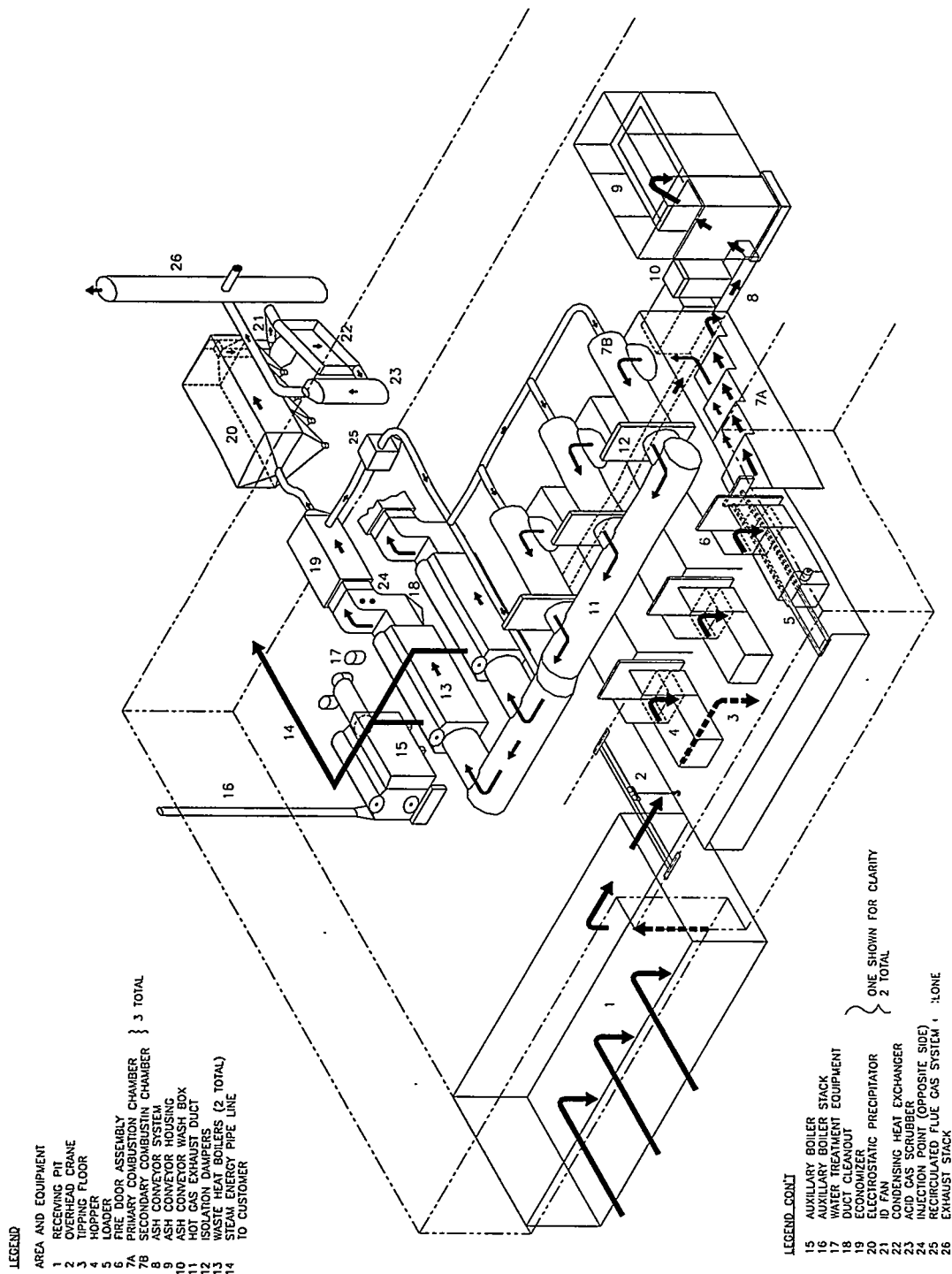


Figure 2. General isometric arrangement drawing of EAC/Pittsfield facility.

Complete Refurbishment Of An Existing Hazardous Waste
Incinerator In Eastern Germany On a Turn-Key Contract Basis

Hans-Ulrich Hartenstein
L. & C. Steinmüller GmbH
Fabrikstrasse 1
D-51643 Gummersbach, Germany

Hans-Dietrich Sonneck
Broerius Abfallwirtschaft Sachsen GmbH
Werkstraße
D-04564 Böhlen, Germany

INTRODUCTION

The area around Leipzig and Halle in eastern Germany attracted the chemical industry already in the 1920's. The abundance of lignite that could be easily mined in open pits served as an ideal source of inexpensive energy and raw materials supply.

Before the second world war the area hosted some of the largest chemical production facilities in the world. In 1990, shortly after the reunification of Germany, most of that pre-war structure was still in operation and largely unchanged.

During privatization, a large complex was formed to become the Buna-SOW-Leuna-Olefin Verbund (BSL) which is being taken over by Dow Chemical. Part of the BSL-structure is the Saxonian olefin production facility in Böhlen near Leipzig. The site originally covered 5.8 square kilometers including a 4 x 200 MW lignite fired power plant. Due to the fact that each chemical production facility generates various environmentally harmful residues, a combustion plant was built in 1974 and commissioned in 1977. The Rückstandsverbrennungsanlage RVA Böhlen (= residue combustion plant Böhlen) was nestled in the center of the chemical complex. Today after major restructuring of the complex, it is located directly adjacent to the new 2 x 930 MW_e lignite fired power plant Lippendorf, which is currently under construction.

The RVA Böhlen, as commissioned in 1977, was finally shut down at the end of March 1997. Figure 1 shows the old facility. It consisted of various storage tanks for aqueous and halogenic liquid wastes, an open pit bunker for solid hazardous wastes, a counter current fired rotary kiln, a horizontal secondary combustion chamber (SCC), a low pressure steam waste heat boiler, a multi cyclone fly ash separator, an I.D. fan, and a 90 m brick stack.

Due to insufficient throughput capacity, totally outdated technology and wear and tear of 20 years of operation, it was decided that everything except the bunker and the stack has to be replaced. The new plant, as shown in Figure 2, consists of the existing but refurbished open pit bunker, a refurbished crane for solid hazardous waste, the new feed system, a new cocurrent fired rotary kiln, a new vertical SCC, a new waste heat boiler, a new 7-stage APC-train, a new tank storage facility and various other new balance of plant (BOP) equipment such as weighing station, container storage, and I + C system etc.

In 1992, when the RVA Böhlen was privatized, the grace period given by the Reunification Contract was 4 years and ended on December 1st, 1996. On that day, the old facility was destined to be shut down unless it would fulfill the requirements of the German 17th BImSchV¹ in all respects. A complex planning and bidding process for a total overhaul of the plant was started. Various concepts were developed and scraped again.

Finally in April 1995, way too late to meet the December 1996 deadline, the turn-key contract for the complete refurbishment of the existing hazardous waste incinerator was awarded to the L. & C. Steinmüller GmbH (LCS), Gummersbach. In the meantime some minor but badly needed improvements were made.

The new storage tank B7 for high calorific liquid hazardous waste was installed, the office building was refurbished completely and some infrastructure repairs were carried out. The permitting procedure for the new facility had also been started. After contract award in April 1995, the first priority was to obtain a permit for the construction of the new facility as quickly as possible. These efforts came to an abrupt halt when the owner decided to abandon all plans and sell the plant. In October 1995 the plant was purchased by its current owner, the Broerius Abfallwirtschaft Sachsen GmbH (BAS).

SCHEDULING

In October 1995, after takeover of the plant by its new owner, time was the biggest problem in three ways:

1. The plant had been shut down by the local permitting agency, the RP Leipzig, because it was evident that the plant could not be brought into compliance with the requirements of the 17. BImSchV by the imposed deadline of December 1st, 1996.
2. The downtime of the plant was the most critical economical factor for the new owner due to the fact that each day out of operation generated cost but no revenue.
3. With the market for hazardous waste to be incinerated being highly competitive, each day away from the market due to downtime of the plant meant that customers would find alternative ways of disposing of their hazardous waste.

Fortunately intense political interest in keeping the only hazardous waste incinerator in the state of Saxony in operation led to a deal between the new owner and the permitting agency, which accommodated the interests of both parties to the most possible extent.

The terms² agreed upon in late 1995 can be summarized as:

1. The plant can go back on line immediately after it is upgraded with an ESP, thus reducing the emissions of particulate matter to below 30 mg/Nm³.
2. The plant will be operated only with a restricted input menu (no halogenated waste, no heavy metals in the waste)
3. The plant will be ultimately shut down by March 31st, 1997
4. The plant will be upgraded with state-of-the-art equipment by September 30th, 1997, leading to emission limits fixed in the permit³ in the range of 5 to 10 times below the values required in the 17th BImSchV for acid gases and heavy metals. Table 1 summarizes the emission limits imposed through the permit.

4. The owner will demonstrate the seriousness of the plan to complete refurbishment of the plant by submitting the permitting documents by December 31st, 1995 and by starting construction on site by mid 1996.

Based on that, a new contract was negotiated between BAS and LCS. The milestones of that contract in terms of keeping the tight schedule imposed by the permitting agency were:

- December 4, 1995: - submittal of the permitting documents for the ESP-retrofit
- December 9, 1995: - start of construction for the ESP-retrofit (based on a special interim permit)
- December 31, 1995: - submittal of the main permitting documents for the complete refurbishment of the plant
- March 15, 1996: - start-up and commissioning of the old plant with the new ESP
- submittal of the remaining documents to accompany the permitting process
- March 31, 1996: - start of commercial operation of the old plant upgraded with the new ESP
- June 1, 1996: - start of construction of the new APC-plant
- August 1, 1996: - start of erection of the new APC-plant
- October 15, 1996: - start of construction of the new SCC, waste heat boiler, and tank storage facility
- December 15, 1996: - start of erection of the new SCC, waste heat boiler, and tank storage facility
- March 31, 1997: - decommissioning and clean up of the old plant
- April 14, 1997: - start of demolition of the old plant and start of construction of the new rotary kiln and remaining BOP-equipment (new feed system, feed water storage tank, etc.)
- May 13, 1997: - start of erection of the new rotary kiln and remaining BOP-equipment
- July 1, 1997: - start-up and commissioning of the new APC-plant
- July 14, 1997: - start-up and commissioning of the new rotary kiln, SCC, waste heat boiler, tank storage facility, and remaining BOP-equipment

- October 1, 1997: - burning of the first hazardous waste
- November 11, 1997: - start of the trial run
- December 19, 1997: - preliminary acceptance and take over the plant by BAS

This extremely tight schedule, allowing only 3 months between the end of operations of the old plant and start-up of the new plant, required thorough planning of each individual step in order to identify the critical path.

GENERAL AND INFRASTRUCTURAL CONSIDERATIONS

Whereas the APC-plant and the tank storage facility could be erected adjacent to the old plant on an open site, the major part of the BOP-equipment, the SCC, the waste heat boiler and especially critical, the rotary kiln had to be placed into the existing plant.

The new plant, as can be seen in Figure 3, has a layout similar to the old one. This was mandatory due to the fact that the open pit bunker with the crane feeding solid hazardous waste could not be relocated. Another fix point besides that building was the existing steel structure to support the pipe connections to the existing infrastructure of the adjacent industrial /power generating complex. This pipe support structure Q2 is the umbilical cord of the entire hazardous waste incinerator. Since the plant itself does not generate electricity, but exports steam, the pipe support structure is crucial to the plant's concept. The following media are supplied to and exported from the hazardous waste incinerator via Q2:

- Low pressure steam (4.8 bar, 250°C) is exported into the low pressure steam district heating system of the BSL (after 2001 the low pressure steam will be used in the newly erected lignite fired power plant for the primary air heaters).
- Boiler feed water is imported from the BSL net (later from the power plant)
- Pressurized air is imported from the BSL net
- Nitrogen gas is imported from the BSL net
- Water is supplied through the BSL net
- Sewage is discharged into the BSL sewage treatment plant

The technological and economical concept of the plant is based on utilizing the existing infrastructure of the surrounding industry. Thus the plant can not be viewed as an independent operation.

The most important connection is the feed water import / steam export loop. The new steam generator is designed to supply approximately 15 t/h of steam @ 25 bar, 270°C (363 psi, 518°F). Since the plant does not generate any electricity, the entire electrical consumption must be purchased through the public grid at a cost of about 0.23 DM/Kwh (15 cents/Kwh). Therefore it is mandatory to reduce electric power consumption to the absolute minimum. In the new plant, the I.D. fan as one of the main consumers will not be driven by an electric motor, but by a steam turbine.

The turbine will be fed with high pressure steam directly from the boiler (25 bar, 270°C) and will discharge low pressure steam (4.8 bar, 250°C) into the BSL net. Various other consumers of high and low pressure steam within the plant are also connected as shown in Figure 4.

PHASE I - THE NEW ESP

In October 1995, the most important task was to bring the old plant back online as soon as possible. Under the settlement with the permitting agency, operation could be resumed only after the retrofit of an ESP.

However, the ESP had to be erected in such a way that:

- It must be easily incorporated into the layout of the entire refurbishment
- It must not interfere with erection of the new APC-plant or the new SCC and waste heat boiler
- it must directly connect to the new waste heat boiler on one side and to the APC plant on the other side without extensive duct work.

In order to balance these criteria, the general arrangement of the new plant had to be laid out. Figure 5 shows how the new ESP was fitted to the old plant. Several changes had to be made to accommodate the new ESP without violating the criteria outlined above. First the flue gas inlet at the old brick stack had to be rotated 90° clockwise to the south. This was necessary for two reasons. First, the original flue gas duct and inlet at the stack was in the way of the new waste heat boiler. Second, the final flue gas duct had to be installed in order to accommodate the continuous emission monitoring system (CEMS) required during operation. Therefore, the new ESP was located bridging the roadway between the existing old plant and the location for the new APC-plant. The new waste heat boiler had to be tailored into the remaining space between the stack, the new ESP, and the existing old I.D. fan. To allow for maximum possible space the old I.D. fan was rotated 180° and the interim duct work from the old boiler / multi-cyclone outlet was detoured in a wide angle to the inlet of the new ESP. As can be seen on Figure 5 the inlet duct to as well as the outlet from the new ESP, and the inlet to the new flue gas duct to the stack past the CEMS were kept clear for the connection of the new waste heat boiler and the new APC plant respectively. On the side connecting to the new APC plant this was realized by utilizing what was meant to become the bypass duct of the APC plant after the complete refurbishment.

The extremely short period of time between beginning of construction on December 9th, 1995 and beginning of start-up and commissioning on March 15th, 1996 could only be realized taking into account the fact that the chosen ESP size and design was already in operation elsewhere, so that the engineering time could be reduced to an absolute minimum.

PHASE II - THE NEW APC-PLANT

The design of the APC-plant was governed mainly by the extremely low emission limits imposed on the plant by the permitting agency combined with the legal requirements of a waste water free zero discharge plant and the necessity to recycle the maximum possible amount of residues. Considering these factors a state-of-the art 7-stage APC-train was planned.

It consists of the ESP followed by Steinmüller's patented Sodium Tetrasulfide injection system for the removal of mercury, especially elemental mercury. As detailed in Figure 6, the next stage is a spray dryer and a baghouse to collect the dried neutral salts from the first scrubber. After the baghouse, a two stage wet scrubber for the removal of HCl and HF is installed. The effluent from this first scrubber is neutralized externally with slaked quick lime followed by a flocculation and precipitation process to complex the heavy metals. The generated liquor consists mostly of Calcium Chloride (CaCl_2), Calcium Fluoride (CaF) and complexed heavy metals. The dissolved salts and the complexed heavy metals are dried in the spray dryer and removed from the flue gas stream in the baghouse. The residual mixture is combined with the fly ash from the ESP and disposed of in an underground landfill. These underground landfills commonly represent former salt mines, where the formed caverns need to be refilled for structural support. This way of disposal is currently considered recycling in some cases, such as this one.

The next stage is a second wet scrubber for the removal of SO_2 . Slaked quick lime is used as a scrubbing liquor in order to form marketable gypsum. The flue gas polishing is done by the Steinmüller patented activated carbon reactor (ACR) followed by a low temperature SCR-De NO_x -reactor (LTSCR).

In order to enter the ACR, the flue gas leaving the scrubber must be reheated from its saturation temperature of approximately 65°C (150°F) to about 130°C (265°F). This is achieved in the first stage by a steam reheater for the primary drying of the flue gas followed by a cross-flow heat exchanger.

After the ACR, NH_3 is injected into the flue gas for the LTSCR-process⁴. The temperature of the LTSCR is set at 170°C (340°F). Heating the flue gas from the ACR-temperature of 130°C (265°F) to 170°C (340°F) is done in a first step by the I.D. fan. It supplies about 10 - 13 K to the flue gas due to the pressure drop of approximately 130 mbar (1.88 psi) across the entire flue gas path. The second step is overcome by another steam reheater for the final adjustment of the flue gas to the LTSCR temperature.

The flue gas leaving the LTSCR is discharged through the cross-flow heat exchanger prior to the ACR and then past the CEMS into the stack. As shown in Figure 7, the APC-plant is set up in a very compact open steel structure. Only the spray dryer, the baghouse and the ACR have a penthouse for the weather protection of their critical components.

Adjacent to the APC-train is the pump building, housing all the pumps and vessels handling the two different scrubbing liquors. The main circulation pumps for the wet scrubbers as well as most of the vessels are located on the ground floor. The first floor is occupied by the lime slakers, the gypsum centrifuges, and the neutralization, flocculation and precipitation system for the effluent of the HCl-scrubber. The second floor accommodates the entire low voltage switch gear and electrical equipment

for the APC-plant. The storage facility is located on the west side of the APC-plant. Due to the green field advantage, construction and erection of the APC-plant is not further detailed.

PHASE III - THE NEW INCINERATOR

November 15th, 1996 marked the start of Phase III of the project. This must be considered the beginning of the critical path and, therefore, the most important phase within the entire project.

Comparing Figure 5 and Figure 8 gives a rough idea about what it means to start construction and erection of major pieces of equipment such as the SCC or the steam generator literally inside the operating hazardous waste incinerator.

In Phase III, the renewal of the following pieces of equipment are summarized:

1. The bunker crane for feeding solid hazardous waste
2. The feeding system for solid hazardous waste including the feed hopper, the belt conveyor, the drum feeder etc.
3. The primary and secondary air system, including fans etc.
4. The rotary kiln, including burners, cooling systems etc.
5. The SCC, including burners, ash extractors etc.
6. The waste heat boiler including the feed water system, the ash extractors, the steam system etc.
7. Parts of the electrical power supply for the entire plant.

Technologically, none of those components deviate from the well known, well proven, state-of-the-art hazardous waste incineration technology based on the rotary kiln technique. Therefore, the equipment is not further detailed from a technological point view.

The first problem was to clear the space for the steam generator and the SCC. Unfortunately the main power supply lines, as well as some controls, the natural gas lines to the burner of the existing rotary kiln and various other critical media supply pipes had to be cleared before construction could begin. The only time available for that was a scheduled 8 day maintenance outage of the old plant in October 1996. After that hurdle was successfully overcome construction of the large foundation for the boiler and the SCC resumed.

The most critical difficulty for this foundation was first, the slight overlap of it onto the existing foundation of the stack, and second the interference with the existing foundation of the front end of the old rotary kiln. The first difficulty posed a problem because it was absolutely mandatory to avoid inducing any weight onto the foundation of the existing stack in order not to interfere with its statics. The second one forced a gap in the new foundation for the SCC and the boiler, which had to be filled after the existing plant was demolished. After months of detailed planning, endless calculations and numerous different ideas and suggestions on how to solve the two problems, the foundation was finally poured into place touching the existing foundation on all four sides. In early December 1996,

the new foundation was in place and by about December 10th the erection of the steel structure supporting the SCC and the waste heat boiler was started and completed before Christmas.

Due to the large weight of the SCC after being refractory lined, its supporting frame had to be adjusted about 10 - 12 cm (4 -5 inches) above the support frame of the boiler. Here the much higher compression of the steel structure had to be compensated for, so that after completion, the inlet of the steam generator and the outlet of the SCC would be leveled.

Just before Christmas the steam generator could have been erected. Due to the Christmas holiday season and a very harsh winter, it was chosen to preassemble the pressure part of the waste heat boiler to a maximum possible extent in our shop in Gummersbach and deliver it in 3 preassembled sections to the site by the end of January 1997. The size of the preassembled sections was determined by the maximum permissible dimensions for the road transport. The pressure part of the boiler was erected in about 5 days on site with a minimum of welding. It was completed with the drum and the connecting pressure pipes by the end of February 1997. The pressure test was delayed until the end of March due to weather conditions and the fact that the supports for the insulation had to be mounted first to avoid any possible leakage by improper mounting.

In early January 1997 the old plant had another scheduled maintenance outage of 10 days. This outage was used to refurbish the existing bunker crane. After a week of 16 hour work days, operation of the old plant was resumed with a refurbished crane.

The next critical milestone was the erection of the SCC, weighing about 42 tons. Due to its size, it was shipped in eight sections from the Steinmüller workshop in Poland and preassembled to three pieces on site. One piece represented the quarter spherical head piece connecting the cylindrical part of the SCC to the waste heat boiler. The second piece was the above mentioned cylindrical part with the third piece being the bottom of the SCC with the inlet housing for the end of the rotary kiln. Since the steel frame supporting the SCC was above the front end of the operating old rotary kiln, this third piece would only be lifted to the inside of the steel structure and rested on the concrete bottom underneath. The remaining two pieces were erected on February 4th, 1997.

Great care had to be taken since the steel structure of the SCC touched the platform on the front end of the operating rotary kiln at various points, and the distance between the new SCC and the burner of the operating rotary kiln underneath is merely 3 feet.

After the erection of the SCC and completion of the steam generator, the time in February and March was mostly spent completing these components, building the new road ways on site and preparing for the decommissioning and the demolition of the old plant. During that time most of the APC-plant was completed, construction of the tank storage facility was finished and the new I + C system was partly installed. On March 17th, 1997 the first life line of the old plant was cut. Due to the facts that the throughput of the refurbished plant is about 60 % higher than of the old plant and there wasn't any kind of APC-equipment before, the electrical consumption of the new plant exceeds by far the capacity of the transformers of the existing plant.

One of the two redundant 6 KV-transformers, each with a capacity of 1.200 Kwh/h was replaced by the first one of the new used 1.600 Kwh/h transformers. This left the plant and the construction site running on only one transformer for about 6 weeks.

In the same week, the new foundations for the new rotary kiln were poured elsewhere on site. These prefabricated concrete blocks were lifted into place about a month later. Pouring the concrete foundations externally at a different location than they ultimately rest saved about 4 weeks in time. The tight schedule after shut down of the plant did not allow for conventional construction by excavating the foundation pit, casting the mold, introducing the steel reinforcement pouring the concrete and letting it harden and dry. In early May, after the old rotary kiln was demolished and the new foundation pits excavated, the precasted new foundation blocks were lifted in place without interrupting the erection process for the new plant.

The old plant was decommissioned and handed over for demolition starting April 14th. Only two days were available to completely dismantle the front end platform of the rotary kiln, remove the burner and the rest of the combustion equipment and take off the front end plate of the rotary kiln. At the same time the refractory lining of the old rotary kiln and the old SCC was broken out. Immediately after that the rotary kiln was disassembled into three sections.

These were lifted out by a large crane. By early May the demolition process of the old plant was almost completed and the new foundations for the new rotary kiln were in place. What had been in operation for 20 years vanished in less than 3 weeks!

The steel structure of the old SCC and the old waste heat boiler was saved to be reused in the new plant. The new 80 m³ boiler feed water storage tank was rested on the steel frame of the old boiler. The old SCC steel structure serves well in supporting numerous pipelines, the primary air duct, cables, platforms and the new feed belt conveyor.

Parallel to dismantling the old rotary kiln the inlet duct to the ESP had to be removed quickly. It blocked the critical path from the ESP via the existing boiler feed water degasifier to the main building. Since the main building not only contains the control room but also holds the low voltage switch gear and electrical equipment room for the entire plant (except the APC plant) it was very time critical to clear that path as quickly as possible.

Two weeks were available for demolition of the old equipment and erection of pipe and cable support ways between the ESP and the main building. At the beginning of May, the start for laying cables and pipes was made. By early June the plant was fully hooked up electrically and the first function checks were performed.

At the other end of the busy site, the beginning of June marked a very critical time. At the second of June the new rotary kiln was delivered on site and lifted in place by a large caterpillar crane. At this point in time the 250 tons of refractory lining in the new SCC were completely installed. One

week later, the new rotary kiln was assembled to the point for the refractory lining to be started. Lining the kiln would take about four weeks until almost the middle of July 1997.

With the rotary kiln, as the last major component in place, the most critical part of the erection of the new plant was completed.

BOP-EQUIPMENT AND COMMISSIONING

Besides the major components mentioned above, numerous other things had to be installed. Fortunately none of them were conflicting with the time critical path.

Among the numerous BOP-equipment was:

- A new entrance gate
- A new weighing station
- New I & C equipment and a new digital control system (DCS)
- A new container storage building
- A refrigerated storage container for medical waste
- A new drum feeder
- A new tank storage facility including 3 unloading stations for tank trucks
- New roadways including lighting and run off collection
- A new control room
- A complete new fire protection system for the entire plant
- A safety platform for securing leaking tank trucks etc.
- Landscaping of sites where old equipment was removed
- Other details and odds and ends which are needed to make the refurbished hazardous waste incinerator fully operational.

In the first half of July 1997, the refurbished plant will be started up and commissioned. Loop checks, function tests and cold test runs will occupy most of July and August. During September 1997, the hot commissioning will start by firing the burners on natural gas, thus drying out the refractory lining, cooking the boiler, and for the first time, producing flue gas.

The first hazardous waste feed is scheduled for early October. After balancing the plant and adjusting all controls to ensure normal operation, a trial run period of six weeks is anticipated from November 7th, 1997 to December 19th, 1997. On that day, the preliminary acceptance and hand over of the new plant to the owner is planned.

CONCLUSION

From starting the project in late October 1995 to hand over in late December 1997, a time of only 26 months will have expired. A 20-year old hazardous waste incinerator will have been completely

demolished and rebuilt with a downtime of only 3 months between decommissioning the old plant and commissioning the new plant. Only 6 months from stopping to resuming the incineration of hazardous waste mark a true accomplishment, especially due to the fact that this retrofit is a very complicated one. Constructing and erecting an almost entirely new plant around an existing old one during full operation as in Phase I and II is already a task in itself. But constructing and erecting a new steam generator, SCC, rotary kiln, feed system etc. within an existing hazardous waste incineration plant not only requires exact planning, scheduling and precise execution of the job, but also a lot of enthusiasm, personal motivation and engagement of the engineers in the offices and the erection crew on site. The greatest quest for project management, in order to accomplish that task, is to keep the spirit alive and ensure that the team stays on track. And most important of all, only if the vendor and the customer pursue the same goal together as a team can the goal be reached successfully.

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Table 1. Emission limits imposed by the permit in comparison to the German 17th BImSchV.

Emissions Controlled by a Continuous Emissions Monitorius System (CEMS)					
Pollutant	24 Hour Mean		30 min. Mean		Unit
	RVA Böhlen	17. BImSchV	RVA Böhlen	17. BImSchV	
PM	5	10	10	30	mg/m ³
NO _x	70	200	200	400	mg/m ³
HCl	2	10	10	60	mg/m ³
SO _x	5	50	20	200	mg/m ³
HF	0.25	1	1	4	mg/m ³
C _{org}	5	10	10	20	mg/m ³
CO	50	50	100 ¹	100 ¹	mg/m ³

Emissions Controlled by Individual Measurements

Pollutant	RVA Böhlen	17. BImSchV	Sampling Time	Unit
Class I	0.01	0.05	> 30, < 120 minutes	mg/m ³
Class II	0.01	0.05	> 30, < 120 minutes	mg/m ³
Class III	0.1	0.5	> 30, < 120 minutes	mg/m ³
PCDD/F	0.05	0.10	> 500, < 960 minutes	ng I-TEQ/m ³
NH ₃	5	---	120 minutes	mg/m ³

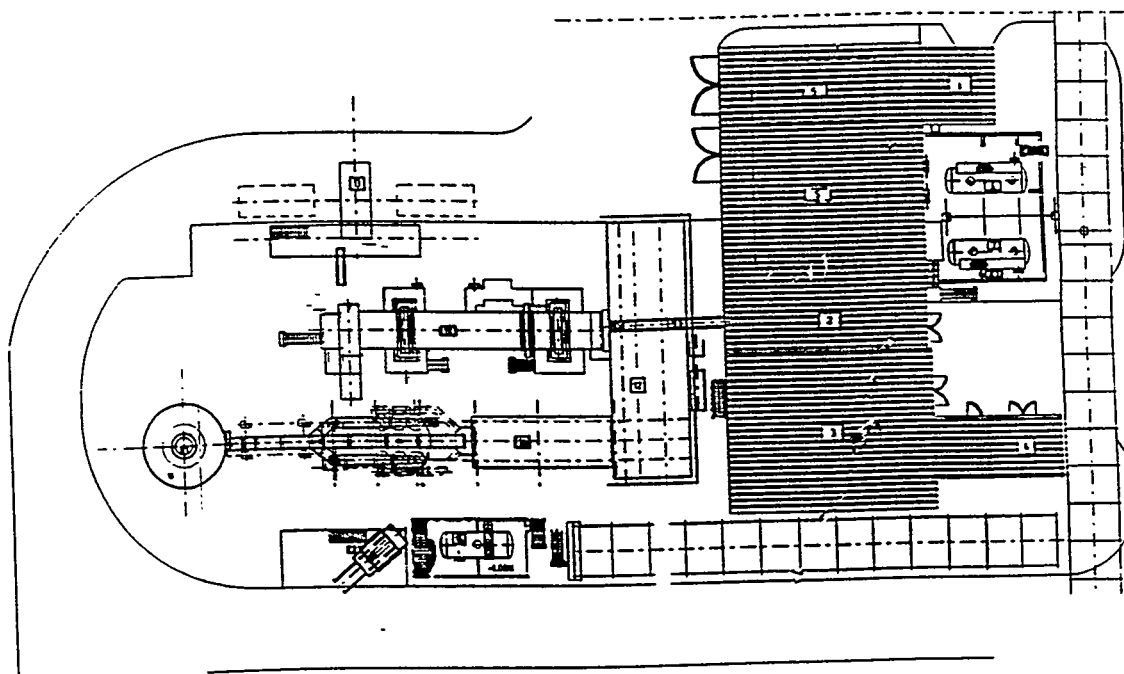
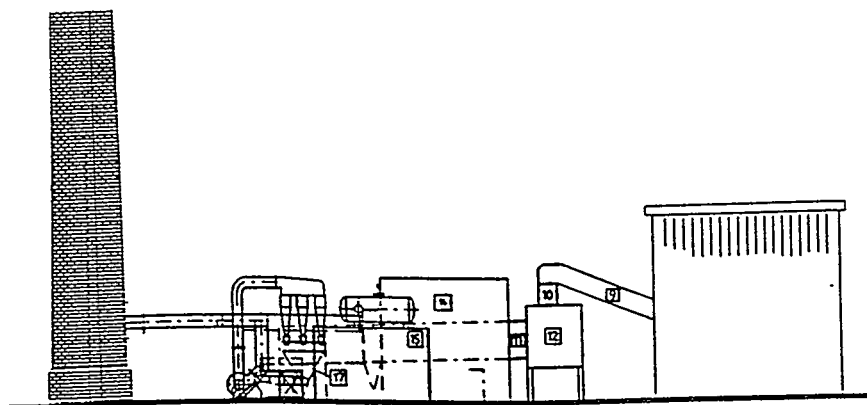
Class I heavy metals = (Cd + Tl)

Class II heavy metals = total Hg

Class III heavy metals = (Sb + As + Co + Cr + Cu + Mn + Ni + Pb + Sn + V)

¹ = 1 hour mean

- o All values are based on dry flue gas @ 101.3 Kpa (29.92 in of Hg) and 0°C (32°F) and, with the exception of CO, are to be corrected to 11 % O₂ only if the actual O₂ exceeds 11%.
- o Combustion temperature must be $\geq 1.200^{\circ}\text{C}$ (2.192°F) for ≥ 2 seconds after the last air injection.



- | | |
|-------------------------------|-----------------------------------|
| 1 = primary air fan | 12 = secondary combustion chamber |
| 2 = waste feed system | 13 = ash handling system |
| 3 = control building | 14 = waste heat boiler |
| 4 = maintenance building | 15 = feed water degasifier |
| 5 = waste storage pit | 17 = multi cyclone |
| 6 = liquid waste storage tank | |
| 7 = liquid waste storage tank | |
| 9 = waste feed conveyor | |
| 10 = waste chute | |
| 11 = rotary kiln | |

Fig. 1. Site Plan of the Old RVA Böhlen

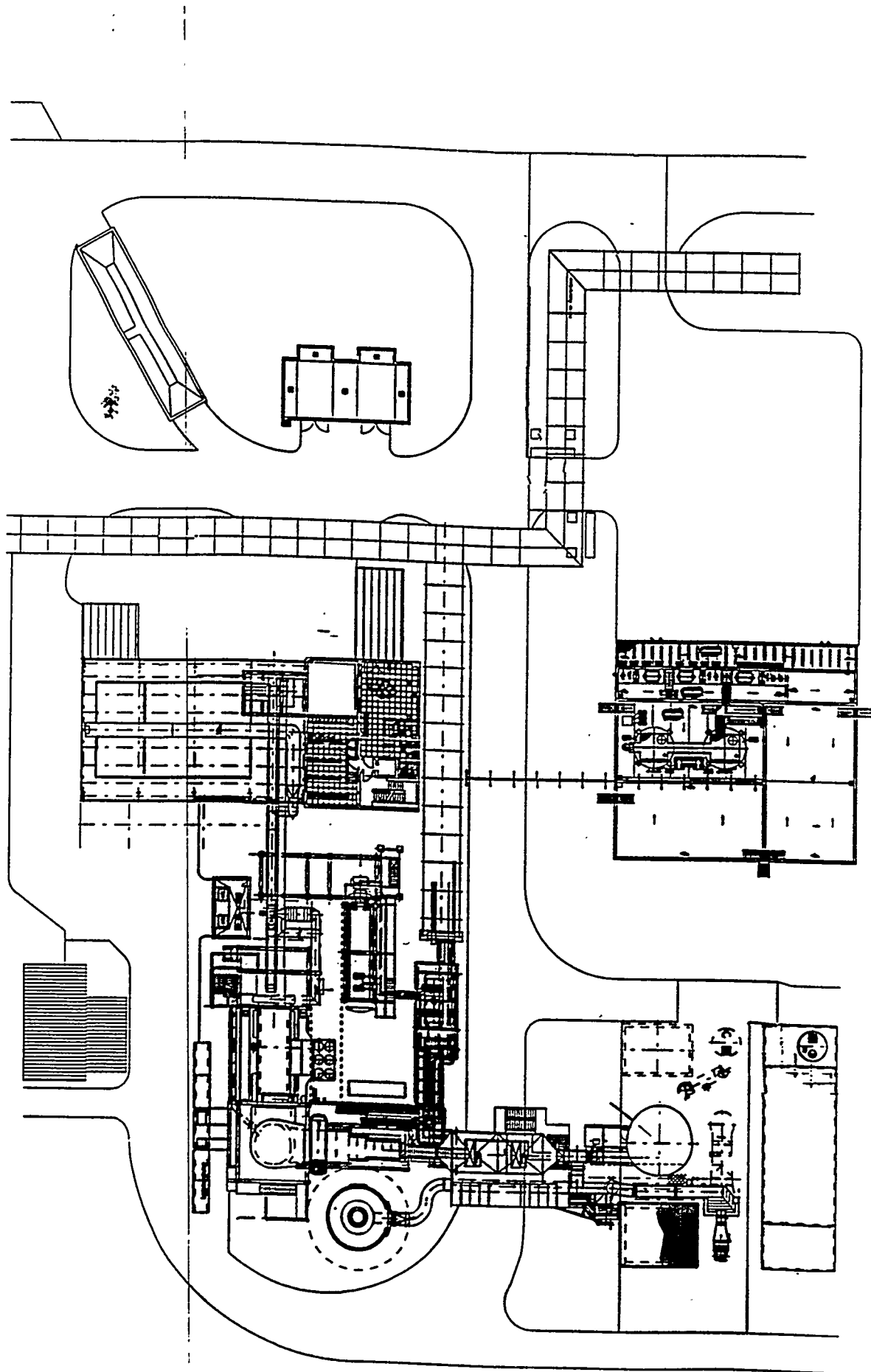


Fig. 2. General Arrangement of the New
Hazardous Waste Incineration Plant

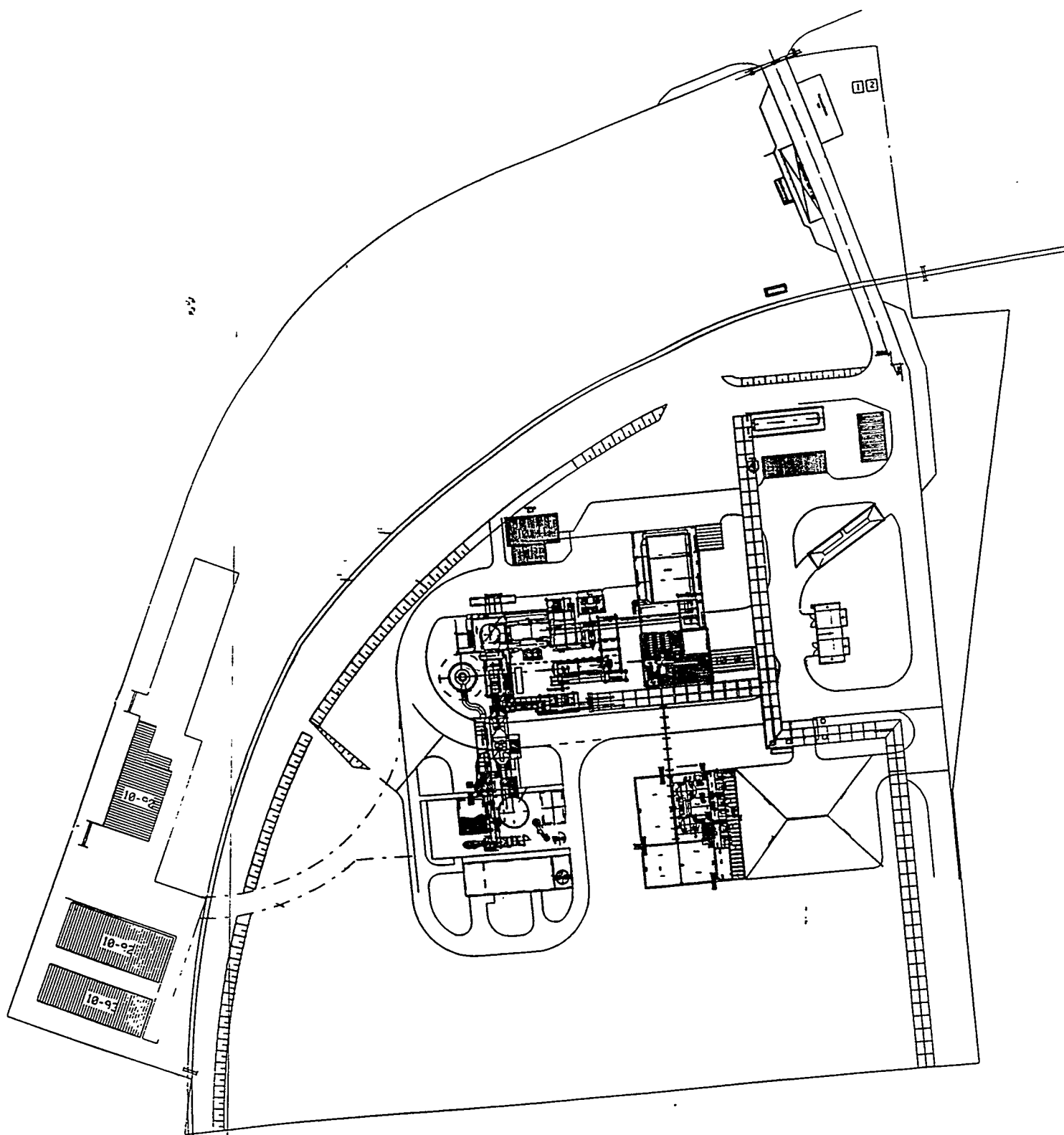


Fig. 3. Site Plan of the New RVA Böhlen

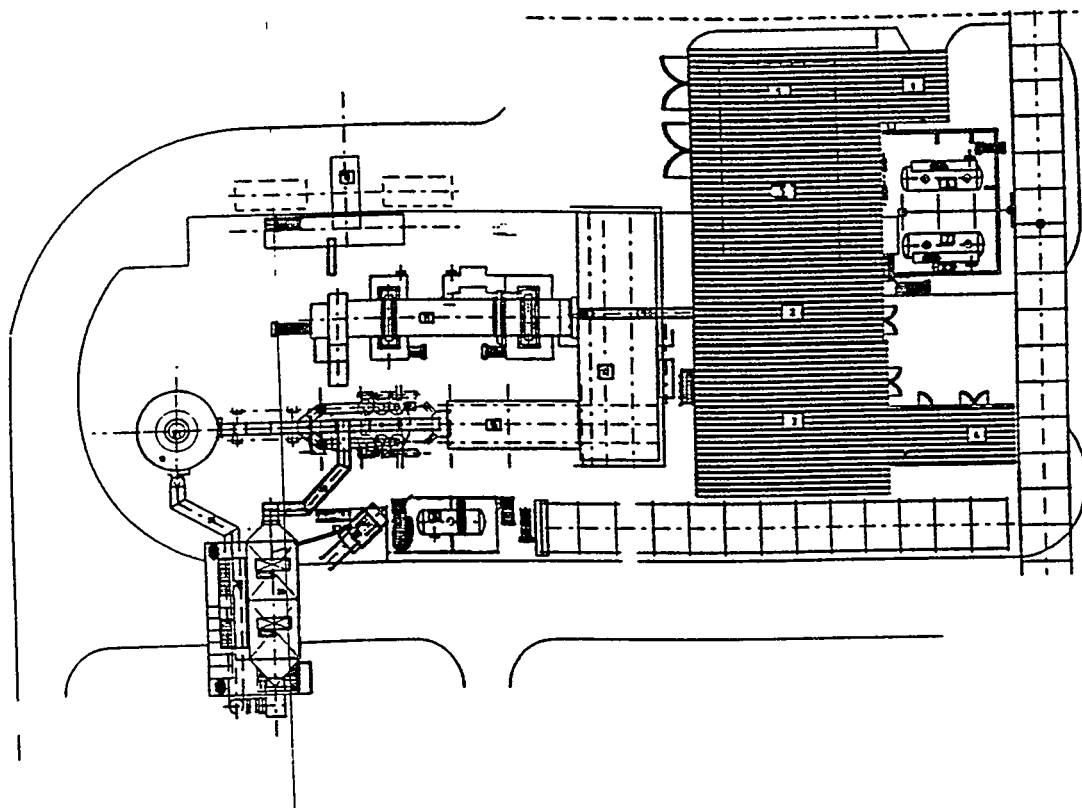
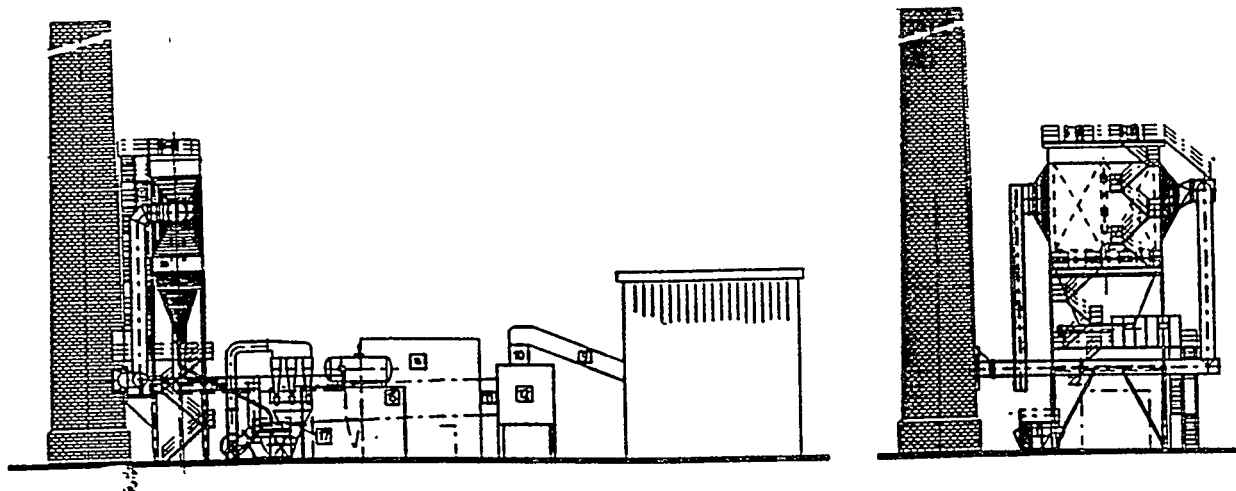


Fig. 5. General Arrangement for the Old Plant With the New ESP

- | | |
|-------------------------------|-----------------------------------|
| 1 = primary air fan | 12 = secondary combustion chamber |
| 2 = waste feed system | 13 = ash handling system |
| 3 = control building | 14 = waste heat boiler |
| 4 = maintenance building | 15 = feed water degasifier |
| 5 = waste storage pit | 17 = multi cyclone |
| 6 = liquid waste storage tank | 20 = ESP |
| 7 = liquid waste storage tank | 21 = flue gas duct to stack |
| 9 = waste feed conveyor | 22 = interim flue gas duct |
| 10 = waste chute | |
| 11 = rotary kiln | |

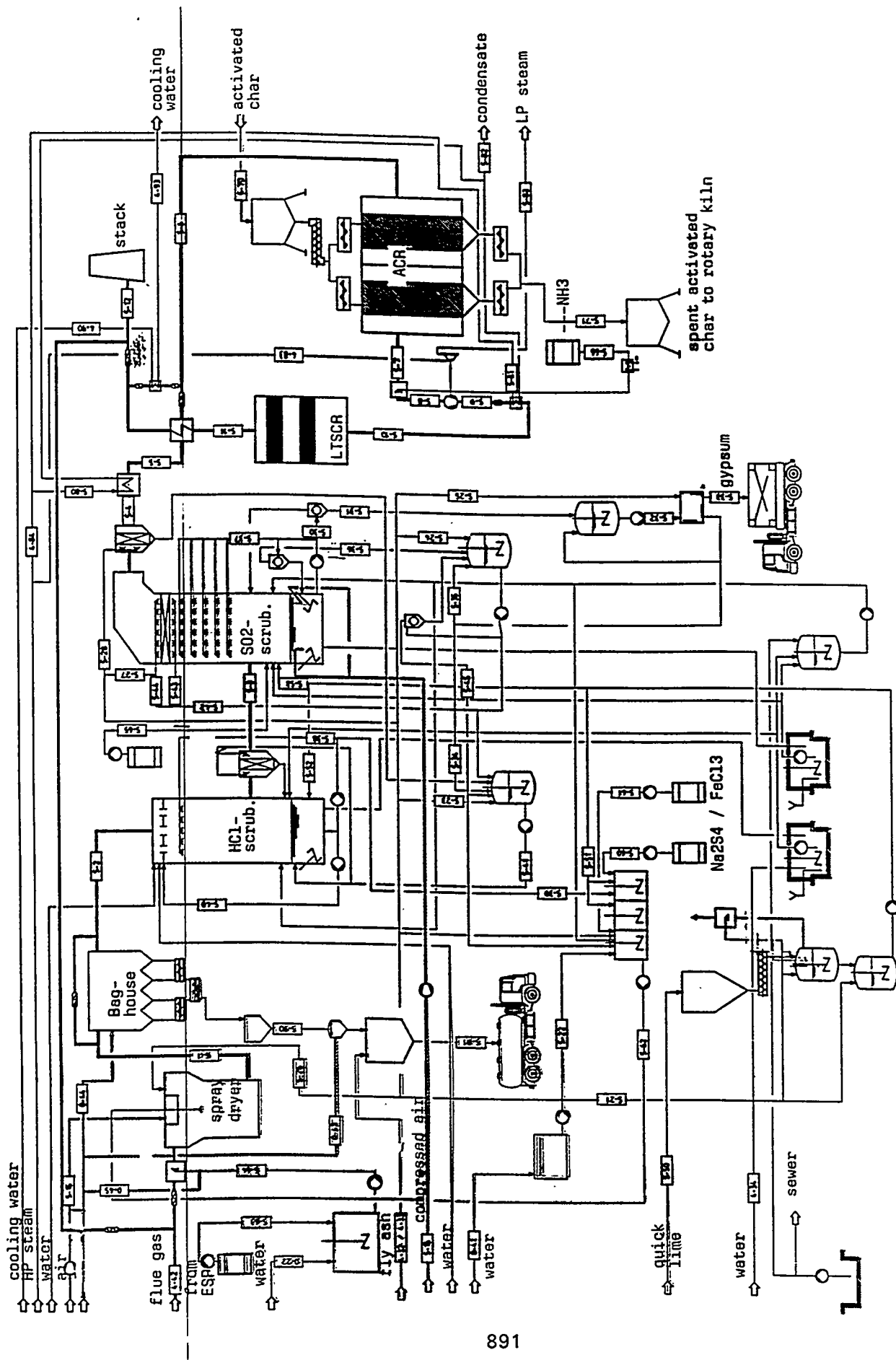


Fig. 6. Process Flow Diagram of the New APC-Plant

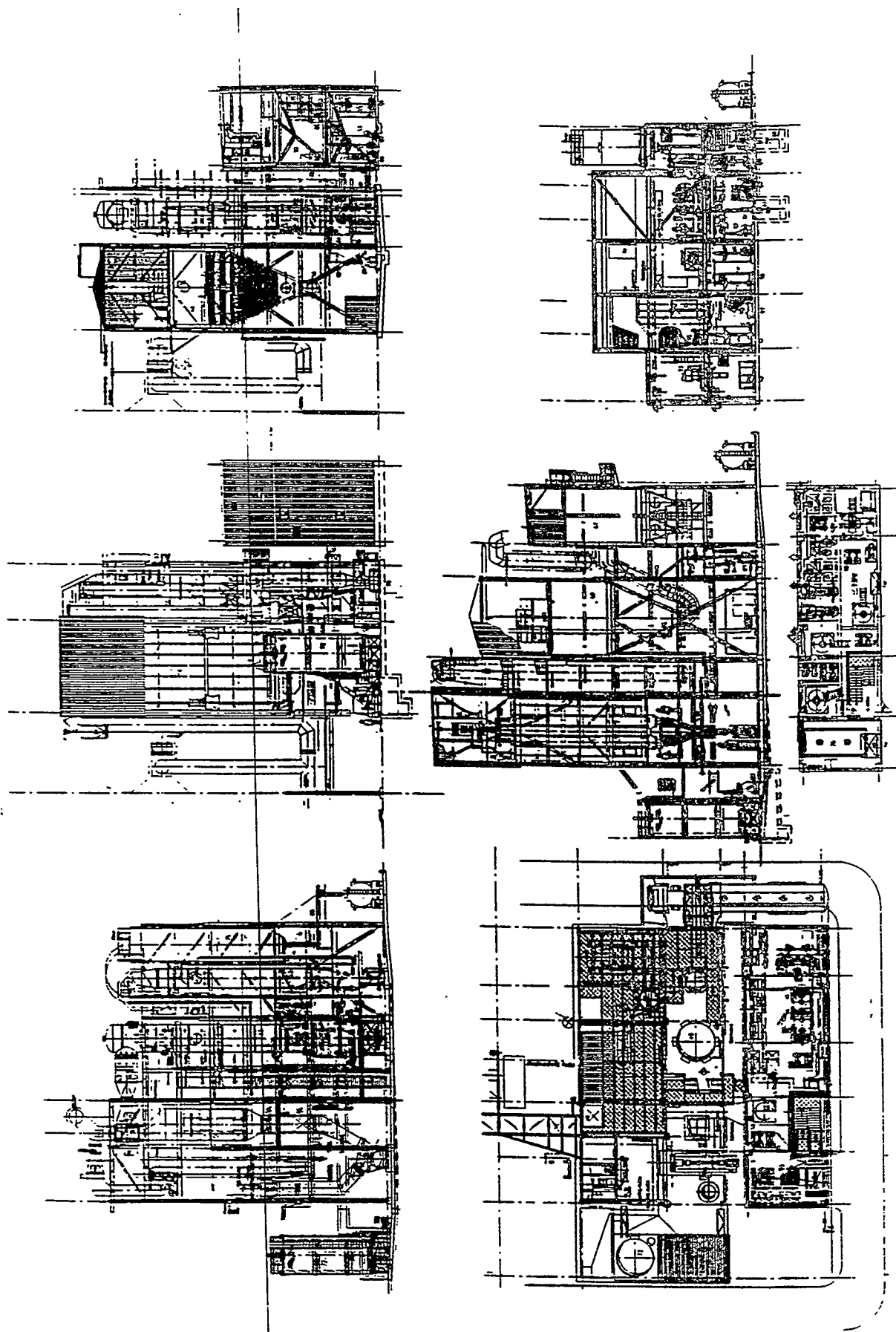


Fig. 7. General Arrangement of the New APC-Plant

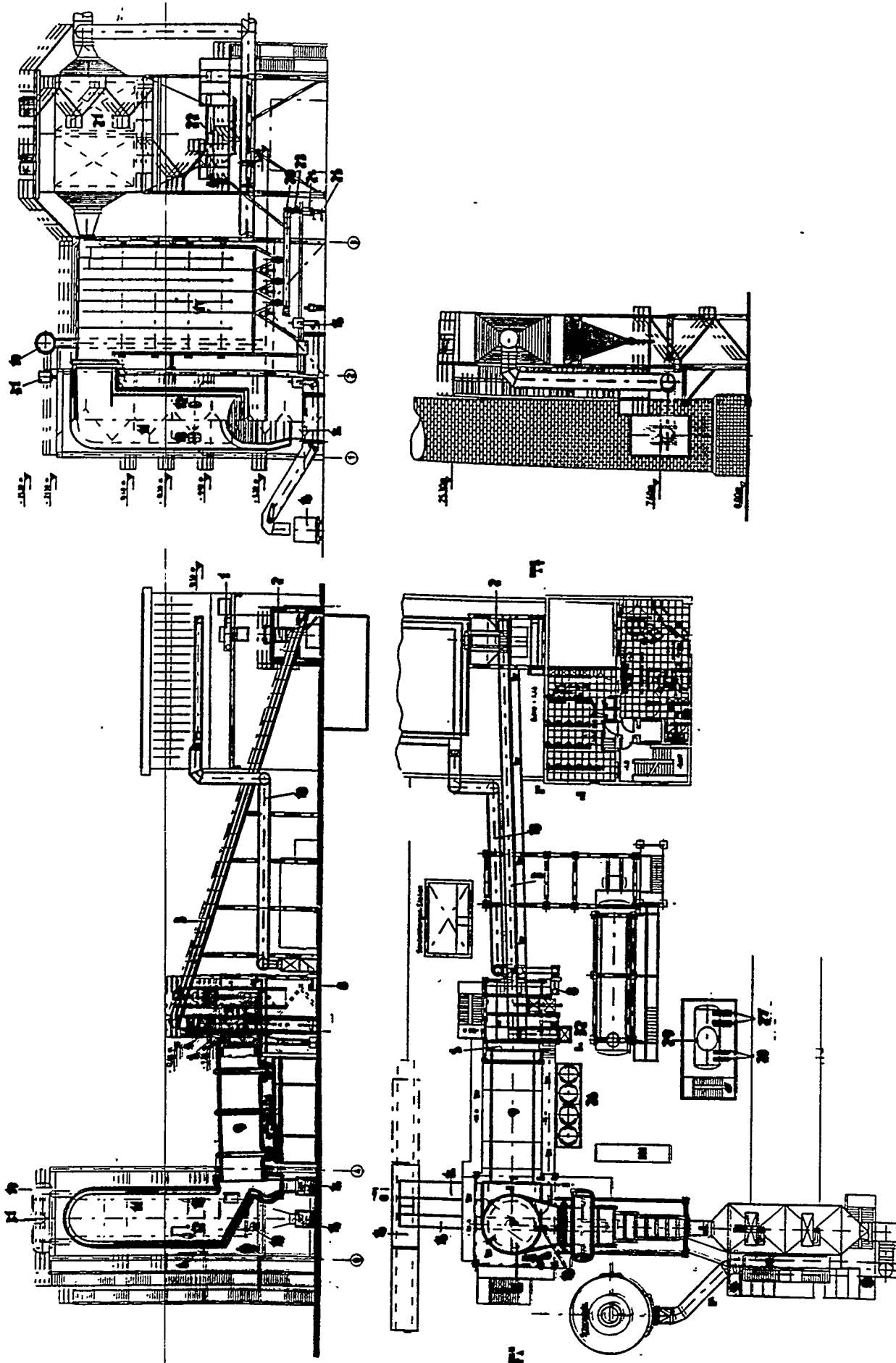
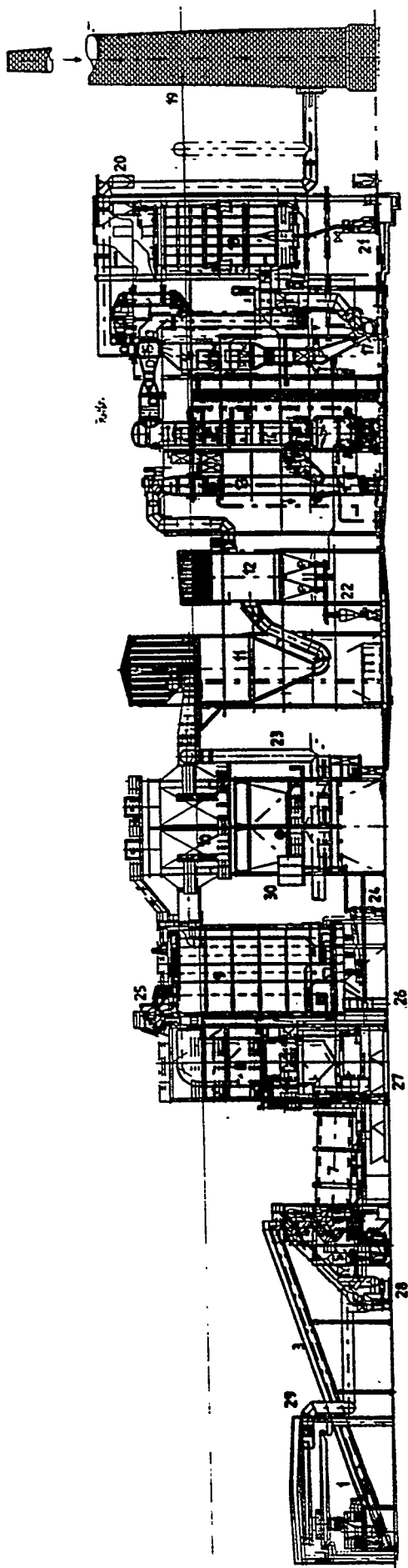


Fig. 8. General Arrangement of the New Incineration



- | | | |
|----------------------------------|--|---|
| 1 = pit building | 11 = spray dryer | 21 = spent activated char collection |
| 2 = feed system | 12 = bag house | 22 = fly ash / salt collection system |
| 3 = waste conveyor | 13 = HCl-scrubber | 23 = bypass |
| 4 = bucket waste feeder | 14 = SO ₂ -scrubber | 24 = ash collection boiler and ESP |
| 5 = spent activated char feed | 15 = cross-flow heat exchanger | 25 = boiler drum |
| 6 = burners | 16 = SCR ₁ -DeNO _x | 26 = ash collection boiler |
| 7 = rotary kiln | 17 = ID-fan | 27 = ash collection rotary kiln and SCC |
| 8 = secondary combustion chamber | 18 = ACR | 28 = primary air fans |
| 9 = waste heat boiler | 19 = stack | 29 = primary air duct |
| 10 = ESP | 20 = activated char feed | |

Fig. 9. Side View of the New RVA Böhlen

TECHNICAL SESSION V

Health & Safety

**Attaining VPP Star Status: A Case Study of the American Ref-Fuel
Waste-to-Energy Facilities**

**Joseph R. Vengen
American Ref-Fuel Company
777 North Eldridge
Houston, TX 77079**

INTRODUCTION

The Occupational Safety and Health Act of 1970 was enacted into law by the 91st Congress of the United States to address the issue of safety in the workplace, as stated in the OSH Act Section 2(a):

“The Congress finds that personal injuries and illnesses arising out of work situations impose a substantial burden upon, and are a hindrance to, interstate commerce in terms of lost production, wage loss, medical expenses, and disability compensation payments.”

Furthermore, Congress declared its purpose in enacting the Act in Section 2(b):

“The Congress declares it to be its purpose and policy, through the exercise of its powers to regulate commerce among the several states and with foreign nations and to provide for the general welfare, to assure so far as possible every working man and woman in the nation safe and healthful working conditions and to preserve our human resources.”

In the Act, Congress therefore outlines the means by which it intends to achieve the goals set forth in the OSH Act. A review of the listing provided in Section 2(b)(1) of the OSH Act reveals what was assuredly regarded as a proactive approach towards implementation. The plan in part calls for the enhancement of employee/employer relations in the areas of hazard identification and prevention, the identification of necessary training and provisions for such training and the development and promulgation of occupational safety and health standards. Also provided for under Section 2(b)(10) of the Act was “an effective enforcement program which shall include a prohibition against giving advance notice of any inspection and sanctions for any individual violating this prohibition.”

In the early 1970s, the predominant management style for achieving the desired results of an organization was still closely associated with the antiquated technique of compliance through enforcement. It was not until the late seventies and early eighties that the threat of the United States losing its front-runner position in the emerging world market forced corporate America to reexamine the link between management practice and overall employee productivity and well being. The perceived adversarial climate created by the Occupational Safety and Health Administration's efforts at compliance with the new act emerged as a product of contemporary society as it mirrored the accepted management practices of the era. By the mid eighties, the economic hardships created by the emergence of the global economy had forced a management revolution where traditional ways of doing business were challenged and in many cases abandoned for new ideas. Many of the newly accepted management practices rejected ideas such as the myth that compliance can only be gained through the threat of enforcement. Instead, the new ideas focused on gaining employee trust and commitment through empowerment, by subscribing to the idea that employees were assets and not simple commodities, and that true cooperation between employer and employee was the singularly most important aspect of successful management.

OSHA was no different than the private sector, in that for the agency to achieve its goals, it had to have in place management systems that not only worked within the agency but were compatible with the systems in place for the industries which the agency regulated. OSHA also came to realize that the

agency practice of enforcement to gain compliance was not producing the intended results and would not be effective in helping them to realize their goals as promulgated under the OSH Act. Because this understanding became more prevalent as time went on, the Voluntary Protection Programs (VPP) were developed. The Voluntary Protection Programs are implemented under Section 2(b)(1) of the Act, which encourages employers and employees to “reduce hazards, implement new programs, and perfect existing programs for providing safe and healthful working conditions.”

This study will integrate an overview of the VPP process with an exploration of the merits of the program based upon measurable benefits to Waste-to-Energy Facilities as well as to OSHA through this cooperative effort.

CORE PRINCIPLES

Safety and Health Excellence

Since the company's inception, management has continually demonstrated a steadfast commitment to the goal of securing a leadership position in the continually developing Waste-to-Energy market. By embracing a common belief system and shared vision, management set the tone for what was to be considered the company “blueprint” for ensuring present and future successes.

The most highly regarded aspect of this “blueprint” was how the company came to establish and prioritize the implementation of its operating philosophy. For the American Ref-Fuel Waste-to-Energy Facility, this was accomplished by first understanding the need to develop and nurture a strong safety and health culture. The operating philosophy makes it very clear that strict attention to safety and health concerns are a prerequisite for accomplishing all other company goals such as operating a profitable organization and optimizing plant performance and throughput. It is a strongly held common belief among American Ref-Fuel employees that as long as safety is integrated into the decision making process and into all activities, positive production and profitability statistics follow as part of a natural progression.

Because American Ref-Fuel operates under the concept that a strong safety culture will act as a catalyst for successful operations on all fronts, the company has enjoyed continuing success in many areas. As a result, American Ref-Fuel has come to lead the Waste-to-Energy business in many categories, including the development of industry standard safety programs and statistics, protection of the environment, tons processed, and profitability, both on an individual and cumulative basis.

Collaboration and Teamwork

From the beginning, American Ref-Fuel management clearly understood that the managerial practices of the past would not provide the framework necessary to succeed in today's business environment. Because of thought processes much like the ones which led to OSHA's realization concerning how to best gain regulatory compliance, American Ref-Fuel early in its existence established a relationship with its employees where cooperation, empowerment and trust were held in highest regard. When American Ref-Fuel was first introduced to the VPP in 1993 by the local New York OSHA office area

administrator, it seemed a natural step for the company to pursue participation in the program. American Ref-Fuels core values were about to be put to the test.

VPP PREPARATION

The Self Assessment Process

Once a mutual decision by management and the employees to pursue acceptance into the VPP was made, the process of self assessment commenced. Conducting this part of the process was critical to the desired outcome in that the results would dictate the future course of action. First, the assessment would provide an objective account of the degree to which the safety and health policies outlined in the various company documents were being practiced. Secondly, it would illustrate the resources required to meet the standards of the company if the assessment process showed a disconnect between stated and practiced policy. Finally, the assessment would be used as the primary indicator for the decision whether or not to continue with the process by submitting the application to OSHA and the subsequent scheduling of the on-site review.

The following is the list of areas in which the OSHA evaluation team was interested in reviewing, and around which the self assessment audits were designed and conducted by American Ref-Fuel employees.

- Management Commitment
- Employee Involvement
- Worksite Hazard Analysis
- Hazard Correction and Control
- Training

The process used by American Ref-Fuel to accomplish the self assessments consisted of the following elements:

- Review the applicable chapters of the facility Safety Manuals as well as other related documentation to ensure an understanding of all associated requirements. Update the assessment guidelines with any new requirements as found during the review.
- Conduct random spot interviews with employees to determine whether the standards set are understood and being practiced in the field.
- Conduct physical inspections of the facility to determine if standards are being met. This should include observations specific to the standard being reviewed i.e., lockout/tagout and confined space entry evolutions.
- Document all findings, enter action items into an assessment action item database.

This process proved to be an invaluable experience for each of the facilities undertaking the process. What became readily apparent to management and employees alike was the degree to which this activity furthered the cause of safety and health within each facility. This employee led program review produced valuable recommendations on how to make a good program “Star” quality, and generated the

employee enthusiasm and commitment necessary to produce positive results. This is considered as one of the major benefits of involvement in the VPP, as the employee led objective review has improved the safety process as well as formed cooperative bonds within the organization. The following is a short list of improvements made to our safety management systems as a result of VPP and the continuing self-assessment process:

- Improved Hazard Recognition Processes
- Better Tracking Systems and Completion Rates for Action Items
- Improved Incident Reporting
- Increased Levels of Knowledge and Retention Due to Improved Training
- Increased Employee/Management Communications

These improvements and many others were made because the VPP process forced the site to look openly and objectively at its safety and health program. The act of self assessment empowered the employees to create an atmosphere where excellence was expected, and this expectation was bought into and backed by facility management. This idea is probably the most important and self-sustaining benefit achieved.

The VPP Application Process

Coincident with the self assessment process, the employees commenced work on the VPP application. OSHA provided the employee group with the "VPP Application Guidelines" which outlined the application requirements. Aside from the statistical and identification information, the finished application was compiled by mostly using information gathered during the self assessment process, as these categories are common. Table 1 illustrates the requested information categories and what documentary information was included to demonstrate adherence to the VPP standard.

The application was approved by OSHA, and the pre-approval onsite review was scheduled.

VPP Pre-approval Onsite Review

The purpose of the on site review was for the OSHA team to conduct a thorough review concerning the site's management of its safety and health program. There are basically four objectives for the which the review was designed to address:

- Verification- was the information concerning the safety and health program at this site consistent with information supplied in the application.
- Audit- to determine the strengths and weaknesses of the sites current program
- Quality- determine if the program provided sufficient protection from real and potential site hazards
- Recommendation- provided information to the Assistant Secretary of Labor to assist in the final decision

The agenda for the OSHA team followed this outline:

- Opening Conference- this meeting was attended by management, employees, and the OSHA VPP team. It's purpose was to set the tone for the onsite review process, to let the site know what to expect from the team, and to inform the site of what assistance would be needed. The four objectives of the review team were discussed along with proper protocol for the interviews.
- Document Review- this was accomplished in order to verify the information submitted in the application. For each of the line items illustrated in Table 1, supportive documentation was made available to the review team.
- Plant Walkthrough- The purpose of the walkthrough was for the evaluation team to assess the viability of the site's program through visual observation. Any discrepancies found were attended to immediately, and the status of their resolution was reviewed at each days closing meeting.
- Employee Interviews- Interviews were held with management, employee, and contract personnel. The interviews were conducted either one-on-one privately, or out in the field while the employee was in the execution of the job function. The questions surrounded the common themes of employee awareness to job hazards, management's correction and control of hazards at the site, and the proper levels of training which keep the employees safe. Another common theme addressed by the team was that of identified hazards being part of a management process which tracked the hazard from identification through final abatement.
- Closing Conference- This meeting occurred at the conclusion of the on site review. The facility was presented with the review teams findings and a recommendation for program participation which would be sent to the Assistant Secretary of Labor for the final decision. We were also presented with a list of items which were required to be completed in ninety days.

The following are examples of the review teams positive findings:

- Found the training programs to be well planned and executed, exceeding the minimum requirements
- Was impressed by the Performance Development System
- Liked the idea of technicians performing Safety Observations on other technicians
- Found the safety bonus system geared towards rewarding performance
- Rated the Industrial Hygiene Program as excellent

The following are examples of recommendations for improvement:

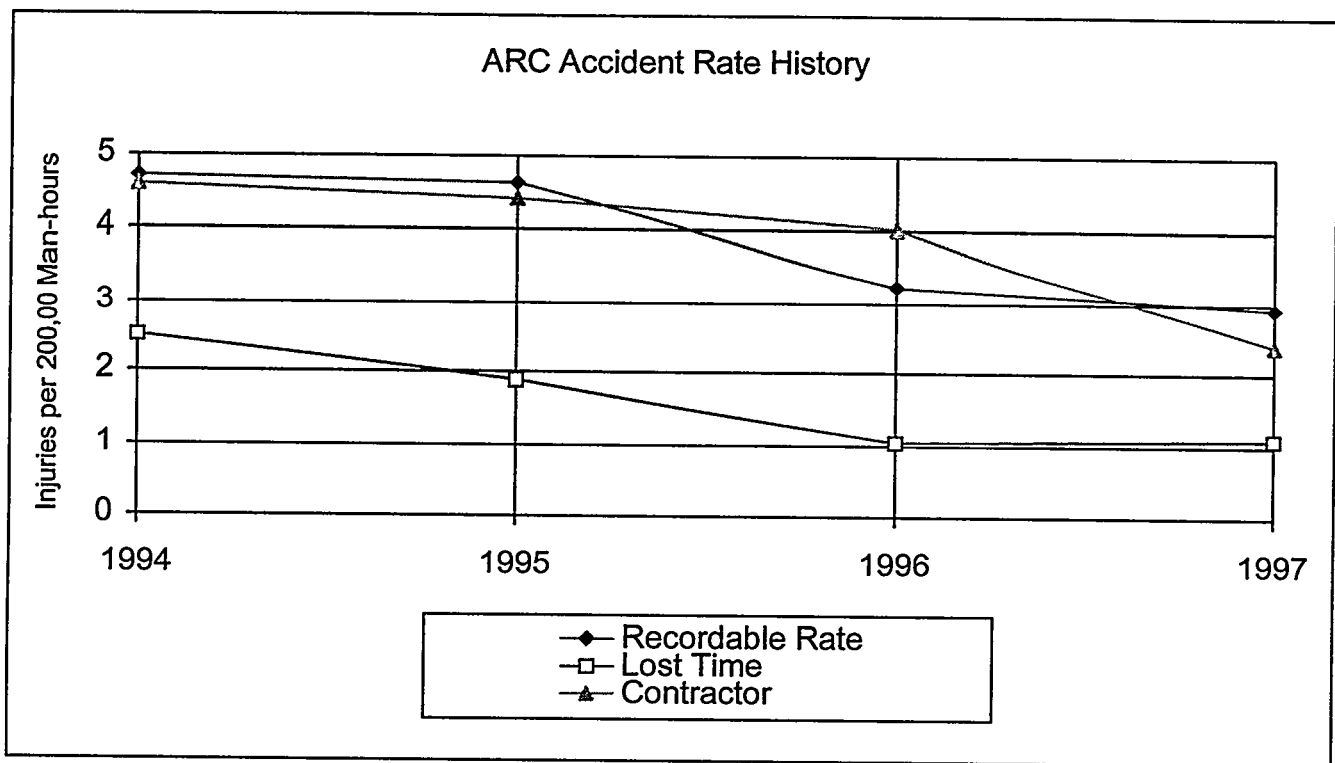
- Perform the annual self-assessments using an integrated team approach
- Ensure persons wearing dust-masks for protection against nuisance dust are clean shaven to assure proper seal
- Ensure personnel understand labeling requirements for chemicals under their control
- For an often used Contractor whose workforce is predominantly Spanish, provide training on a bi-lingual level, and hire a bilingual trainer/supervisor

The American Ref-Fuel Hempstead Facility was awarded the "Star" designation based upon the recommendation of the review team to the Assistant Secretary of Labor. Through the review process, the Hempstead team continually demonstrated by the proper implementation of a well defined safety and health program the kind of commitment necessary to reach its goal of program acceptance at the "Star" level.

Conclusions

The cooperative programs administered by OSHA have inherent benefits. By participating in this process, we have experienced many of them, some obvious in nature and others somewhat subtle.

- **Employee Participation in the Safety Process-** management has made the statement that they are committed to an effective safety and health program and turned the reigns over to the employees. Cooperation is an essential element as management realized that the workers are the closest to the hazards and that once empowered are better suited for effecting the abatement process. One obvious outcome of this experience was that for a safety and health program to be truly effective, the process must be driven by the employees.
- **Self Assessment Process-** the objective review conducted to gain participation in the program continues throughout each year, producing an accurate indicator of current conditions. This assessment is also used to measure continuing progress and as a guideline for resource allocation.
- **Definite Statistical Improvement-** Lower incident and compensation rates.



- **Increased Productivity-** No longer are we focusing on accident investigation, but accident prevention. This frees much time for involvement in value added activities.
- **Incident Severity and Rate-** the occurrence rate and associated severity levels of incidents has been reduced. Employee participation in the safety process is a key element.
- **Cooperative Relationship with OSHA-** It is a great resource to have access to the Cooperative Programs staff within OSHA as there have been instances where benefit has been attained through contact and problem resolution.

- Networking- through the Voluntary Protection Programs Participants Association (VPPPA) Regional and National Conventions, we have been able to share and benchmark with other companies in the program.
- Recognition- In the community and among industry, membership in the VPP means that you are recognized as a leader in safety and health.

The success experienced at the Hempstead facility was soon to be mirrored by the three additional plants making up the American Ref-Fuel fold at that time. As the company has grown, the process of maintaining VPP has proven to be a key element in maintaining one safety and health culture. VPP has helped each of the facilities to maintain its focus on the safety process and to reinforce the reasons why acceptance into the VPP program for all ARC facilities was made a corporate goal- it fits well within the culture of the company, it is aligned with our core values, and it empowers the employees. The end result is a cooperative effort between management, labor, and OSHA which helps each of us to attain the common goal of protecting the American worker. We feel the program works and will continue to work in its spirit.

Table 1. VPP Application Requirements

Heading	Supporting Documentation
1.0 General Information	
1.1 Company Name and Representatives	Provided Names of Company, Plant Manager, Site VPP Representative, and Site Safety Supervisor
1.2 Corporate Name and Representatives	
1.3 Description of Work Performed	
1.4 Company Data	Number of Employees, Union Status, Nested Contractor Information, and SIC Code Injury Statistics for Current and Past 2 Years
1.5 Injury Rates	
2.0 Management Commitment and Planning	
2.1 Commitment	Provided Management Statement
2.2. Organization	Provided Organizational Chart and Job Descriptions
2.3 Responsibility	Provided Management Statement
2.4 Accountability	Provided Management Statement
2.5 Resources	Described Safety and Health Budget
2.6 Planning	Described Safety and Planning Integration
2.7 Contractor Workers	Described Contractor Safety Policy
2.8 Employee Notification	How VPP was Presented to the Employment
2.9 Site Plan	Included Current Site Plan
3.0 Worksite Analysis	
3.1 Pre-Use Analysis	Described FCN and Hazard Analysis Process
3.2 Comprehensive Surveys	Air Quality, Noise, Heat, etc.
3.3. Safety and Industrial Hygiene Inspections	Safety Permit System, Safety Observations, Safety Equipment Inspections, Fire Protection, etc.

Table 1. Continued

Heading	Supporting Documentation
3.4 Job Hazard Analysis	Described the JHA Process
3.5 Employee Notification of Hazards	Near Miss/Safety Suggestion Program
3.6 Accident Investigation	Described Accident Investigation Procedures
3.7 Medical Program	Described the Companies Medical Program
4.0 Hazard Prevention and Control	
4.1 Professional Expertise	Staff Safety Professionals, Certifications
4.2 Safety and Health Rules	Described the Formal Discipline Program
4.3 Personal Protective Equipment	List Standard PPE for Plant Operations
4.4 Emergency Preparedness	Contingency Plan Table of Contents
4.5 Preventive Maintenance	Provided Descriptive Statement
5.0 Safety and Health Training	
5.1 Employee Orientation	Provided Orientation Cover Sheet
5.2 On the Job Training	Provided Job Training Instructions
5.3 Offsite Training	Described Vendor Supplied Training
5.4 Plant Drills	Described the Facility Drill Process
6.0 Employee Involvement	
6.1 Employee Participation	Included Safety Bonus Information
6.2 Safety Committee	Describe Charter, Listed Members
7.0 Program Evaluation	Offered Complete Set For Review During On Site Assessment

Accidental Release Prevention Requirements: Risk Management Programs Under Clean Air
Act Section 112(r)(7)

Jeffrey Hahn, P.E., D.E.E., Q.E.P.
Executive Vice President, Ogden Energy Group
Past Chairman, Health & Safety Committee
Integrated Waste Services Association
40 Lane Road
Fairfield, New Jersey 07007

INTRODUCTION

The Occupational Safety and Health Administration promulgates and enforces regulations that govern the health and safety of our workers. OSHA rules often are considered to govern what happens "inside the fence line," or within the physical boundaries of the facility.

In some ways, the U.S. Environmental Protection Agency takes over where OSHA leaves off. The U.S. EPA is responsible for environmental programs "outside the fence line." The concept is as simple as drawing a line, or is it?

Anyone developing and implementing compliance programs, whether for OSHA or EPA, will tell you nothing is that simple. EPA's recent promulgation of rules pertaining to risk management programs is a case in point.

A new EPA rule is intended to compliment OSHA requirements under the Process Safety Management (PSM) rule. Under the OSHA rule, plant operators developed programs that ensure safe measures are in use when handling certain chemicals. During the past three years, waste-to-energy facilities faced difficult decisions when complying with the PSM requirements.

Plant operators developed programs in particular for the continued use of anhydrous ammonia and chlorine. Anhydrous ammonia is used as part of the Thermal DeNOx systems that clean flue gasses of nitrogen oxides. Some plant operators, after completing the PSM requirements, switched from chlorine because of the added regulatory burden placed on the regulated community by PSM in handling this chemical and the ready availability of substitute chemicals.

Earlier this year, the U.S. EPA promulgated its 112 (r) (7) rule that is intended to "compliment" OSHA's PSM requirements. This is not always the case. Unfortunately, these new Clean Air Act requirements do not always complement, but may instead confuse plant operators. For example, EPA's 112 (r) rule may force plant operators to change, once again, their decisions on the use of selected chemicals.

The U.S. EPA estimates that approximately 66,000 facilities, including the 114 waste-to-energy facilities nationwide, may be affected by the list and risk management planning rules. The facilities include chemical and many other manufacturers, cold storage facilities with ammonia refrigeration systems, public water treatment systems, wholesalers and distributors of these chemicals, propane retailers, utilities, and federal facilities.

REQUIREMENTS OF 112(r)

Section 112(r) of the Clean Air Act calls for regulations that prevent the accidental release of listed chemicals and further minimize the consequences of any such release. The owners and operators of stationary sources producing, processing, handling, or storing such substances have a general duty to identify hazards which may result from such releases using appropriate hazard assessment techniques, to design and maintain a safe facility taking such steps as necessary to prevent releases and to minimize the consequences of accidental releases which do occur.

The U.S. EPA provided a list of substances which, according to the Agency, are known to cause or may reasonably be anticipated to cause death, injury, or serious adverse effects to human health or the environment. The list is amended to this paper. In compiling the list, the U.S. EPA considered the severity of any acute adverse health effect, the likelihood of accidental release, and the potential magnitude of human exposure to the accidental releases of the substances. The list also includes a threshold quantity for the substance. In establishing the threshold quantity, the U.S. EPA considered the volatility, dispersibility, combustibility, and flammability of the substance and the amount of the substance which, as a result of an accidental release, is known to cause or may reasonably be anticipated to cause death, injury or serious adverse effects to human health.

The list EPA promulgated includes 77 acutely toxic chemicals, 63 flammable gases and volatile flammable liquids, and Division 1.1 high explosive substances. The final rule established threshold quantities for toxic substances ranging from 500 to 20,000 pounds. For all listed flammable substances, the threshold quantity is 10,000 pounds, while all explosive substances have a threshold quantity of 5,000 pounds.

REQUIREMENTS OF 112(r)(7)

Section 112(r)(7) requires the U.S. EPA to promulgate release prevention, detection, and correction requirements including monitoring, recordkeeping, reporting, training, vapor recovery, secondary containment, and other design, equipment, work practice, and operational requirements. The regulations make distinctions between various types, classes, and kinds of facilities, devices and systems by taking into account the size, location, process, process controls, quantity of substances handled, potency of substances, and response capabilities present at any stationary source.

The regulations require an owner or operator of a facility to detail the use, operation, repair, replacement, and maintenance of equipment and periodic inspections at a facility. Regulations also require an owner or operator to provide procedures and measures for emergency response after an accidental release of a regulated substance in order to protect human health and the environment.

The regulations requires owners and operators of stationary sources to carry out the following six elements of risk management planning:

- (1) An offsite consequence analysis that evaluates specific potential release scenarios, including worst-case and alternative scenarios;
 - (2) A five-year history of certain accidental releases of regulated substances from covered processes;
 - (3) An integrated prevention program to manage risk;
 - (4) An emergency response program;
 - (5) An overall management system to supervise the implementation of these program elements;
- and,

(6) A Risk Management Program, revised at least once every five years, that summarizes and documents the above activities for all covered processes.

The Risk Management Program is intended to detect and prevent or minimize accidental releases of a stationary source and to provide a prompt emergency response to any release. The Program consists of numerous requirements that need to be completed by plant operators within three years. First, plant operators need to provide a hazard assessment to assess the potential effects of an accidental release of any regulated substance. This assessment includes an estimate of potential release quantities and a determination of downwind effects, including potential exposures to affected populations. Such assessment includes previous release history of the past five years, including the size, concentration, and duration of releases, and shall include an evaluation of worst case accidental releases.

Second, the Risk Management Program includes a program for preventing accidental release of regulated substances, including safety precautions and maintenance, monitoring, and employee training measures to be used at the source.

Third, a response program must be included that provides for specific actions that will be taken in response to an accidental release of a regulated substance so as to protect human health and the environment. The response program need include procedures for informing the public and local agencies responsible for responding to accidental releases, emergency health care, and employee training.

Several waste-to-energy facilities currently are conducting the analysis necessary to prepare the Risk Management Program. Waste-to-energy facility operators are looking in particular at the impact from the use of ammonia and propane.

After preparation of the Risk Management Program, an owner or operator must register the plan with the U.S. EPA. The Program also is submitted to the Chemical Safety and Hazard Investigation Board, to the State in which the stationary source is located, and to any local agency or entity having responsibility for planning or responding to accidental releases. In addition, the Program must be available to the public.

The U.S. EPA regulations will have added meaning for waste-to-energy facilities as MACT regulations are implemented and the use of either anhydrous or aqueous ammonia, or urea is selected for DeNOx systems.

The U.S. EPA currently is working to develop a reporting mechanism and form to collect the information required by stationary sources under this rule and make the risk management programs available to the general public via "electronic transmission." The detailed information required, potentially complex information to be transmitted, coupled with the wide distribution anticipated make the 112(r) rule an extremely important requirement for the waste-to-energy industry.

**Alphabetical Listing of Toxic Substances and Threshold Quantities (TQ)
for Accidental Release Prevention (OSHA vs. EPA)**

CAS No.	Chemical Name	OSHA PSM TQ (lbs) (from 29 CFR 1910.119 Appendix A)	EPA RMP TQ (lbs) (from Table 1 of 40 CFR 68.130)
75-07-0	Acetaldehyde	2500	
107-02-8	Acrolein (2-Propenal)	150	5000
107-13-1	Acrylonitrile		20,000
814-68-6	Acrylyl chloride	250	5000
Varies	Alkylaluminums	5000	
107-18-6	Allyl alcohol		15,000
107-05-1	Allyl chloride	1000	
107-11-9	Allylamine	1000	10,000
7664-41-7	Ammonia (anhydrous)*	10,000	10,000
7664-41-7	Ammonia (aqueous solution)*	15,000 (> 44 % concentration)	20,000 (≥ 20 % concentration)
7790-98-9	Ammonium perchlorate	7500	
7787-36-2	Ammonium permanganate	7500	
7784-34-1	Arsenous trichloride		15,000
7784-42-1	Arsine (arsenic hydride)	100	1000
542-88-1	Bis (chloromethyl) ether or Chloromethyl ether	100	1000
10294-34-5	Boron trichloride	2500	5000
7637-07-2	Boron trifluoride	250	5000
353-42-4	Boron trifluoride compound with methyl ether (1:1)		15,000
7726-95-6	Bromine*	1500	10,000
13863-41-7	Bromine chloride	1500	
7789-30-2	Bromine pentafluoride	2500	
7787-71-5	Bromine trifluoride	15,000	
75-91-2	Buryl hydroperoxide (tertiary)	5000	
614-45-9	Buryl perbenzoate (tertiary)	7500	
75-15-0	Carbon disulfide		20,000
353-50-4	Carbonyl fluoride	2500	

*Required to be on EPA's list by the 1990 Clean Air Act Amendments.

**Alphabetical Listing of Toxic Substances and Threshold Quantities (TQ)
for Accidental Release Prevention (OSHA vs. EPA)**

CAS No.	Chemical Name	OSHA PSM TQ (lbs) (from 29 CFR 1910.119 Appendix A)	EPA RMP TQ (lbs) (from Table 1 of 40 CFR 68.130)
9004-70-0	Cellulose nitrate (concentration > 12.6% nitrogen)	2500	
7782-50-5	Chlorine*	1500	2500
10049-04-4	Chlorine dioxide	1000	1000
13637-63-3	Chlorine pentafluoride	1000	
7790-91-2	Chlorine trifluoride	1000	
97-00-7	1-Chloro-2,4-dinitrobenzene	5000	
96-10-6	Chlorodiethylaluminum (diethylaluminum chloride)	5000	
67-66-3	Chloroform		20,000
107-30-2	Chloromethyl methyl ether	500	5000
76-06-2	Chloropicrin	500	
None	Chloropicrin and methyl bromide mixture	1500	
None	Chloropicrin and methyl chloride mixture	1500	
123-73-9	Crotonaldehyde (trans-2- butenal)		20,000
4170-30-3	Crotonaldehyde		20,000
80-15-9	Cumene hydroperoxide	5000	
460-19-5	Cyanogen	2500	
506-77-4	Cyanogen chloride	500	10,000
675-14-9	Cyanuric fluoride	100	
108-91-8	Cyclohexylamine		15,000
110-22-5	Diacetyl peroxide (concentration > 70%)	5000	
334-88-3	Diazomethane	500	
94-36-0	Dibenzoyl peroxide	7500	
19287-45-7	Diborane	100	2500

*Required to be on EPA's list by the 1990 Clean Air Act Amendments.

**Alphabetical Listing of Toxic Substances and Threshold Quantities (TQ)
for Accidental Release Prevention (OSHA vs. EPA)**

CAS No.	Chemical Name	OSHA PSM TQ (lbs) (from 29 CFR 1910.119 Appendix A)	EPA RMP TQ (lbs) (from Table 1 of 40 CFR 68.130)
110-05-4	Dibutyl peroxide (tertiary)	5000	
7572-29-4	Dichloro acetylene	250	
4109-96-0	Dichlorosilane	2500	
557-20-0	Diethylzinc	10,000	
105-64-6	Diisopropyl peroxydicarbonate	7500	
105-74-8	Dilauroyl peroxide	7500	
124-40-3	Dimethylamine (anhydrous)	2500	
75-78-5	Dimethyldichlorosilane	1000	5000
57-14-7	1,1-Dimethylhydrazine	1000	15,000
97-02-9	2,4-Dinitroaniline	5000	
106-89-8	Epichlorohydrin		20,000
1338-23-4	Ethyl methyl ketone peroxide (methyl ethyl ketone peroxide; concentration > 60%)	5000	
109-95-5	Ethyl nitrite	5000	
75-04-7	Ethylamine	7500	
371-62-0	Ethylene fluorohydrin	100	
75-21-8	Ethylene oxide*	5000	10,000
107-15-3	Ethylenediamine		20,000
151-56-4	Ethyleneimine	1000	10,000
7782-41-4	Fluorine	1000	1000
50-00-0	Formaldehyde (formalin)	1000 (≥37% concentration based on a PSM interpretation letter dated 7/28/92)	15,000 (solution; no concentration given)
110-00-9	Furan	500	5000
684-16-2	Hexafluoroacetone	5000	
302-01-2	Hydrazine		15,000

*Required to be on EPA's list by the 1990 Clean Air Act Amendments.

**Alphabetical Listing of Toxic Substances and Threshold Quantities (TQ)
for Accidental Release Prevention (OSHA vs. EPA)**

CAS No.	Chemical Name	OSHA PSM TQ (lbs) (from 29 CFR 1910.119 Appendix A)	EPA RMP TQ (lbs) (from Table 1 of 40 CFR 68.130)
7647-01-0	Hydrochloric acid (solution, concentration $\geq 30\%$)		15,000
74-90-8	Hydrocyanic acid (hydrogen cyanide, anhydrous)*	1000	2500
10035-10-6	Hydrogen bromide	5000	
7647-01-0	Hydrogen chloride (hydrochloric acid, anhydrous)*	5000	5000
7664-39-3	Hydrogen fluoride (hydrofluoric acid, anhydrous)*	1000	1000 ($\geq 50\%$ concentration)
7722-84-1	Hydrogen peroxide (concentration $\geq 52\%$)	7500	
7783-07-5	Hydrogen selenide	150	500
7783-06-4	Hydrogen sulfide*	1500	10,000
7803-49-8	Hydroxylamine	2500	
78-82-0	Isobutyronitrile		20,000
108-23-6	Isopropyl chloroformate		15,000
75-31-0	Isopropylamine	5000	
463-51-4	Ketene	100	
78-85-3	Methacrylaldehyde	1000	
126-98-7	Methacrylonitrile (methyl acrylonitrile)	250	10,000
920-46-7	Methacryloyl chloride	150	
30674-80-7	Methacryloyloxyethyl isocyanate	100	
74-83-9	Methyl bromide	2500	
74-87-3	Methyl chloride*	15,000	10,000
79-22-1	Methyl chloroformate	500	5000
453-18-9	Methyl fluoroacetate	100	
421-20-5	Methyl fluorosulfate	100	

*Required to be on EPA's list by the 1990 Clean Air Act Amendments.

**Alphabetical Listing of Toxic Substances and Threshold Quantities (TQ)
for Accidental Release Prevention (OSHA vs. EPA)**

CAS No.	Chemical Name	OSHA PSM TQ (lbs) (from 29 CFR 1910.119 Appendix A)	EPA RMP TQ (lbs) (from Table 1 of 40 CFR 68.130)
60-34-4	Methyl hydrazine	100	15,000
74-88-4	Methyl iodide	7500	
624-83-9	Methyl isocyanate*	250	10,000
74-93-1	Methyl mercaptan*	5000	10,000
556-64-9	Methyl thiocyanate		20,000
79-84-4	Methyl vinyl ketone	100	
74-89-5	Methylamine (anhydrous)	1000	
75-79-6	Methyltrichlorosilane	500	5000
13463-39-3	Nickel carbonyl (nickel tetracarbonyl)	150	1000
7697-37-2	Nitric acid	500 (≥ 94.5% concentration)	15,000 (≥ 80% concentration)
10102-43-9	Nitric oxide	250	10,000
100-01-6	Nitroaniline (paranitroaniline)	5000	
10102-44-0	Nitrogen oxides (NO; NO ₂ ; N ₂ O ₄ ; N ₂ O ₃)	250	
10544-72-6	Nitrogen tetroxide (nitrogen peroxide)	250	
7783-54-2	Nitrogen trifluoride	5000	
10544-73-7	Nitrogen trioxide	250	
75-52-5	Nitromethane	2500	
8014-95-7	Oleum (fuming sulfuric acid)	1000 (65% to 80% SO ₃ concentration)	10,000 (SO ₃ concentration not specified)
20816-12-0	Osmium tetroxide	100	
7783-41-7	Oxygen difluoride (fluorine monoxide)	100	
10028-15-6	Ozone	100	
19624-22-7	Pentaborane	100	
13463-40-6	Pentacarbonyl-iron	250	2500

*Required to be on EPA's list by the 1990 Clean Air Act Amendments.

**Alphabetical Listing of Toxic Substances and Threshold Quantities (TQ)
for Accidental Release Prevention (OSHA vs. EPA)**

CAS No.	Chemical Name	OSHA PSM TQ (lbs) (from 29 CFR 1910.119 Appendix A).	EPA RMP TQ (lbs) (from Table 1 of 40 CFR 68.130)
79-21-0	Peracetic acid	1000 (> 60% concentration of acetic acid; peroxyacetic acid)	10,000
7601-90-3	Perchloric acid (concentration > 60% by weight)	5000	
594-42-3	Perchloromethyl mercaptan	150	10,000
7616-94-6	Perchloryl fluoride	5000	
75-44-5	Phosgene (carbonic chloride; carbonyl chloride)*	100	500
7803-51-2	Phosphine (hydrogen phosphide)	100	5000
10025-87-3	Phosphorus oxychloride (phosphoryl chloride)	1000	5000
7719-12-2	Phosphorus trichloride	1000	15,000
110-89-4	Piperidine		15,000
106-96-7	Propargyl bromide (3-bromopropyne)	100	
107-12-0	Propionitrile		10,000
109-61-5	Propyl chloroformate		15,000
627-3-4	Propyl nitrate	2500	
75-55-8	Propyleneimine		10,000
75-56-9	Propylene oxide		10,000
107-44-8	Sarin	100	
7783-79-1	Selenium hexafluoride	1000	
7803-52-3	Stibine (antimony hydride)	500	
7446-09-5	Sulfur dioxide*	1000 (liquid)	5000
5714-22-7	Sulfur pentafluoride	250	
7783-60-0	Sulfur tetrafluoride	250	2500
7446-11-9	Sulfur trioxide (sulfur anhydride)*	1000	10,000
7783-80-4	Tellurium hexafluoride	250	

*Required to be on EPA's list by the 1990 Clean Air Act Amendments.

**Alphabetical Listing of Toxic Substances and Threshold Quantities (TQ)
for Accidental Release Prevention (OSHA vs. EPA)**

CAS No.	Chemical Name	OSHA PSM TQ (lbs) (from 29 CFR 1910.119 Appendix A)	EPA RMP TQ (lbs) (from Table 1 of 40 CFR 68.130)
116-14-3	Tetrafluoroethylene	5000	
10036-47-2	Tetrafluorohydrazine	5000	
75-74-1	Tetramethyl lead	1000	10,000
509-14-8	Tetranitromethane		10,000
7719-09-7	Thionyl chloride	250	
7550-45-0	Titanium tetrachloride		2500
26471-62-5	Toluene diisocyanate (mixed isomers)*		10,000
584-84-9	Toluene 2,4-diisocyanate*		10,000
91-08-7	Toluene 2,6-diisocyanate*		10,000
1558-25-4	Trichloro (chloromethyl) silane	100	
27137-85-5	Trichloro (dichlorophenyl) silane	2500	
10025-78-2	Trichlorosilane	5000	
79-38-9	Trifluorochloroethylene	10,000	
75-77-4	Trimethylchlorosilane		10,000
2487-90-3	Trimethyoxysilane	1500	
108-05-4	Vinyl acetate monomer		15,000

*Required to be on EPA's list by the 1990 Clean Air Act Amendments.

**Alphabetical Listing of Regulated Flammable Substances
for Accidental Release Prevention (from Table 3 of 40 CFR 68.130)**

CAS No.	Chemical Name	CAS No.	Chemical Name
75-07-0	Acetaldehyde†	78-79-5	Isoprene
74-86-2	Acetylene	75-31-0	Isopropylamine†
598-73-2	Bromotrifluoroethylene	75-29-6	Isopropyl chloride
106-99-0	1,3-Butadiene	74-82-8	Methane
106-97-8	Butane	74-89-5	Methylamine†
106-98-9	1-Butene	563-46-2	2-Methyl-1-butene
107-01-7	2-Butene	563-45-1	3-Methyl-1-butene
25167-67-3	Butene	115-10-6	Methyl ether
590-18-1	2-Butene-cis	107-31-3	Methyl formate
624-64-6	2-Butene-trans	115-11-7	2-Methylpropene
463-58-1	Carbon oxysulfide	504-60-9	1,3-Pentadiene
7791-21-1	Chlorine monoxide	109-66-0	Pentane
557-98-2	2-Chloropropylene	109-67-1	1-Pentene
590-21-6	1-Chloropropylene	646-04-8	2-Pentene, (E)-
460-19-5	Cyanogen†	627-20-3	2-Pentene, (Z)-
75-19-4	Cyclopropane	463-49-0	Propadiene
4109-96-0	Dichlorosilane†	74-98-6	Propane
75-37-6	Difluoroethane	115-07-1	Propylene
124-40-3	Dimethylamine†	74-99-7	Propyne
463-82-1	2,2-Dimethylpropane	7803-62-5	Silane
74-84-0	Ethane	116-14-3	Tetrafluoroethylene†
107-00-6	Ethyl acetylene	75-76-3	Tetramethylsilane
75-04-7	Ethylamine†	10025-78-2	Trichlorosilane†
75-00-3	Ethyl chloride	79-38-9	Trifluorochloroethylene†
74-85-1	Ethylene	75-50-3	Trimethylamine
60-29-7	Ethyl ether	689-97-4	Vinyl acetylene
75-08-1	Ethyl mercaptan	75-01-4	Vinyl chloride*
109-95-5	Ethyl nitrite†	109-92-2	Vinyl ethyl ether
1333-74-0	Hydrogen	75-02-5	Vinyl fluoride
75-28-5	Isobutane	75-35-4	Vinylidene chloride
78-78-4	Isopentane	75-38-7	Vinylidene fluoride
		107-25-5	Vinyl methyl ether

NOTE: All EPA flammable liquids and gases have a common TQ of 10,000 lbs. Materials marked with a dagger (†) are also in Appendix A of toxic and reactive materials under OSHA's PSM rule (29 CFR 1910.119) with TQs less than or equal to 10,000 lbs. Materials marked with an asterisk (*) are required to be on EPA's list by the 1990 Clean Air Act Amendments.

Summary of Coverage Differences Between EPA's RMP Rule and OSHA's PSM Regulation

Chemical Name	OSHA Limits		EPA Limits	
	Threshold Concentration	Threshold Quantity (lb)	Threshold Concentration	Threshold Quantity (lb)
SUBSTANCES ADDED BY EPA				
Arsenous trichloride				15,000
Boron trifluoride with methyl ether				15,000
Chloroform				20,000
Hydrazine				15,000
Isopropyl chloroformate				15,000
Methyl thiocyanate				20,000
Tetranitromethane				10,000
Titanium tetrachloride				2,500
Toluene diisocyanate				10,000
SUBSTANCES WITH LOWER EPA THRESHOLD QUANTITY				
Methyl chloride		15,000		10,000
SUBSTANCES WITH LOWER EPA CONCENTRATION LIMIT				
Ammonia, aqueous	44%	15,000	20%	20,000
Formaldehyde	37%	1,000	none given	15,000
Hydrogen chloride	anhydrous	5,000	30%	15,000
Hydrogen fluoride	anhydrous	1,000	50%	1,000
Nitric acid	94.5%	500	80%	15,000
Oleum	65%	1,000	none given	10,000
EPA's rule for toxic and flammable mixtures not having a specified lower concentration limit will likely cause more process areas to be covered than under OSHA's PSM regulation				
OSHA EXEMPTIONS NOT CURRENTLY ALLOWED BY EPA				
Atmospheric storage and transfer of flammable liquids (ASTFL)	Flammable gas or liquids used solely as hydrocarbon fuels in the workplace	Retail facility	Normally unoccupied remote facility	Oil and gas well drilling or servicing

The Impact Of OSHA Upon Waste-To-Energy Employers

Stephen C. Yohay
McDermott, Will & Emery
1850 K Street, NW
Washington, D.C. 20006

This paper is prepared for those who are not OSHA specialists. The objective is to provide a broad overview of the requirements and enforcement of the Occupational Safety and Health Act as it applies to waste-to-energy employers.

WHO ARE THE SAFETY AND HEALTH REGULATORS?

The federal Occupational Safety and Health Act ("the Act")¹ governs occupational safety and health among private employers in states subject to federal jurisdiction. This includes private employers who operate facilities under agreements with state or local government agencies.

OSHA addresses only safety and health in employment. It does not regulate public safety.

Twenty-six states have obtained OSHA's approval of their state's plan for the enforcement of safety and health regulation.² In those states, private and some public employers are subject to state-administered safety and health programs.

In states subject to federal jurisdiction, the Act is enforced by the United States Department of Labor ("DOL"), through its Occupational Safety and Health Administration ("OSHA"). When employers challenge (or "contest") citations issued by OSHA, the cases are adjudicated by the Occupational Safety and Health Review Commission ("OSHRC"), an independent federal agency which is not part of DOL. OSHRC consists of three Commissioners appointed by the President with the advice and consent of the United States Senate. OSHRC delegates to Administrative Law Judges ("ALJ's") the task of conducting trials on contests of OSHA citations.

In state plans, each state has its own mechanism for enforcing safety and health standards, and for adjudicating citation contests.

WHAT ARE AN EMPLOYER'S OBLIGATIONS UNDER OSHA?

Employers have two main obligations under OSHA. First, they must comply with specific regulations, called standards, which OSHA issues. Standards address particular workplace hazards. Some are quite specific in their requirements. Others are stated more generally in terms of objectives employers are to achieve; these are called "performance standards."

When Congress passed the Act and created OSHA in 1971, it realized that the agency would not have the time or resources to issue a standard governing every hazard to which employees may be exposed in American industry. Desiring to protect employees nonetheless, Congress included in the Act the so-called "General Duty Clause."³ That provision states:

5(a) Each employer -

- (1) shall furnish to each of this employees employment and a place of employment which are free from recognized hazards that are causing or are likely to cause death or serious physical harm to his employees.

As a practical matter, this section means that employers must protect their employees against hazards that are recognized in the industry as presenting danger. "Recognition" often is established by reference to sources such as national consensus standards (*e.g.*, standards issued by ANSI, ASME, or other similar standards-setting organizations). Thus, waste-to-energy employers should understand that they must keep abreast of developments in the industry as to safety and health, because even though OSHA may not have issued a standard addressing a particular hazard or practice, the employer may be cited for not having taken the precautions to address such a hazard that others in the industry have concluded are prudent.

It is important to understand that there need not be an accident for there to be an OSHA violation. Unlike in other areas of law, such as ordinary negligence, the violation consists of an employer exposing an employee to a prohibited hazard of which the employer knew or should have known. The hazard need not result in an accident for there to be a violation.

STANDARDS OF PARTICULAR CONCERN TO WASTE-TO-ENERGY EMPLOYERS

OSHA has issued so many standards that it would be impossible to include a comprehensive review in this paper. Some of the standards which are of particular interest to waste-to-energy employers are the following:

1) Control of Hazardous Energy Sources, 29 CFR § 1910.147

This standard sets forth detailed requirements for the control of machinery and equipment during operations and maintenance. It is one of the most oft-cited OSHA standards.

2) Permit Entry Confined Spaces, 29 CFR § 1910.146

This standard sets forth requirements for procedures to be followed when entering and working in confined spaces, and when performing rescue within such spaces.

3) Process Safety Management of Highly Hazardous Chemicals 29 CFR § 1910.119

This is one of OSHA's most important recent standards. Where sufficient quantities of those hazardous chemicals listed in the standard are located at a facility, the standard imposes detailed requirements for the development of process hazards analyses, and other procedures, aimed at avoiding catastrophic accidents.

The PSM standard is closely related to a new regulation promulgated by the Environmental Protection Agency under the Clean Air Act, known as the section "112(r)" rule. That rule imposes requirements aimed at avoiding accidental releases of hazardous chemicals.

4) Hazardous Waste Operations and Emergency Response, 29 CFR § 1910.120

This standard specifies precautions to be taken at hazardous waste cleanup sites. It also contains requirements for procedures to be implemented in the event of an emergency at any type of industrial facility. It is closely related to OSHA standards on fire safety.

5) Bloodborne Pathogens, 29 CFR § 1910.1030

This standard specifies procedures to be taken where an employee may be exposed to bloodborne pathogens. It is important in the waste-to-energy industry where employees may be exposed to medical waste, including sharps.

6) Occupational Exposure to Cadmium, 29 CFR § 1910.1027

This standard establishes permissible limits for employee exposure to cadmium, as well as procedures for minimizing and monitoring exposure.

7) Personal protective equipment, 29 CFR § 1910.132-138

These standards include requirements for equipment to protect employees from a variety of hazards, including eye and face, respiratory, head, foot, electrical and hand protection. 29 CFR § 1910.132 includes a requirement that the employer perform an assessment of its workplace to determine what hazards requiring personal protective equipment may be present.

CURRENT ISSUES INVOLVING OSHA

1) Ergonomics

In recent years, OSHA has become concerned with so-called "ergonomic" hazards. In 1992, it began to develop a proposed standard to address these hazards. However, when the Republicans took control of Congress following the 1994 elections, riders to the legislation authorizing OSHA's budget prohibited the agency from developing the standard.

Now, however, there are no legal impediments to OSHA's work on the issue. Accordingly, the agency has resumed work in developing a proposed standard. It is expected to be highly controversial.

One state plan state - California - is nearing final completion of a standard addressing ergonomics.

2) Safety and Health Programs

OSHA has been discussing a possible new, comprehensive standard that would require all employers to develop safety and health programs. Superficially, the concept seems appealing. However, as the details of what OSHA may be contemplating have become known, there is growing concern in industry that OSHA may be preparing to impose a detailed and burdensome new set of requirements upon industry. This issue, too, is expected to be controversial if OSHA determines to move ahead with the development of a proposed standard.

1. 29 U.S.C. § 651, *et seq.*
2. The following states have approved state plans: Alaska, Arizona, California, Hawaii, Indiana, Iowa, Kentucky, Maryland, Michigan, Minnesota, Nevada, New Mexico, North Carolina, Oregon, South Carolina, Tennessee, Utah, Vermont, Virginia, Washington, and Wyoming.
3. Section 5(a)(1) of the Act, 29 U.S.C. § 654(a)(1).

KEY WORDS:

OCCUPATIONAL

HEALTH

SAFETY

OSHA

OSHRC

STANDARDS

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Worker Safety at MRF'S -- Where Are We Going ?

**Nathiel G. Egosi
and
Carmela Bedregal**

**RRT Design & Construction Corp.
125 Baylis Road
Melville, NY 11747**

INTRODUCTION

There is hardly a community in the United States that does not have a material recycling facility to support the area's waste management program. In the past six years, over 500 such facilities have been constructed now employing an estimated work force of over 10,000 persons. The applicability of current OSHA regulations has been a major concern, but lack of data has delayed the implementation of appropriate safety guidelines to address Material Recovery Facilities (MRF's) specifically. Leading MRF designers like RRT, have been directly responsible for advancing the industry's "Best Practices" and have yielded measurable results in quality projects. Unfortunately, many other projects were built without professional engineering guidance. Projects were being developed with different interpretations of OSHA and in many cases without the input of qualified individuals and valid data.

In response and through the efforts of many operators and regulators, new guidelines, recommendations and standards have now been instituted to protect the worker. Designers will now follow a newly established "industry practice": ANSI Z245. However, is this enough? European guidelines are stricter. MRF technology keeps changing. Economic pressures are upon the industry. With these changing forces, where are we going? This paper summarizes present trends and major concerns in order to predict future design and operations requirements. This information will be beneficial to system operators, facility owners, equipment manufacturers and system designers in identifying and correcting safety shortfalls in both new and existing man/machine systems and preparing facilities to meet current OSHA safety regulations and future more stringent safety requirements which are expected to be published by the end of 1997.

HEALTH AND SAFETY RISK ASSESSMENT AT RECYCLING FACILITIES

As concluded by R.F. Weston¹ in "Environmental, Economic and Energy Impacts of Material Recovery Facilities", workers at recycling facilities do not appear to be exposed to health or safety hazards when they follow established safety requirements. Parameters analyzed by R.F. Weston included air contaminants, as dust, silica, metals, CO, Hg Vapor; PCBs and pesticides, airborne and surface samples of bacteria and fungi; noise exposure; physical safety hazards and ergonomic stressors. Based on their health and safety risk level these parameters can be classified in:

- Low Risk Parameters. Common air contaminants were found to be of low health risk. Air concentrations of dust, silica, metals, CO, Hg Vapor; PCBs and pesticides were recorded below applicable regulatory standards and in most instances below the detection limits of the recommended test methods.
- Risk Parameters to be Avoided by Following Safety Programs. Noise exposure and physical safety hazards present in MRF's can be avoided by following established OSHA programs. The operations which exceeded regulated noise exposure levels were the truck unloading activities, trommels, glass crushers and can flatteners. Employee noise exposure can be reduced to accepted levels by following the guidelines indicated in the Hearing Conservation Program. Main safety hazards can be avoided by following the Energy Control Program, the Personnel Protective Equipment Program, the Blood Borne Pathogens Program, etc.
- Parameters Requiring Additional Evaluation. Bacteria and fungi airborne samples as well as ergonomic stressors risk factors were parameters defined as to require additional evaluation because of the rapidly developing knowledge in these areas. In the case of bacteria and fungi, regulatory standards or guidelines have not been established yet. Airborne samples of bacteria and fungi were recorded consistent throughout the facility and were rated at one order of magnitude higher than the

one observed outside the facility. Most of the bacteria and fungi species detected were classified as environmental species, which are commonly found in soil and water. Pathogenic micro-organisms detected were of the opportunistic type i.e. they are most likely to affect hypersensitive people or people with compromised immune systems. Some of the pathogenic micro-organisms detected are capable of causing disease at high concentrations, although there is very little information on the required exposure levels for adverse reactions to happen. The main ergonomic stressor identified by R.F. Weston was the improper sorting station design that caused repetitive or awkward motions. Main factors identified to cause extensive repetitive motions were extremely wide sorting belts, lack of foot stools, excessive belt speed and over feeding of recyclable materials.

THE INDUSTRY RESPONSE

The ANSI Z245 Report : Facilities for the Processing of Commingled Recyclable Materials - Safety Requirements

Safety practices at Material Recovery Facilities are currently regulated by the Occupational Safety and Health Administration (OSHA) under the Code of Federal Regulations 29 CFR 1910² for general industry. The American National Standards Institute (ANSI) Z245³ document is independent of OSHA 29 CFR 1910 and is currently being developed to provide detailed information and voluntary standards regarding safety practices at MRFs to be used by operators, engineers, equipment manufacturers and OSHA inspectors. ANSI documents, while voluntary, are typically used for interpretation by both OSHA inspectors and by the legal profession in the settlement of cases. ANSI is recognized by the Federal Government as a major source of National Consensus Industrial Standards. Additionally, ANSI standards are frequently cited in the OSHA regulations, and thus become part of the National Standard for which industry must comply⁴; examples of this include industrial forklifts, balers and compactors.

The ANSI document strives to address in detail, system safety requirements, and is currently in draft form. The intent is to receive approval by the ANSI Board of Standards Review so it can be published by the end of 1997, whereby ANSI can petition OSHA to "incorporate by reference" the documents in accordance with 1 CFR part 51. The legal effect of incorporation by reference is that the material is treated as if it were published in full in the Federal Register. Regarding compliance with ANSI Z245, existing facilities will have 5 years after the approval date to comply with Sections 5, 6, and 7. Section 8, which concerns training, will be effective 18 months after approval. New facilities placed in operation 18 months after the approved date of the standard will have to comply with the entire standard.

The ANSI Z245 report provides two major benefits to the industry. The first, it establishes a complete, standard worker protection approach by including ergonomic factors, system design parameters and real operation safety needs, which were not considered when following the previous general ANSI guidelines. The second benefit is that it provides the facility operators and owners with a set of total system safety guidelines that their engineers/systems providers need to follow. This, for example, will direct the type of acceptable equipment that can meet minimum safety guidelines. Current practice is to rely on equipment vendors for what is purchased, however many vendors exclude from their scope the responsibility to comply with regulations regarding safety. Furthermore, the expertise for engineering and safety issues is typically not held by manufacturers beyond their own machines and disclaimers.

The document covers four major topics and is divided into eight (8) Sections.

- General information and definitions (Sections 1-3).

- Site requirements (Section 4), reserved for future preparation.
- Mobile equipment, physical plant and processing machinery requirements (Sections 5-7).
- Safety programs and Safety requirements that apply to MRFs (Section 8).

Following are the highlights of the principal standards, Sections 5-8:

Mobile Equipment (Section 5): Mobile equipment is classified into two categories: Collection and Transportation Equipment and Powered Industrial Trucks. Each equipment category should be operated in accordance with its related ANSI standard. The major concerns to ensure the safe use of mobile equipment are:

- The employment of certified drivers and equipment operators by facility owners and users. Truck drivers loading or unloading material at the facility should be trained as required by OSHA standards specified in the Code of Federal Regulations Part 29 Subpart 1910.178.
- The accessibility and control of personnel in traffic areas such as the tipping floor and loading docks.
- The importance of awareness training and supervision by employers.
- The use of personal protective gear that meets specified ANSI standards.
- The fabrication and use of mobile equipment that meets specified technical requirements.
- The adequate maintenance and periodical inspections by service providers and employers.
- The report of safety related conditions by employees.

An example of a specific requirement for a piece of mobile equipment, used in or around the facility, is a backup alarm capable of emitting a warning signal 10 dBA above ambient noise level (ANSI/SAE J994b) and a protective shield or cage that will protect the operator from any falling objects.

Buildings and Plant Systems (Section 6): Facility operators are responsible for the safety training and supervision of their employees and the performance of regular maintenance and safety inspection programs. Facilities should have a traffic plan and use all necessary devices to minimize safety risks through the utilization of barriers, signs, separation partitions, communication devices, etc. In addition, the facility operator should designate Special Work Areas and limit employee access within 1.8 m (6 ft.) around them. Special Work Areas are distinctly identified areas where the use of guards and railings is functionally impractical and where specific training of affected employees is effective to avoid hazards within it.

With regard to the engineering of building and plant systems, the following are examples of new standards:

Facility Design Considerations. Building design should account for a minimum of six air changes per hour, have a fire exposure control and evacuation plan.

Tipping Areas. Mobile equipment traffic and sorting activities should be considered when designing tipping areas. Safety markings and signs to be used must comply with ANSI standards, audible alarms must emit a signal of at least 87 dBA or 10 dBA above ambient noise level and visual alarms must be visible from all affected areas. In addition specific signs are required in higher risk areas in order to limit personnel access. Higher risk areas include: unloading pit areas, the tipping floor, bale stacking and storage areas, industrial truck operating areas (such as aisles), etc.

Unloading Pits. As long as toeboards and guardrails which comply with ANSI A1264.1-1989 standards do not interfere with mechanized unloading operations, they should be installed on all sides of unloading pits or bunkers adjacent to walking or working areas. In the case of trucks unloading into pits, warning signs as barricades, stop logs, hand or mechanical signals should be provided.

Visitor/Public areas. Access by public visitors is prohibited during any time the facility is in operation. Access is limited to observation rooms and work areas not in operation.

Material Storage Areas. Fire protection procedures in these areas should follow standards specified in NFPA 101, Life Safety Code. Storage areas layout should provide access routes for employees that consider a minimum of 1.2 meters (4 feet) of separation from mobile equipment operating areas. Floor loading limits and lateral wall loading limits, if applicable, shall be posted. Bale stacking is allowed for stable, homogeneous, properly tied bales. Bales stacks shall be limited to four (4) high, any higher stacks should be arranged in a stair stepped fashion, interlocking fashion or use supplemental restraint devices. Bale storage areas are considered special work areas and have limited personnel access. Bales in stacks should be inspected daily for integrity.

Processing Machines and Systems (Section 7): Facility operators are directly responsible for the compliance of their systems. System engineers, machinery manufacturers, employees and service contractors (for maintenance, modification or remanufacture of machinery) are to follow the standards applicable to them. Major duties for above mentioned parties are:

- Proper operation and maintenance of machinery. The machinery manufacturers and system engineers should provide the system operator with a recommended operations and maintenance manual that includes safety features. The maintenance program must be performed by the system operator. The system engineer should provide adequate work area around each machinery for safe maintenance and inspection.
- Training, supervision and safety audits. The system operators must provide training to their employees, supervision and perform safety audits to verify the correct performance of the system safety features. Employees should only operate equipment for which they have been previously trained.
- Energy Control Program. The operator is responsible to perform an Energy Control Program and lockout/tagout of energy sources prior to performing servicing or maintenance. The machinery manufacturers and system engineer should provide the system operator lockout/tagout instructions compatible with 29 CFR Part 1910.147.
- Operator protection: Work surfaces or platforms at distances equal or less than 2.1 meters (7 ft) from unguarded points of operation should have railings no less than 1067 mm (42 in) high.
- Automatic mode equipment. Equipment functioning in automatic mode should not have its loading chamber accessible to employees.
- Riding on conveyors should not be permitted unless they have been designed for this purpose.
- Access to Special Work Areas within 1.8 meters (6 ft) is restricted to employees with the training and experience to avoid hazards.
- Equipment modifications. The contractor must obtain written permission from the operator to perform any modifications. If applicable, new operation, maintenance or safety precautions instructions will be issued. A label on the modified equipment shall list the contractor's name and the date the equipment was modified.

Control Systems. One of the most advanced features of ANSI Z245 is the controls and energy control systems standards. Aspects covered are control system design guidelines, location and equipment control features:

- Must be labeled.
- Must be designed and located to prevent unintentional activation (i.e. start buttons).
- Must meet minimum dimensions (minimum button surface is 1 inch, full hand controls activation surface is minimum 4.25 in.).
- Must be accessible.
- Must use one master control panel per processing system. It should override local controls with exception of emergency stops and discharge end controls. It should be located in manner that all affected operations are visible from it.
- Emergency buttons must be easily noticeable (in red and of larger size).

Energy controls must meet additional requirements to ensure that machinery will stop right on time, for the period desired and will re-initiate operations without creating any hazardous conditions. Energy controls are used to stop machinery when it is necessary to inspect, maintain, clean, unclog, remove contaminants etc. The most important recommendations are:

- Use of a Power Disconnect (lock in the off position).
- Use of Emergency Stops (E-stop) of the maintain contact type. (should be accessible to all affected employees and within 914 mm or 3 ft. of the Point of Operation or Feed Point Chute).
- Use of Pause/Resume control for regular system stops.
- Use of an interlock on all machinery access doors.
- Provide a key lock switch at discharge points not visible from the operator station.
- Hydraulic and electrical systems must comply with ANSI/NFPA related regulations.

Warnings, Signs and Alarms. Warnings, signs and visual alarms must comply with their related ANSI standards and be placed in areas where they are visible by all affected employees. Audible alarms must provide a pulsing or intermittent signal of at least 87 dBA or be preset to at least 10 dBA above ambient noise level to ensure workers response. System start-up alarms should be audible and visual and provide a initial 5 seconds signaling and a minimum 15 second delay to the start of the main motor. Equipment manufacturers are required to locate specific machinery warning signs on all equipment with moving parts. For example an access point warning would be to locate a sign next to a baler, commanding employees to disconnect and lock out power before opening a baler chamber gate.

Machine Guarding. Guards or enclosures are required for all equipment comprised of moving components which contain a Pinch Point or create a safety hazard. A Pinch Point is a point at which it is possible for a person's member or clothing to be caught between moving parts or between moving and stationary parts of a piece of equipment. Guard access covers should be secured by lock or require hand tools to be opened. Guarding is also used to control material flow particularly during transitions to prevent overflows within a reach of 2.1 m (7 ft.). In the event that it is impossible to install a guard in a point of operation, an E-stop and a control to either reverse, open the pinch point or disengage the mechanism is necessary.

Conveyors. Conveyor safety requirements are as a minimum the existing ANSI/ASME requirements. Equipment manufacturers should provide detailed information on the type, volume and weight the conveyor is capable to transport. Additional safety concerns are:

- Use of guards and skirts (elevated conveyors) to prevent a reach within 2.1 m (7 ft.) of the intersection or transition of conveyors.
- Provide guards for mechanical mechanisms and the return side (bottom) of conveyors.
- Conveyor sections transporting material next to sorting stations should be fully enclosed.
- Conveyor pits should use either an access cover, rails with gates interlocked to an E-stop or all moving elements of the conveyor fully enclosed.
- Sub-floor conveyors are considered Special Work Areas and have restricted access.

Sorting Stations. The sorting station standards section is probably one of the most interesting parts of the ANSI document because in addition to covering traditional safety features, it also includes ergonomic design considerations and engineering design parameters to define the system standards. Engineering parameters to be factored are Average Flow Rate, Material Density, Conveyor Belt Width, Average Belt Speed and Average Burden Depth. Furthermore, the standard recommends that engineers and equipment manufacturers apply ergonomic design features for repetitive physical tasks during their designs. The main factors discussed are:

- Work environment. For proper ventilation, a nominal air flow rate of 0.425 cubic meters (15 cubic meters) per employee or six fresh air changes per hour, whichever is greater, should be provided.
- Safety controls. Installation of E-stops within 0.9 meter (3 ft.) of each employee working position are required. The E-stop should interrupt all upstream feed and any system immediately downstream of the sorting line.
- Layout. The conveyor sort belt height should be no less than 762 mm (30 in.). The conveyor should include a toe cut-out to account for proper sorter posture. The toe cut-out dimensions should be 127 mm (5 in.) deep and 125 mm (5 in.) high. The sorting chute height should be no less than 762 mm (30 in.) on the loading side and 1067 mm (42 in.) on the others. In the event that the conveyor height plus the average burden depth height is greater than 1016 mm (40 in.) a riser should be added.
- Communication. All working positions should be visible from the control panel position and all sort station employees should be able to communicate with the control panel operator.
- Safety Features. Floors should be made of slip resistant material and be easy to clean. Guard rails should be provided for elevated sorting stations according to existing ANSI standards.

Electromagnetic Radiation Equipment. System layout and management should include provisions to maintain worker exposure to electromagnetic field emissions (EMF) under regulated maximum limits. As a minimum, guarding should be installed to prevent access within 1 meter (3 ft.) of the EMF source. The equipment manufacturer is required to provide data regarding field strength and flux density at a radius of 1 meter (3 ft) from the radiation source, both at a continuous average and at maximum continuous power. The system operator is responsible to verify equipment manufacturer information in the field and monitor EMF exposure at a work station closest to the EMF source. The radiation should be monitored for eight hour periods and their weighted average should not exceed the following limits:

- Magnetic Flux ≤ 1 mT (milliTesia) or
- Field Strength ≤ 25 kv/m (if the frequency is less than 100 Hz)
- Field Strength ≤ 625 kv/m (if the frequency is greater than 100 Hz)

Safety Program and Training (Section 8): Facility operators are responsible to perform a hazard assessment survey and an evaluation of the proper methods for controlling these hazards in accordance

with industry and regulatory requirements. As a result the facility's engineer in cooperation with the operator should develop a written program which would include all operation, inspection, maintenance and training procedures necessary to comply with existing regulations. In order to comply with the program, the personnel should be trained at the start of new assignments and refresher training should be given periodically as required. Training records detailing date and content should be maintained as required by applicable regulations. The training curricula should comply with OSHA or other federal agency requirements. Training can be classified as general safety training mandatory for all the personnel, detailed safety training for specific positions or awareness training for the recognition and avoidance of hazards. Following is a list of the written safety programs required.

Site Safety Orientation. Includes general work rules and regulations, familiarization with facility processing, explanation of signs and other prevention warnings, the emergency action plan and accident reporting.

Basic Hazard Communications (Hazcom). Used to inform employees about any hazardous material they may be exposed to in the work areas. Material Safety Data Sheets (MSDS) are also used for this purpose. Employees are instructed as how to read and interpret MSDS's information, the location of this information and the facility protection measures.

Walking - Working Surfaces. Employees are trained to recognize and avoid hazards encountered in special work areas of the facility as ladders, platforms aisles, etc.

Spill Response Program. It instructs employees to identify and handle unauthorized material, as for example hazardous waste inadvertently delivered with the recyclable material to the facility.

Blood Borne Pathogens Program. It provides training to employees regarding the hazards of infectious diseases as Hepatitis B or HIV.

Energy Control Program. It explains the risks of unexpected energizing or starting up of a machine and the lockout/tagout procedure.

Confined Space Program. Also called the permit spaces program, it provides training to prevent the hazards of working in confined spaces.

Heat/Cold Stress Program. It provides training to prevent or minimize safety or health risks caused by heat and cold stress.

Personal Protective Equipment Program. The employer should provide personal protective equipment appropriate to the job duties as required by 29 CFR 1910.132 and in compliance with its related ANSI standards.

Hearing Conservation Program. It provides awareness training regarding the hazards of high noise level exposure, prevention and protection instructions.

Traffic Control Program. Employees are trained on basic operational procedures that regulate mobile equipment traffic in the MRF as flow/routes, signals/markings, hazards, vehicle types, pedestrian routes and safety rules. The use of enhanced visibility clothing is an example of compliance.

Material Processing Equipment Program. Previous to the operation or maintenance of any piece of equipment in the facility, the employee must receive a comprehensive training on operation, maintenance and safety procedures.

Ergonomics Program. It provides information on ergonomic risk factors and preventive actions including the description of cumulative trauma disorders, recommended lifting and sorting techniques.

Electrical Safety Practices Program. Awareness training as well as specific training in electrical safety issues are to be provided to all employees according to the levels of risk at which they are exposed. Recommended work practices should comply with NFPA standards.

Fire Safety Program. It includes a fire safety awareness training and a task specific training for employees who are members of the incipient fire response program.

Material Control Program. Training is provided to minimize safety and health risks because of the handling and storage of materials around the facility. Employees are instructed on materials being processed, plant layout, traffic routes, etc.

What Is Happening in Other Countries? The Germany Example

Safety regulations for the Germany Recycling Industry⁵ were published in July 1995 to ensure proper work conditions of approximately 11,000 workers employed at 300 sorting plants. The document was prepared by the Committee for Industrial Protection and Safety together with the representatives of the Federal Institute for Industrial Protection, the Federal Institute of Industrial Medicine and the various responsible vocational associations. The major safety concern in this document is to reduce the exposure of workers to micro-organisms (bacteria, fungus, viruses, etc.) that may cause diseases. With these concerns, as well as others, the German regulations for system design are more stringent than the ANSI Z245 report. Examples of the more stringent German regulations are listed below:

- Tipping Floor. In contrast with US standards, German regulations specifically do not allow personnel to sort materials in the tipping floor area. Tipping areas must be physically separated from sorting areas.
- Mobile Equipment. The operator's cabin should additionally include a filtering device or a pressurized air tanks system to ensure proper air quality.
- Mechanical pre-sorting. Trommels and vibrating screens should be enclosed and have dedicated dust collection and exhaust systems.
- Sorting Stations. Standing sorting positions from one side of the belt should be designed considering a reach of 0.6 m (23.6 in.). For sort stations picking from both sides of the belt, the maximum belt width should be 1 meter (39.4 in.). Sorting stations should be designed to be a combination of standing and sitting work stations. The belt speed should not exceed 10 meters/minute (32.8 fpm). Ventilation devices should be periodically checked for micro-organisms present in the air.
- Hygienic Arrangements. The clothing storage areas (lockers) for work clothing and street clothing should be separated by a washroom with showers. Break-rooms are to be accessed by going through wash facilities.

- **Physical Examinations.** An initial physical screening and follow up examinations should be performed in 12 or 24 month intervals in order to establish a history and a follow up of any changes in physical conditions. This information will be the basis for a better understanding of the potential long term and short term conditions caused by micro-organisms commonly present in recycling manually sorting environments.

What are Present Industry Practices? The RRT Example

The recycling industry growth in the recent years has diversified work conditions and technologies across the country. Many facilities will require extensive retrofits in order to comply with safety standards being developed today, in particular those that were not designed and integrated by a professional engineer. The ANSI Z245 Report will guide the MRF owners' systems engineer when determining upgrade requirements. Facilities designed to exceed the minimum health and safety standards will reward their owners by minimizing lost time accidents and reducing insurance premiums.

Industry safety practices can be classified into two categories: operational practices and system engineering practices. Compliance is achieved when both the operator and system engineer follow established requirements. "Potential Hazards Associated with Municipal Solid Waste Recycling" were well documented⁶ in 1991. As a leading systems engineer, RRT has been including in their designs since the early 1990's the safety features only now being enacted by ANSI. Four (4) examples of these features are highlighted below:

Comprehensive Control Systems. The layout of system controls at RRT facilities follow the NFPA 79 Electrical Standard for Industrial Machinery. The process system motor control enclosure (MCE) is housed in a UL inspected, NEMA 12 enclosure using standard IEC/NEMA components including a programmable logic control (PLC) and a modem for remote interfacing. In automatic mode the system sequentially starts equipment in a preprogrammed logic which prevents the feeding of stopped equipment. In the event of a failure occurrence, equipment upstream will be stopped. Upon restarting, equipment will start in sequence in automatic mode after sounding a safety horn. The panel is equipped with mimic status lights indicating process conditions including equipment, emergency stops and pull cord lanyards. The system has a manual mode of operation for maintenance and adjustment activities.

Operator control stations including start/stop buttons, variable speed potentiometers, and E-stops are provided at the sorting stations for local control. Sorting conveyors are equipped with safety lanyards. Additional safety switches are used on various equipment as necessary. Each motor is interfaced with the PLC to signal running equipment through the status of the disconnect. Knife-style disconnects including the capability for local safety lock-out are typically specified. In the event an emergency stop is pushed, all equipment in the process system shuts down. There are emergency stops strategically located throughout the facility for safety purposes. The corresponding E-stop light on the mimic board indicates the specific location of the affected area.

Restricted Pedestrians Access to Mobile Equipment Traffic Areas. In some facilities, materials are floor sorted at the baler infeed areas because elevated sorting platforms are not available, or in other cases pre-sorting of reject material is performed at the tipping floor because of the system design limitations. At RRT facilities, an elevated conveyor serving as an initial quality control station is provided where reject material is sorted and directed to a separate storage area.

Operations, Maintenance and Safety Manuals. Prior to the start-up of any new or modified recycling facility, RRT provides the owner/operator formal operation, maintenance and safety guidelines for the equipment. This includes both hands-on and classroom instructional programs in the following areas:

- Process flow and system operation
- Safety training
- Baler training
- Sorter operations
- Quality control
- Mobile equipment operations
- Maintenance and repair procedures
- Preventive maintenance training
- Housekeeping

Future employees are trained in order to comply with system safety standards, design throughput and quality specifications. RRT's safety training emphasizes the use of personal safety equipment and safety controls including restarting and troubleshooting system failures. Additionally, employees are trained to handle medical wastes and sharps that may have been erroneously disposed with the recyclable material.

Ergonomics Considerations. RRT's ergonomic considerations during the design of recycling sorting systems are intended to minimize risks associated with Repetitive Stress Injuries (RSI's). The main affected areas for MRF workers are the upper extremities and the back. Sorting conveyor design considerations propose to optimize posture and angular deflection of joints while reducing worker's exposure to vibration. As a result, optimum sorting conveyor width, height, side skirt height, chute positioning and dimensions have been determined. Operation parameters, such as sorting belt speed and average burden depth, are correlated to the infeed stream composition in order to determine an optimum presentation of materials. Additionally, sorting station design includes proper lighting and ventilation. Working under ergonomically correct standards promotes a healthy work environment, improves productivity rates and reduces operating costs.

A comparison of ANSI Z245, German and RRT sorting station design standards is presented in Table 1. Similar design standards among all sources were observed for factors as ventilation, illumination, working height, toe cut-out room and chute height. Differences were observed for sorting belt width, sorting belt speed and burden depth considerations. The observed regulatory agencies trend is the use of narrower, slower and more heavily loaded sorting belts. The potential adverse effect of the institution of these standards is the considerable increase of operation costs because of the lower productivity per worker.

- Belt widths recommended in the ANSI and German documents were rated at 60 to 80% of present industry practices. RRT standards are based on ergonomic design consideration in addition to extended time and motion studies⁷ in existing facilities. These case studies were oriented to define sort station design standards that maximize productivity by providing the most comfortable work station.
- The importance of setting appropriate burden depth levels should not be underestimated. Systems running at high burden depths offer a poor presentation of materials thereby increasing sorting difficulty. Determination of optimum burden depth depends on the type of material being sorted and the stream composition, e.g. the optimum burden depth for a residential fibers mix is different from a commingled containers stream.

- Belt speed considerations were only found in the German document as they are still being developed for the ANSI Z245 report. The recommended German sorting belt speed is 40% to 50% of RRT standards. RRT case studies indicate that for different composition streams sorting belt speeds should vary between 80 - 100 fpm. These higher speeds ease burden depths and have not been shown to be detrimental to the employee. As such ANSI Z245 does not limit speed of belt travel.
- RRT includes among its standards, chute design considerations depending on the material being sorted. Practical experience shows that “toss-across” chutes are more appropriate for commingled containers sorting lines, while “toss-to-the-side” chutes provide better ergonomics for paper lines.

During 1996, fifty sorting systems designed and built by miscellaneous companies around the nation were analyzed by RRT. Most of them presented one or more deficient ergonomic design or operating features which were reflected in lower sorting rates and higher work force requirements. Commingled containers sort rates were typically recorded to be below 75% of acceptable sorting standards and as low as 35%. Major ergonomic design considerations leading to poor ergonomic conditions were thick burden depth, low sorting belt heights and the use of floor sorting operations. All of these pose safety risks to the worker.

- Thick burden depth was observed because of poor engineering and in some cases lack of engineering. Sorters were frequently observed “rummaging” through or “digging” into the material instead of sorting.
- Low sorting belt heights were observed at facilities where sorting stations were added to existing baling systems. Low sorting belt height and high burden depth situations often occur simultaneously. These systems record the lowest productivity standards.
- Floor sorting operations are frequent for commercial fiber streams (old corrugated containers mixed with trash) when mechanical means of separation were not available.

CONCLUSIONS

Workers at recycling facilities do not appear to be exposed to health and safety hazards when they follow prescribed safety requirements and facilities are properly designed. The development of safety standards specific to the recycling industry will provide comprehensive safety coverage for the worker. ANSI Z245 addresses these issues clearly for the engineer and operator. The main improvement over current standards will be the optimization of employee work conditions by the integration of ergonomics, safety and health features. These improvements come with a cost and with the continuing increase in manual sorting costs, research and experimentation on mechanical sorting separation systems will be further stimulated. The technology of recycling facilities will also be further expanded through the extensive use of integrated logic controls including energy controls and alarm systems. Maintenance, employee training and housekeeping operations will become more important as their role in the prevention of health and safety risks becomes more explicit. Further research will be performed in order to obtain a better understanding of the health risks associated with micro-organisms exposure and ergonomic stressors in recycling operations. It is the opinion of the authors that future requirements will adopt the “good, generally accepted practices” already found in the German regulations. Certainly many of these measures will derive mixed views. Controversy with regard to the analysis for justification of cost versus savings will continue as the industry matures.

ACKNOWLEDGMENT

We wish to thank Ernie Romeo for his assistance in this effort.

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Table 1. Sorting Station Design Standards¹

Parameters	ANSI Z245 Report version 2/10/97	German Regulations ³	RRT Design Standards
1. Ventilation	6 fresh air changes per hour 0.43 m ³ /minute-employee (15 cfm/employee) or		6 fresh air changes per hour
2. Illumination			
3. Sorting Conveyor			
3.1 Sorting belt width			
a. Picking from one side of the belt	≤ 0.46 m (18 in.)	≤ 0.60 m (23.6 in.)	≤ 0.76 m (30 in.)
b. Picking from both sides of the belt	≤ 0.91 m (36 in.)	≤ 1.00 m (39.4 in.)	≤ 1.52 m (60 in.)
3.2 Sorting belt height	≥ 0.76 m (30 in.)		= 0.86 m (34 in.)
3.2 Side skirt height	≤ 0.26 m (10 in.)		0.10 - 0.15 m (4 - 6 in.)
3.3 Working height ²	≤ 1.02 m (40 in.)		
3.4 Toe cut-out	depth = 0.13 mm (5 in.) height = 0.13 mm (5 in.) loading side ≥ 0.76 m (30 in.) other sides ≥ 1.07 m (42 in.)		depth ≥ 0.13 mm (5 inches) ⁴ height ≥ 0.13 mm (5 inches) 0.97 - 1.02 m (38 - 40 in.)
3.4 Chutes height			
4. Sorting belt speed		10 m/min (32.8 fpm)	containers 18.3 - 30.5 m/min (60 - 100 fpm) paper 24.4 - 36.6 m/min (80 - 120 fpm) Lanyard and local control panel
5. System controls	E-stops at 1 m (3 ft) from each work station		
6. Flooring	Slip resistant material		Diamond plating floors
7. Platforms	Guard rails, toe plates		Guard rails, toe plates. Chains are provided on all ladders.
7. Additional considerations		Sorting stations should be a combination of standing/sitting work. Padded belt frame.	Drop chutes have a "rolled" or "square" edge avoiding sharp edges to hurt employees

¹ This table compares US ANSI standards (2/10/97), German LASI standards and RRT standards.

² Is equal to the conveyor belt height plus the side skirt height. If the working height exceeds the specified limit a riser should be provided.

³ As indicated in "Guidelines of Industrial Protection in Commodity Sorting Plants" 1995.

⁴ Conveyors legs are supported by platform steel avoiding the use of many legs. This provides spacious foot room underneath the conveyor and facilitates cleaning.

TECHNICAL SESSION V

Ash Utilization

Ash Recycling - The Coming of Age!

Jan M. Barnes
Duos Engineering (USA) Inc.
6622 Southpoint Drive S., Suite 310
Jacksonville, Florida 32216

Haia K. Roffman
Radian International
Penn Center West
Building III, Suite 300
Pittsburgh, Pennsylvania 15276

Frank J. Roethel
Waste Reduction and Management Institute
State University of New York
Stony Brook, New York 11794-5000

INTRODUCTION

A major concern of the Waste-To-Energy (WTE) industry is ash disposal and the uncertainty of controlled long term ash management. Ash management costs have risen steadily over the last ten years making it the fastest rising cost segment of the WTE industry. The challenge of how to curb the rising cost while maintaining the protection of human health and the environment has been accomplished by responsibly recycling the ash on a commercial basis.

American Ash Recycling Corp. (AAR), utilizing the Duos Engineering (USA), Inc. patent pending ash recycling technology, has promoted ash recycling on a commercial basis in the United States. An important product of the processing and recycling of non-hazardous municipal waste combustor (MWC) ash is Treated Ash Aggregate (TAA). Additionally, ferrous and non-ferrous metals are recovered and unburned materials removed and returned to the WTE facility for re-combustion. The TAA is sized and then treated by the WES-PHix® immobilization process in order to reduce the potential solubility and environmental availability of the metal constituents of the MWC ash. The TAA is available for commercial use in such applications as an aggregate substitute in roadway materials, asphalt and concrete applications, as structural fill, and as landfill cover.

Commercial and technical considerations that must be addressed before ash can be beneficially recycled are: permitting requirements, physical and chemical characteristics, potential end uses, environmental concerns (product safety), product market development, and economic viability. True recycling only occurs if all of these considerations can be addressed.

This paper presents the details of AAR's most recent experience in the development of an ash recycling facility in the State of Maine and the associated beneficial use of the TAA product. Each of the considerations listed above are discussed with a special focus on the permitting process. A major component of the permitting process involved the development of a comprehensive life-cycle human health and environmental risk assessment to evaluate the potential long term effects which may arise from the beneficial use of AAR's TAA product. The extensive analytical data required in both the development of the risk assessment and the physical and chemical characteristics of the TAA will be reviewed. AAR's process and the permitted beneficial uses of the TAA product are explored as well as the methodology and overall approach utilized in the development of the project.

PROCESS DESCRIPTION

The process description outlined below is based on Duos Engineering (USA), Inc., an AAR affiliated company, patent pending design.

Incoming MWC ash will be received at the designated material input staging area of AAR's ash recycling facility. From there, the ash is conveyed to initial screening, which separates it into two size gradations consisting of less than and greater than 3", for further processing.

The larger size gradation is conveyed to a slow speed, high torque shredder for size reduction. After being reduced to a proper size, it is combined with the smaller of the two size gradations. The combined material stream next passes magnetic separation which extracts the ferrous metals. The ferrous metals

are directed to the ferrous cleaning unit where any ash adhering to the metal is removed. The removed ash is reintroduced into the process for further processing.

After magnetic separation, the remaining material is screened into the two sizes: less than 3/8" and greater than 3/8". The smaller fraction is treated using the patented WES-PHix® chemical immobilization process and subsequently conveyed to the TAA storage area. The larger fraction is directed to the Windzifter®, which uses proprietary air separation technology to remove unburned combustibles such as paper, plastic, and wood from the ash stream.

The unburned combustibles are then discharged through air locks and conveyed to a controlled storage area. The unburned stream is then returned to the MWC for recombustion. After the unburned combustibles are removed, the material flows to the eddy-current separator for non-ferrous metal removal. The remaining material (after non-ferrous metal removal) is conveyed to a crusher where it is reduced to 3/8" or less. This material is reintroduced to the process at a point prior to magnetic separation for further processing and ferrous and non-ferrous recovery. The non-ferrous material is conveyed to the MartinTag non-ferrous cleaner which uses a proprietary metals cleaning technology to remove any residual ash. The cleaned non-ferrous metals are then separated into their individual components, i.e., brass, copper, coins, and aluminum.

The process is designed to keep the material in a continuous loop until substantially all metals and unburned combustibles have been removed and the remaining ash has reached a uniform size gradation. The ash is then treated with the WES-PHix® chemical immobilization process in order to produce the final product, TAA, which is suited for beneficial use.

PERMIT REQUIREMENTS

In order to utilize the TAA, beneficial use permits are typically required. Several states have developed beneficial use regulations of MWC ash while many others are in the process. The main concern of any environmental agency is: What is the effect on human health and the environment when beneficially using this product? A myriad of other issues must be addressed during the permitting process but the main question of the safety of the product must be answered in a scientifically defensible way.

This paper focuses on AAR's most recent experience in the State of Maine for obtaining environmental permits. The three permits required for AAR to operate and beneficially use their product within the State were: 1) Solid Waste Processing Facility Permit, 2) Minor Source Air Permit, and 3) Special Waste Utilization License (Beneficial Use).

The Processing Facility permit application was typical for processing facilities as was the Air Permit. The Air Permit was required because of AAR's use of the Windzifter®, which removes the unburned material from the ash. The Windzifter® utilizes a baghouse to control any discharge of particulates to the air but since it has a potential to emit, a minor source air permit was required. The Beneficial Use permit is product specific and unique, therefore, it will be discussed in detail.

The following requirements must be met in order to obtain a Beneficial Use Permit:

- The beneficially used waste-derived-product must perform equivalently to the material it is replacing;

- The beneficial use shall produce a product which meets or exceeds the generally accepted product specifications and standards for the same product produced using a raw material; and
- The beneficial use will not pollute any waters of the state, contaminant the ambient air, constitute a hazard to health or welfare or create a nuisance during and after the active life of the project.

The Maine Department of Environmental Protection (DEP) requires the following material be included as part of the Beneficial Use of a Special Waste Permit application:

- 1) General description of the waste-derived-product and its proposed use;
- 2) Specific information regarding the physical, chemical or biological characteristics of the waste-derived-product;
- 3) The quantities, by weight and/or volume of the solid waste and waste-derived-product;
- 4) Waste characterization plan - analytical data demonstrating that the solid waste is non-hazardous;
- 5) Demonstrated Product Markets. The following information may be submitted in support of this requirement: a) Contract to purchase proposed product; b) Description of how the proposed product will be used; c) Demonstration that the proposed product complies with industry standards and specifications for that product; d) Other documentation that a market for the proposed product or use exists;
- 6) Demonstration that the nature of the proposed use of the waste-derived-product constitutes a beneficial use rather than disposal;
- 7) Description of the operation of the facility which is proposing to use the solid waste and the product produced or the manner in which the waste shall be used. The complexity and degree of detail of the description will vary depending on the magnitude and complexity of the process;
- 8) A description of how the solid waste and the waste derived product will be stored;
- 9) A technical comparison of the waste derived product and the virgin material it is replacing. An evaluation shall demonstrate that the physical and chemical properties of the materials are comparable and that the waste derived product will serve as an effective substitute for the analogous raw material. This demonstration may include a discussion of the risks and drawbacks and an assessment of similar application of the proposed beneficial use; and,
- 10) Records and Annual Reporting.

AAR submitted the permit applications to the Maine DEP after detailed discussions which outlined the specific information that would be acceptable in order to meet all of the requirements. The most difficult question to answer in a scientifically defensible way was: Is this material safe to human health and the environment when beneficially used in the requested applications? AAR approached this question, in agreement with the DEP, by performing a chemical characterization of the TAA and a comprehensive human health and environmental risk assessment (HRA) based upon the chemical constituents found in the characterization report. The HRA evaluated the potential long-term environmental effects which may arise from the beneficial use of TAA.

CHEMICAL CHARACTERISTICS OF TAA

In order to obtain specific information regarding the physical and chemical characteristics of both the ash and TAA, MWC ash from an operational waste-to-energy facility in Maine was transported to the AAR Nashville facility for processing in October 1995. Composite samples of the MWC ash were collected prior to processing and multiple composite samples of TAA were collected as well. TAA

samples were collected after 10, 20 and 30 tons of the aggregate were produced. All of the composite samples were forwarded to the State University of New York (SUNY) for both physical and chemical characterization. A characterization report titled "Chemical and Physical Characteristics of AAR's Processed Ash Aggregate Produced from Maine Energy Recovery Company's MWC Combined Ash"¹ was prepared by the University (Roethel, 1995) which detailed the analytical results, analytical methods, and the appropriate quality control/quality assurance data.

Figure 1 outlines the analyses which were performed on TAA and leachates reported in the study. A broad spectrum of analytical analysis was performed on the TAA in order to demonstrate to the Maine DEP the complete TAA characterization. The chemicals of concern, as determined in Roethel, 1995, that were used in the risk assessment include metals and dioxins/furans analysis. The metals considered in the HRA were: arsenic, barium, cadmium, chromium, copper, lead, mercury, selenium, silver and zinc. Metal leachate data was obtained in accordance with the US EPA Monofilled Waste Extraction Procedure, more commonly known as EPA Method SW-924. This multiple extraction leaching test is significantly more predictive of how TAA will behave in the environment than the TCLP test.

Dioxin/furan data were obtained from samples of TAA. This data was used in exposure scenarios which evaluated direct contact with TAA and served as the basis of the modeled airborne particulate concentrations and deposition rates. Actual dioxin leachate data was obtained from the US EPA's Characterization of MWC Ashes and Leachates from MSW Landfills, Monofills, Co-disposal Sites², September 1987. The dioxin leachate data did not represent AAR's TAA but were provided as a worst-case approximation of leaching from landfills when municipal solid waste and MWC ash are deposited together.

In establishing the inorganic composition of the ash and TAA, samples were digested using hydrofluoric and boric acids ($\text{HF}/\text{H}_3\text{BO}_3$) which is a departure from the standard EPA total metal digestion protocol incorporating nitric acid (HNO_3). This modification was undertaken to permit an analysis of metals bound within a siliceous matrix which would not be digested if nitric acid were utilized. Typically, the concentrations measured using the more aggressive $\text{HF}/\text{H}_3\text{BO}_3$ digestion technique are higher, increasing between 10%-30% above those determined using HNO_3 . This was done to determine the true total metals concentrations.

Dioxin and furan concentrations were determined for duplicate samples of TAA. Toxicity Equivalent Factors (TEF's) were used to express the concentration of the different isomers and homologs of dioxin/furans as an equivalent amount of 2,3,7,8-Tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD).

The physical characterization showed that the AAR process yields a uniform product, consistently achieving a particle size distribution appropriate for a diverse array of applications. The data indicated the aggregate is well graded, consisting of about 30 percent gravel, 65 percent sand size particles, and 8 percent fines (smaller than 200 mesh). The particle size distribution and percent volatile matter are both very similar to existing TAA data produced at AAR's Facility in Nashville, TN. The data in this investigation, the previous data gathered by AAR and the completed HRA all suggest the use of TAA is an environmentally acceptable beneficial use strategy.

HUMAN HEALTH AND ENVIRONMENTAL RISK ASSESSMENT

In order to demonstrate to the Maine DEP that the TAA would not pollute any waters of the state, contaminate the ambient air, constitute a hazard to health or welfare or create a nuisance, Radian International (Radian) performed a comprehensive HRA to evaluate the potential long-term environmental effects which may arise from the beneficial use of TAA.

The HRA, titled "Assessment of Potential Human Health and Environmental Effects from the Beneficial Use of American Ash Recycling Corporation's Treated Ash Aggregate³" (Roffman, 1995), was a major component in the permitting process. The data utilized in the HRA came from the Roethel, 1995, Characterization Report.

The HRA was conducted in accordance with applicable US EPA and Maine DEP risk assessment guidelines. The risk assessment evaluates the human health and environmental risk associated with the TAA from the time of creation to its beneficial use in roadways, landfills and other potential uses including its final reuse or disposal. The HRA included life cycle analyses which examined stages in the processing and proposed usage of the TAA during which releases may occur. For each stage, a human health risk assessment and an environmental risk assessment were performed for potentially affected receptors. To ensure that potential secondary effects were not overlooked, not only direct contact of receptors with TAA, but also potential impacts on local air and water quality were evaluated in the risk assessments.

The risk assessment presents estimated human health and environmental risks resulting from exposure to chemical constituents in AAR's TAA for the following stages in the potential uses of TAA:

- Loading and unloading of TAA
- Storage of TAA;
- Transportation of TAA;
- Production of asphalt paving material containing TAA;
- Use of TAA as a protected subbase in a roadway;
- Use of TAA as a commercial protected structural fill;
- Use of TAA as daily cover and final cover for landfills;
- Use of TAA as an aggregate substitute in asphalt or concrete materials; and
- Final use or disposal of paving materials containing TAA.

Potential health risks to workers and potentially affected residential receptors were evaluated for each of these stages, when applicable. The exposure pathways considered for this risk analysis are as follows:

- Worker exposure to constituents of TAA by accidental ingestion and inhalation;
- Worker exposure to TAA constituents dissolved in rainwater runoff;
- Inhalation of airborne particulates emitted from a TAA processing facility by residents living near the facility;
- Residential exposure to soils potentially impacted by deposition of particulates of TAA emitted from storage piles, processing plants and the erosion of roadways; Residential exposure of soils potentially impacted by overland transport of TAA constituents via runoff from 100 percent TAA storage piles, and storage piles containing mixtures of 40 percent TAA encapsulated with asphalt or cement;
- Residential exposure to TAA constituents which have been leached from storage piles, roadway

subbase, and landfills utilizing TAA as a daily or final cover. This scenario assumes that the constituents enter a groundwater system which is used for typical residential purposes, including drinking and bathing;

- Exposure to TAA constituents in a surface water body potentially impacted by overland transport from 100 percent and 40 percent TAA storage piles;
- Exposure through the food chain. This scenario assumes food is grown in soils impacted by releases from a TAA processing facility, from storage piles, and from roadway deterioration.

These potential risks were quantified by applicable US EPA risk assessment equations. They used predictive computer models which utilized the physical and chemical data developed in Roethel, 1995.

Throughout the HRA conservative assumptions were employed so that the US EPA concept of a "Reasonable Maximum Exposure (RME)" was maintained. RME's are defined as "the highest exposure that is reasonably expected to occur" for a given exposure pathway. The HRA, therefore, uses exposure factors which are likely to overestimate potential risks, so that the health of the public is safeguarded.

Exposure Assessment

The purpose of the exposure assessment is to estimate the type and magnitude of potential exposures to constituents detected in the TAA. Results of the exposure assessment are combined with chemical-specific toxicity information to characterize the potential human health risks. Table 1 presents the appropriate exposure factors employed in the risk assessment calculations. The exposure assessment consists of the following steps:

- Identification of potentially exposed populations and exposure pathways as described above;
- Determination of exposure concentrations which are estimates of the chemical concentrations to which persons (receptors) may be exposed. In this HRA, exposure point concentrations consist of the following:
 - 1) Determination of soil exposure point concentrations from both deposition and runoff, and
 - 2) Determination of groundwater exposure point concentrations employing ground water modeling using specific input parameters, groundwater fate and transport data and mass input.
- Air emission exposure point concentrations and deposition derivations were determined using the following:
 - 1) Emission rate derivations which include:
 - Truck loading and unloading of TAA;
 - Transport of TAA;
 - Material handling at a production facility;
 - Storage of TAA;
 - Particulate emissions from a mixing plant;
 - Emissions associated with roadbed decomposition.
 - 2) Deposition rate derivations which describe the rate at which particulate matter settle out of the atmosphere onto the ground. This requires knowledge of the average particle size,

the particle density, the viscosity of the air, and the gravitational constant.

- 3) Particulate concentration modeling using the US EPA Industrial Source Complex-Short Term (ISCST2)⁴ model to estimate potential maximum ground-level concentrations of TSP and PM10. The dispersion modeling requires specification of the following parameters:

- Source data;
- Receptor Data;
- Meteorological data;
- Model options;
- Exposure point concentrations.
- Determination of surface water exposure point concentrations; and
- Potential food chain exposure.

Risk Effects

The potential risks assessed in the HRA include both noncarcinogenic (non-cancer) and carcinogenic (cancer) health effects. Each risk is shown as a numeric value which is subsequently compared to US EPA acceptable criteria.

Noncarcinogenic health effects are characterized by a value known as the Hazard Quotient. According to the US EPA guidelines, if the Hazard Quotient is greater than unity (>1), “there may be concern for potential health effects”, and when the Hazard Quotient is less than one (<1), “it is unlikely for even sensitive populations to experience adverse health effects”. It is, therefore, desirable that:

$$\text{Hazard Quotient} < 1$$

The ratio of the Intake to Reference Dose is termed a Hazard Quotient and is a measure of the potential health effect of a given exposure. Therefore,

$$\text{Hazard Quotient} = \text{Intake} / \text{Reference Dose}$$

Carcinogenic risks are expressed as a probability of contracting cancer. This probability is defined as an “incremental probability of an individual developing cancer over a lifetime as a result of exposure to a potential carcinogen”. Incremental refers to the fact that the cancer risk is in excess of the individual’s normal risk without this exposure. The means by which intake is converted to a probability of carcinogenic risk is the Carcinogenic Slope Factor (CSF). To compute the probability of contracting cancer, the intakes are multiplied by the chemical-specific CSF’s. Therefore,

$$\text{Carcinogenic Risk} = \text{Dose} \times \text{CSF}$$

The US EPA states that its carcinogenic risk goal is 1×10^{-6} to 1×10^{-4} where a carcinogenic risk of 1×10^{-6} is equivalent to one excess incidence of cancer in 1,000,000 persons and a 1×10^{-4} risk indicates a risk of one in 10,000 individuals.

Risk Assessment Results

The potential health risks associated with the production and utilization of TAA were in every instance less than the US EPA acceptable criteria for both carcinogenic and noncarcinogenic risks.

The data indicate the potential noncarcinogenic health risks or Hazard Quotient incurred if individuals are exposed to the chemical constituents of 100% TAA storage piles and in environmental media affected by migration of these constituents from the pile, are less than the US EPA acceptable criteria.

The maximum carcinogenic risks to workers and nearby residential adults and children in the considered exposure scenarios were within the US EPA acceptable range.

Results of the LEAD 5 Model

Potential risk to children exposed to lead in residential soils were evaluated by the US EPA's LEAD 5 model. This exposure situation assumed that TAA is blown from storage piles, roadways, and an asphalt mixing plant and that the particulates are then deposited on soils near these sources. It is further assumed that young children play in this soil outdoors, and that soil dusts infiltrate their homes so that they are exposed both outdoors and indoors for a period of six years. US EPA default values were assumed for other media the child may be exposed to, such as contributions from food, waters, and air. It should be noted that the US EPA default values for water and air concentrations in the LEAD 5 model are greater than lead concentrations estimated in the HRA for these media.

Table 2 shows the results of the LEAD 5 model which indicate that the total lead blood level is below the current US EPA acceptable level of 10 µg/dl.

HRA Summary

Human health and environmental risks resulting from exposure to chemical constituents for the following stages in the life of the TAA were assessed in this study: the storage and handling of the TAA, the production of a TAA/asphalt mixture, the use of TAA as a roadway subbase, use as commercial structural fill, and the final disposition of TAA/asphalt or cement paving materials.

Results of this study indicate that both potential noncarcinogenic and carcinogenic risks are well within US EPA recommended goals for all exposure situations evaluated in this HRA. Review of the specific risks shows that much of the estimated risk arises from direct worker contact with 100 percent TAA. The worker exposure scenarios assume that a worker's hands and the full length of both arms are completely covered with TAA every workday for 25 years, i.e., the worker wears no gloves, long-sleeved shirts, or other protective equipment. These risks can easily be reduced by proper administrative and engineering controls.

The HRA confirms the potential carcinogenic and non-carcinogenic risks to residents resulting from air emissions, rainwater runoff, structural fill, and leaching from piles, and roadways are well below US EPA criteria.

Despite the conservative assumptions made throughout the HRA the potential human health risks as well as the potential ecological impacts resulting from the utilization of TAA in storage piles, processing

plants, structural fill, roadways and landfills, are within acceptable ranges. Risks are overestimated following conservative US EPA guidance in order to assure that if error occurs, the error is on the side of safety. The findings of the HRA indicate the potential risks associated with the use of TAA as a product are well within or below US EPA guidelines.

POTENTIAL END USES

The potential end uses for any new product must be determined prior to submitting the permit application. Based upon extensive study and years of commercial operation AAR has determined that TAA is suitable for use as:

- Base and sub-base under roads and other paved surfaces,
- Aggregate for asphalt manufacturing,
- Structural fill material,
- Substitute aggregate in concrete; and,
- Daily landfill cover and closure materials.

PRODUCT MARKETABILITY

AAR has developed a Marketing Plan which is based upon its experience in successfully marketing the TAA and ferrous and non-ferrous metals produced at its Nashville, Tennessee ash recycling facility. AAR has sold, to a variety of end users, more than 260,000 tons of TAA produced to date. TAA is readily accepted by industry based upon its proven similarity in engineering and structural characteristics to natural aggregate. Based upon geographic location, the cost of TAA is typically lower than natural aggregate. In addition, the concept of recycling a material versus using a non-renewable natural resource is an attractive bonus to using TAA.

For the Maine project, AAR was able to demonstrate to the DEP the marketability of the TAA by contracting with a Scarborough, Maine paving company to purchase all of AAR's production. The company has over fifty years experience in the paving and construction industry and upon evaluating the TAA determined it met their strict standards of acceptability as a replacement for natural aggregate.

In addition to the TAA produced by AAR's process, metals are also recycled and sold. The process separates, cleans, and sizes both ferrous and non-ferrous metals which ensures the highest value is received. Again, AAR's experience over the last three and a half years of commercial operation has enabled it to develop a marketing plan for its recycled products that has been proven to be successful.

CONCLUSIONS

The Beneficial Use Permit, the Solid Waste Processing Facility Permit, and the Minor Source Air Permit for the production and beneficial use of TAA in the State of Maine were issued in July 1996. The permitting process is a lengthy and detailed procedure which requires critical reviews of all data, detailed studies, marketability, financial stability, as well as economic feasibility of the overall project. AAR was able to demonstrate the environmental safety of their product and the project's economic feasibility to the satisfaction of the Maine DEP.

New technologies are constantly faced with challenges starting with the initial concept all the way

through to commercial operations. This is especially true for complex issues like MWC ash recycling. Environmental rules and regulations are often conservative to ensure the protection of human health and the environment, yet even with the strict requirements, AAR was able to successfully demonstrate the safety of utilizing their TAA. With the permit approvals for a new facility in the State of Maine, the beneficial use of ash is broadening and can be held up as a model for future projects.

In the hierarchy of integrated waste management, recycling is the major preference over landfilling. AAR's ability to recycle virtually 100% of the incoming MWC ash helps to meet the nations goals of reduction and recycling. AAR has met the challenge of curbing the high cost of ash management while maintaining the protection of human health and the environment with its proven commercial ash recycling technology. AAR's technology and experience on a commercial basis has demonstrated that ash recycling has finally come of age!

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³Roffman, H. K., 1995. Assessment of Potential Human Health and Environmental Effects from the Beneficial Use of American Ash Recycling Corporation's Treated Ash Aggregate, December.

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TABLE 1**Exposure Factors Employed in Risk Assessment Calculations.**

Dermal Contact with Soils / TAA	Child	Adult	Adult
	Resident	Resident	Worker
Skin Surface Area (sq. cm./event)	3910	3120	3120
Soil to Skin Adherence Factor (mg/sq. cm.)	1.0	1.0	1.0
Absorption Factor (unitless)	Chemical dependent	Chemical dependent	Chemical dependent
Exposure Frequency (days/year)	350	350	250
Exposure Duration (years)	6	24	25
Body Weight (kg)	15	70	70

Ingestion of Soils	Child	Adult	Adult
	Resident	Resident	Worker
Ingestion Rate (mg/soil/day)	200	100	NA
Absorption Factor	1.0	1.0	NA
Exposure Frequency (days/year)	350	350	NA
Exposure Duration (years)	6	24	NA
Body Weight (kg)	15	70	NA

Dermal Contact with Groundwater / Runoff	Child	Adult	Adult
	Resident	Resident	Resident
Skin Surface Area (sq. cm./event)	NA	19400	4240
Exposure Frequency (days/year)	NA	350	150
Exposure Duration (years)	NA	30	25
Exposure Time	NA	0.5	0.5
Body Weight (kg)	NA	70	70

Ingestion of Groundwater	Child	Adult	Adult
	Resident	Resident	Worker
Ingestion Rate (l/day)	NA	2	NA
Exposure Frequency (days/year)	NA	350	NA
Exposure Duration (years)	NA	30	NA
Body Weight (kg)	NA	70	NA

Inhalation of Particulates	Child	Adult	Adult
	Resident	Resident	Worker
Inhalation Rate (cu.m./hr)	NA	0.83	0.83
Exposure Time (hours/day)	NA	24	8
Exposure Frequency (days/year)	NA	350	250
Exposure Duration (years)	NA	30	25
Body Weight (kg)	NA	70	70

TABLE 1**Exposure Factors Employed in Risk Assessment Calculations.**

Ingestion of Surface Water	Child Resident	Adult Resident	Adult Worker
Contact Rate (L/hour)	0.05	0.05	NA
Exposure Time (hrs/day)	2.6	2.6	NA
Exposure Frequency (days/year)	350	350	NA
Exposure Duration (years)	6	24	NA
Body Weight (kg)	15	70	NA

Dermal Contact with Surface Water	Child Resident	Adult Resident	Adult Worker
Skin Surface Area (sq. cm./event)	9310	19400	NA
Exposure Time (hrs/day)	2.6	2.6	NA
Exposure Frequency (days/year)	350	350	NA
Exposure Duration (years)	6	24	NA
Body Weight (kg)	15	70	NA

Food Chain Exposure	Child Resident	Adult Resident	Adult Worker
Ingestion Rate (mg/day)	NA	Chemical Specific	NA
Exposure Frequency (days/yr)	NA	350	NA
Exposure Duration (years)	NA	30	NA
Body Weight (kg)	NA	70	NA

TABLE 2

Summary of Human Health Risks Results of US EPA Lead5 Model Runs.

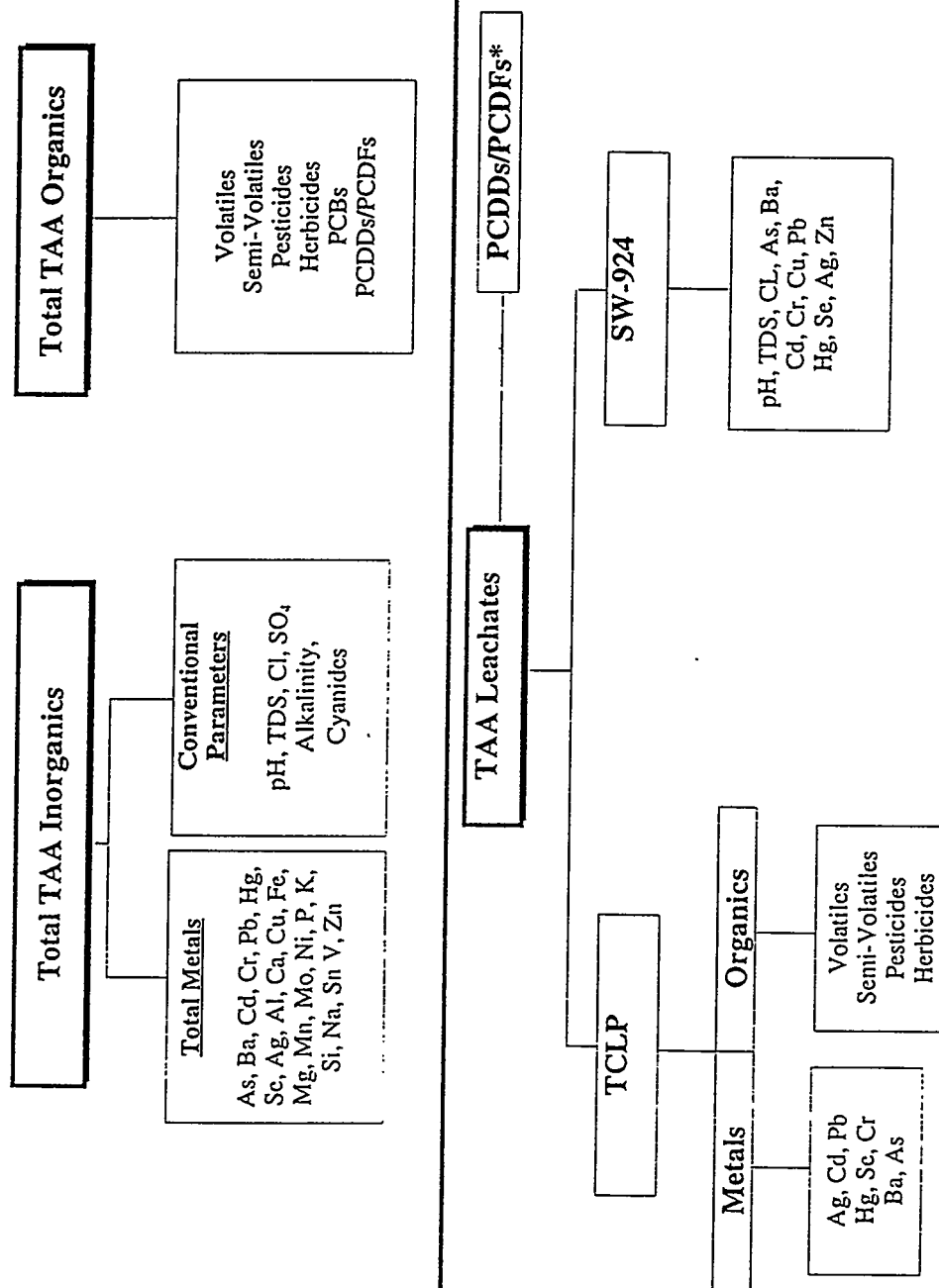
AGE	CHILD BLOOD LEAD LEVELS (ug/dl)		
	Deposition from 100% TAA Storage Pile Soil Lead = 12.0 mg/kg	Deposition from Roadway Soil Lead = 0.112 mg/kg	Deposition from Asphalt Mixing Plant Soil Lead = 4.9 mg/kg
0.5-1	1.68	1.57	1.62
1-2	1.35	1.24	1.29
2-3	1.36	1.26	1.30
3-4	1.40	1.30	1.34
4-5	1.44	1.33	1.38
5-6	1.47	1.36	1.41
6-7	1.53	1.42	1.47

AGE	CHILD BLOOD LEAD LEVELS (ug/dl)	
	Overland Transport 100% Ash Storage Pile Soil Lead = 7.0 mg/kg	Deposition from 40% TAA Storage Pile Soil Lead = 4.8 mg/kg
0.5-1	1.63	1.61
1-2	1.30	1.28
2-3	1.32	1.30
3-4	1.36	1.34
4-5	1.39	1.37
5-6	1.42	1.40
6-7	1.49	1.47

Current US EPA Blood Lead Level Criterion is 10 ug/dl.

FIGURE 1

TOTAL AND LEACHATE ANALYSES PERFORMED ON TAA



* PCDDs/PCDFs in leachates for the daily municipal landfill cover scenario originate from actual leachate samples collected from municipal landfills which also accepted municipal waste combustor ash, as reported in the U.S.EPA Report: Characterization of MWC Ashes and Leachates from MSW Landfills, Monofills and Co-Disposal Sites, EPA 530-SW-87-028, Oct. 1987.

Comparison between MSW Ash and RDF Ash from Incineration Process

Ni-Bin Chang^{*}, H. P. Wang^{*}, W. L. Huang^{}, K. S. Lin^{***} and Y. H. Chang^{***}**

presented to

Fifth North American Waste-to-Energy Conference

Research Triangle Park, NC

April 21-25, 1997

^{*} Associate Professor, Department of Environmental Engineering, National Cheng-Kung University, Tainan, Taiwan, R.O.C.

^{**} Associate Professor and Chairman, Department of Civil Engineering, National Kaohsiung Institute of Science and Technology, Kaohsiung, Taiwan, R.O.C.

^{***} Graduate Student, Department of Environmental Engineering, National Cheng-Kung University, Tainan, Taiwan, R.O.C.

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Ni-Bin Chang, H. P. Wang, W. L. Huang, K. S. Lin and Y. H. Chang

Department of Environmental Engineering
National Cheng-Kung University
Tainan, Taiwan, Republic of China

ABSTRACT

Resource recovery plants with waste sorting process prior to incineration have not been successfully developed in many developing countries. The reuse potential of incineration ash in light of toxicity and compressive strength remains unclear due to the inhomogeneous composition and higher moisture content of solid waste in Taiwan. A comparative evaluation of the ash generated from two types of incineration processes were performed in this paper. The results indicate that fly ash collected from both types of incineration processes are classified as hazardous materials because of higher metal contents. The reuse of bottom ash collected from refuse-derived fuel incineration process as fine aggregate in concrete mixing would present 23% lower compressive strength as compared with the normal condition.

INTRODUCTION

In the midst of fast paced economic activities in Taiwan, the society demands and consumes a lot of natural resources and raw materials in the creation of products to enrich people's life. To cope with large amount of solid waste disposal with the landfill space at a premium in this tiny island, over thirty municipal incinerators were planned to be built in the major metropolitan areas within the next decade. It is estimated that there will have over two millions tonnes of incineration ash generated every year after the year 2000 which would still accelerate the depletion of limited landfill space. However, continuous population growth requires more housing projects which inevitably request more production of river sand as part of the materials in concrete mixing. This further poses problems of erosion in light of the natural balance in the river eco-system. In recent years, several communities in Taiwan encounter an issue that the house they live were built using sea sand as surrogate raw materials in concrete mixing. The fast deterioration of those building would also create a hazard to the residents living in those communities. The term "sustainable development" has

special meanings as the wellbeing of a population of twenty million in Taiwan, with the area no larger than thirty-six thousand square kilometers, must be sustained probably by the reuse of incineration ash as part of the raw materials in the future construction programs. This study tries to achieve part of the life cycle analysis of consumer products as they are destined for final disposal in the municipal incinerators. The evaluation of reuse potential of those end products from incinerators can then be regarded as an action of resource conservation and recycling in the entire life cycle analysis.

Although Taiwan has set a bold agenda of solid waste incineration programs to conserve the landfill space in the last few years, the continuing thinking of an integrated incineration system with the sorting process as a pretreatment unit to improve the incineration efficiency and generate better quality of flue gas and ash has never been tempered. At least two proposals for installing such a sorting process prior to the large scale municipal incinerators, located in the City of Tai-Chung and the County of Taipei, were raised in 1996. In addition, such an integrated incineration system was also chosen for planning several medium size modular incinerators, that are located in the rural areas in Taiwan. But the property and reuse potential of those RDF ash remain unclear. The incineration ash from the MSW burning is currently being used for landfilling only in Taiwan. Backfilling of construction sites, subbase in road construction, and to some extent, reuse for concrete mixing have been fully carried out in several laboratory experiments. This analysis emphasizes the comparative study of property characterization and reuse potential of ash from MSW and RDF incineration processes, using local waste flow as fuels in Tainan area of Taiwan.

Two major facilities, located in Tainan area of Taiwan, were used as pilot plants in this experiment. One is a refuse-derived fuel process, and the other is a modular incinerator. Hence, two types of incineration processes can be arranged. One has a dedicated sorting process associated with a modular incinerator while the other has not such a sorting plant prior to incineration. The samples of municipal solid waste (MSW) in Tainan area of Taiwan were collected and then the refuse-derived fuel (RDF) were generated for the subsequent incineration. Incineration ash from the waste burning process were produced and collected from the bottom of ash discharge and the electrostatic precipitator hopper, as denoted by the "bottom ash" and "fly ash" respectively in this study. The properties of incineration ash were specifically characterized and the reuse

potential of bottom ash as part of the raw materials in concrete mixing was also examined. In the first stage analysis, the unwashed incineration ash were tested and analyzed for TCLP (Toxicity Characteristic Leaching Procedure) metals and chemical composition using XRD and SEM/EDS techniques. In the second stage analysis, to further evaluate the reuse potential of bottom ash, the washed bottom ash from both types of incineration processes were tested by sieve analysis and compressive strength analysis. Final suggestions were made based on the tested properties of those incineration ash.

LITERATURE REVIEW

In the last decade, a number of credible research efforts were carried out in both the European countries and United States ([1]~[3]) and the efficiency and effectiveness of resource recovery from solid waste associated with incineration system has been fully discussed ([4]~[12]). However, the impacts of solid waste sorting on incineration remain uncertain due to the higher moisture content and plastics in solid waste composition in Taiwan, which is not fairly representative of most other countries.

In addition, ash properties have been fully characterized in several municipal incinerators, such as in New York City, California, Singapore, and so on ([13]-[17]). Engineering evaluation of resource recovery for incineration ash has been performed ([18]-[19]). Specific purposes of ash utilization were fully discussed, such as the recovery and reuse of ash as the raw materials in concrete mixing ([20]-[23]), the reuse of ash as the subbase materials in road construction and geotechnical applications ([24]-[25]), and even the recovery of fly ash as zeolite [26].

FACILITY DESCRIPTION

Solid Waste Sorting System

As is illustrated in Figure 1, the solid waste sorting process consists of three major units: shredding, air classification, and screening. The facility can process 30 tons/hr at maximum capacity per one line. The MSW is delivered to the facility by packer trucks. A bag-ripping unit, to open plastic bags, initializes the sorting process. Ferrous metal is then extracted from the MSW stream using magnets. Recovered ferrous metal is conveyed to a ferrous storage bin from

where it is recycled. MSW is then processed in a vertical hammermill shredder to reduce it to a normal size. Shredded MSW is taken to an air classifier, using a belt-type conveyor. Non-ferrous materials, such as aluminum cans and combustibles are crushed by the vertical hammermill shredder. A manual sorting unit or eddy current separator could be added prior to the vertical hammermill shredder for the recovery of aluminum cans in the future. The air classifier, blowing with a regular air stream of $200 \text{ m}^3/\text{min}$ from the vertical hammermill shredder, is intended to separate the inert materials, such as glass, ceramics, and so on, to reduce the content of heavy non-combustible material in the residual MSW streams. Light materials, passing through the air classifier, are sent into the trommel screen for advanced separation. The dimensions of the openings on the surface of trommel screen can be varied to fine-tune the processing function and assure maximum combustibles recovery. The trommel is designed with two concentric shells. The outer shell, with 2.33 meters in diameter and 4.3 meters in length, has many circular holes on the surface which is designed to remove the shredded materials smaller than 25 mm. The inner shell, with 1.9 meters in diameter and 4.56 meters in length, separates partial waste stream with the size between 25 and 100 mm. Three waste streams can be trommeled. In other words, particle size is controlled by the openings design on the surface of the trommel such that the material with the particle size less than 25 mm (trommel underflow) and the particle size between 25 mm and 100 mm (trommel middle flow) are separately arranged by two different sets of openings with a concentric shell configuration. The overflow, passing through this trommel screen, presents the most light portion in the MSW with the size greater than 100 mm (trommel overflow), and can be identified as fluff-RDF. However, both outputs with particle size larger than 100 mm and between 25 mm and 100 mm can be used as fuels in the incineration facilities.

Solid Waste Incineration System

Figure 2 presents the system configuration of the modular incinerator. The 100 Kg/hour modular incinerator was designed is equipped with an electrostatic precipitator and a wet scrubber. From the silo the RDF or MSW is fed into the furnace where the combustion takes place on a 3-step movable grate system. The flue gases generated pass through the first furnace and is cooled down at the outlet of secondary furnace. The heat exchanger is installed at the outlet of secondary furnace for the preheating of auxiliary air. The flue gases are

eventually led through air pollution control system, consisting of a conventional electrostatic precipitator (EP) followed by a wet scrubber. Reheat is provided to prevent visible flue gas emissions due to higher moisture content.

TCLP ANALYSIS

Samples of fly ash and bottom ash were analyzed in accordance with the TCLP requirements. Tables 1 and 2 list the analytical results of TCLP tests for both bottom ash and fly ash. Two replicates were prepared to meet the QA/QC requirements that generate the data ranges in both Tables 1 and 2. The leachability of regulated heavy metals is affected by waste composition, its combustion history, and handling method. This would differentiate the fundamental difference of ash from burning MSW and RDF.

The extracted metals from the fly ash in the RDF incineration process generally exhibit relatively lower concentrations. However, testing fly ash revealed that both types of fly ash generated from burning MSW and RDF can be classified as hazardous materials due to higher heavy metal content. But the extracted metals from the bottom ash of MSW and RDF burning exhibit relatively lower concentrations. The reason for the higher Zinc concentration leached from RDF bottom ash is still unclear. This is probably due to the higher percentages of paper content with printing ink in the RDF that is not Zinc-free products. Table 2 shows that extractable cadmium concentrations in both types of fly ash are far beyond the regulatory levels. This substantial differences would make the fly ash subject to post-treatment requirements, such as stabilization, solidification, vitrification, and even melting processes.

CHEMICAL COMPOSITION ANALYSIS

In order to have more comprehensive insight, tasks of phase identification of both fly ash and bottom ash by X-ray diffraction and SEM/EDS techniques have been performed in this analysis. Table 3 lists the chemical compositions of those fly ash and bottom ash. On the average, the ash mainly comprise of SiO_2 , CaO , Al_2O_3 , Fe_2O_3 , ZnO , MgO , and Cr_2O_3 . It appears that Fe_2O_3 constitutes the major part of fly ash. Besides, CaO is the highest content and SiO_2 is the second largest group in those bottom ash.

EVALUATION OF REUSE POTENTIAL AS FINE AGGREGATE

Sieve Analysis of Bottom Ash

Wider particle distribution exists in the bottom ash of MSW. The shape of the particles of MSW ash is relatively irregular and flaky. Higher amount of aluminum cans, metal tubes, iron wires and other ferrous metals exist in the MSW bottom ash that makes the recovery, recycle and reuse processes become much more difficult. After removing those impurities, Figure 3 illustrates the grading of the MSW and RDF bottom ash. Due to the poor setting of concrete were reported when "raw" incineration residues are used, washing process was therefore employed to remove part of light and fine materials before the samples were used in concrete mixing [21]. The results of sieve analysis of "unwashed" and "washed" ash samples were both listed in Tables 4 and 5. It shows that the particle size distributions of MSW and RDF bottom ash present similar patterns. But relatively higher percentage of light and fine materials exists in MSW bottom ash.

Compressive Strength Analysis

Table 6 lists the properties of normal sand, washed MSW and RDF ash. The fineness modulus of the MSW and RDF particles are 3.34 and 3.59 respectively, indicating a rather coarse grading. The specific gravity of the washed MSW and RDF samples are 2.27 and 2.38, respectively. The water adsorption values are 2.0%, 9.0%, and 7.4% corresponding to the normal sand, MSW, and RDF ash respectively. Although the specific gravity of washed incineration ash is similar to natural sand, the water adsorption value is three more times higher. In addition, the residual carbon contents in MSW and RDF bottom ash ranges from 2.63-2.66 (%) and 0.63-0.66 (%), respectively. These values indicate that MSW bottom ash has a higher amount of unburnt materials.

Tests of compressive strength were conducted using washed bottom ash as fine aggregate in a normal mix of 1:2:4 (cement:sand:coarse aggregate) at water cement ratio of 0.7. Ordinary Portland cement was used as it would be in the normal concrete preparation. The coarse aggregate is 20-mm maximum size crushed granite. The bulk density of concrete mixes using normal sand, MSW, and RDF ash as fine aggregate are 2,340 Kg/m³, 2,100 Kg/m³, and 2,110 Kg/m³,

respectively. The slump values of concrete mix with normal sand, MSW and RDF ash are 100 mm, 10 mm, and 20 mm, respectively. The initial setting time for the concrete with MSW or RDF ash is about 3 hr as compared to 2 hr for the concrete with normal sand. In general, concrete with incineration ash as fine aggregate have longer setting times than the samples with normal sand. It appears that all the mixes with incineration ash have lower workability. However, the setting times are well within the requirements of ASTM standards.

Cubic specimens (12mmx24mm) were then prepared and compressive strength of the specimens at various ages (i.e., 3, 7, 14, and 28 days) were tested according to ASTM Standards. Table 7 shows the ranges and averages of compressive strength of concrete mixes. The strength of different batch with normal sand mixes are generally higher than that of the mixes with washed MSW or RDF bottom ash. The compressive strength ratio versus age for those samples are depicted in Figure 4. The curve corresponding to the case using MSW bottom ash as fine aggregate present inconsistent trend as compared with the other two curves. This is probably due to the inhomogeneous nature of MSW ash samples. The average compressive strength of ash mixes are lower than that of the normal sand mixes at all ages. For concrete mixes with water-cement ratio of 0.7, the compressive strength of the MSW and RDF ash mixes are about 54.7% and 35.2% lower than normal sand mixes at the final stage with the age of 28 days, respectively. The reason why concrete mixes with RDF bottom ash presents higher compressive strength as compared with MSW bottom ash is mainly due to the existing of more uniformly distributed particle size in the RDF bottom ash. However, the design strength of normal concrete mixes is 210 Kg/cm² in Taiwan. This implies that compressive strength of concrete mixes with the washed RDF bottom ash as fine aggregate presents about 23% lower than the designed compressive strength of concrete mixes with normal sand. Such outcomes would limit the reuse potential of RDF bottom ash in some construction programs.

CONCLUSIONS

In recent years, the public is concerned about the changing characteristics of incineration in response to the increase of heating values, incinerator emissions and ash properties. This paper specifically investigates the ash property and reuse potential from burning two types of wastes (MSW and RDF) as fuels. The TCLP tests reveal that the bottom ash generated from burning MSW and RDF can

be classified as non-hazardous materials. But both types of fly ash require post-treatment due to higher content of heavy metals. To evaluate the reuse potential of those bottom ash, compressive strength tests were also conducted using washed bottom ash as fine aggregate in a normal mix at general water-cement ratio conditions. These data are useful in determining which applications may be better suited for different sources of ash. Final suggestions of reuse potential of bottom ash as fine aggregate in concrete mixing can be made based on the tested properties of compressive strength and workability. Test results indicate that mass burn of MSW may result in a lower ash reuse potential due to inhomogeneous mixes. Overall, the inclusion of waste sorting process prior to the incineration facilities can provide RDF with better quality to the mass burn process and higher reuse potential of RDF bottom ash may be attained. However, due to relatively lower compressive strength as compared with normal concrete mixing, the reuse potential of incineration ash is rather limited in some construction programs.

Acknowledgement

The authors acknowledge the financial support from the National Science Council (NSC-85-2621-P-006-033) and helpful comments of anonymous referees in the review process.

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Table 1 : TCLP analysis of bottom ash

	MSW	RDF	TCLP Standards
Pb(mg/L)	ND~ND<0.03	0.11~0.12	5.0
Cd(mg/L)	0.01~0.02	0.05~0.06	1.0
Cu(mg/L)	0.3~0.4	0.39~0.40	15
Zn(mg/L)	1.5~1.6	16.1~16.3	25
Cr(mg/L)	0.03~0.04	0.12~0.13	5.0
Hg(mg/L)	ND~ND<0.0002	ND~ND<0.0002	0.2
As(mg/L)	ND~ND<0.001	ND~ND<0.001	5.0
pH	11.8	10.2	—
Cr ⁺⁶ (mg/L)	0.005~0.006	0.05~0.06	2.5
CN ⁻ (mg/L)	ND~ND<0.002	ND~ND<0.002	—

Table 2 : TCLP analysis of fly ash

	MSW	RDF	TCLP Standards
Pb(mg/L)	9.48~9.65	0.03~0.05	5.0
Cd(mg/L)	4.60~4.67	2.599~2.614	1.0
Cu(mg/L)	22.3~22.4	9.62~9.66	15
Zn(mg/L)	5.22~5.34	21.5~21.8	25
Cr(mg/L)	ND~ND<0.02	0.04~0.06	5.0
Hg(mg/L)	ND~ND<0.0002	ND~ND<0.0002	0.2
As(mg/L)	ND~ND<0.001	ND~ND<0.001	5.0
pH	5.6	5.0	—
Cr ⁺⁶ (mg/L)	0.002~0.004	0.002~0.003	2.5
CN ⁻ (mg/L)	0.002~0.003	ND~ND <0.002	—

Table 3 : Chemical composition of ash

	MSW bottom ash	MSW fly ash	RDF bottom ash	RDF fly ash
CaO(%)	34.678	16.901	44.668	19.546
SiO ₂ (%)	18.653	12.481	19.861	20.186
Al ₂ O ₃ (%)	13.973	5.946	13.392	10.897
Fe ₂ O ₃ (%)	27.053	48.341	10.327	43.978
ZnO(%)	—	13.336	5.325	3.528
MgO(%)	5.492	—	4.577	1.590
Cr ₂ O ₃ (%)	—	2.926	1.836	0.164
total(%)	99.850	99.932	99.987	99.890

Table 4: Particle size distribution of RDF bottom ash

sieve no.	retained amount		accumulated amount		accumulated percent		accumulated percent	
	by weight (g)		by weight (g)		retained by weight(%)		passing by weight(%)	
	washed	unwashed	washed	unwashed	washed	unwashed	washed	unwashed
#4	50	50	50	50	5.38	5.03	94.62	94.97
#8	96	96	146	146	15.70	14.69	84.30	85.31
#16	156	156	302	302	32.47	30.38	67.53	69.62
#30	178	178	480	480	51.61	48.29	48.39	51.71
#50	146	146	626	626	67.31	62.98	32.69	37.02
#100	176	176	802	802	86.24	80.68	13.76	19.32
#200	128	128	930	930	100.00	93.56	0.00	6.44
residual		64		994		100.00		0.00

Table 5: Particle size distribution of MSW bottom ash

sieve no.	retained amount		accumulated amount		accumulated percent		accumulated percent	
	by weight (g)		by weight (g)		retained by weight(%)		passing by weight(%)	
	washed	unwashed	washed	unwashed	washed	unwashed	washed	unwashed
#4	56	56	56	56	6.35	5.81	93.65	94.19
#8	112	112	168	168	19.05	17.43	80.95	82.57
#16	96	96	264	264	29.93	27.39	70.07	72.61
#30	114	114	378	378	42.86	39.21	57.14	60.79
#50	104	104	482	482	54.65	50.00	45.35	50.00
#100	230	230	712	712	80.73	73.86	19.27	26.14
#200	170	170	882	882	100.00	91.49	0.00	8.51
residual		82		964		100.00		0.00

Table 6: Properties of normal sand, MSW and RDF ash

property	average or ranges		
	washed MSW bottom ash	washed RDF bottom ash	normal sand
fineness modulus	3.59	3.34	-
specific gravity	2.27	2.38	2.66
water adsorption (%) (at dry basis)	7.4	9	2.0
carbon content (%)	2.60~2.67	0.63~0.66	-

Table 7: Compressive strength of concrete mixes over different ages

choice of fine aggregate	age (day)	compressive strength (kg/cm ²)	
		ranges	average
normal sand	3	106.1~114.9	111.9
washed MSW bottom ash	3	44.2~70.7	58.9
washed RDF bottom ash	3	88.4~97.3	91.3
normal sand	7	150.3~185.7	167.9
washed MSW bottom ash	7	61.8~79.5	73.6
washed RDF bottom ash	7	70.7~128.2	107.5
normal sand	14	194.5~203.4	197.4
washed MSW bottom ash	14	88.4~114.9	106.1
washed RDF bottom ash	14	97.2~150.3	126.7
normal sand	28	221.1~274.1	241.6
washed MSW bottom ash	28	88.4~123.8	109.1
washed RDF bottom ash	28	132.6~176.8	156.2

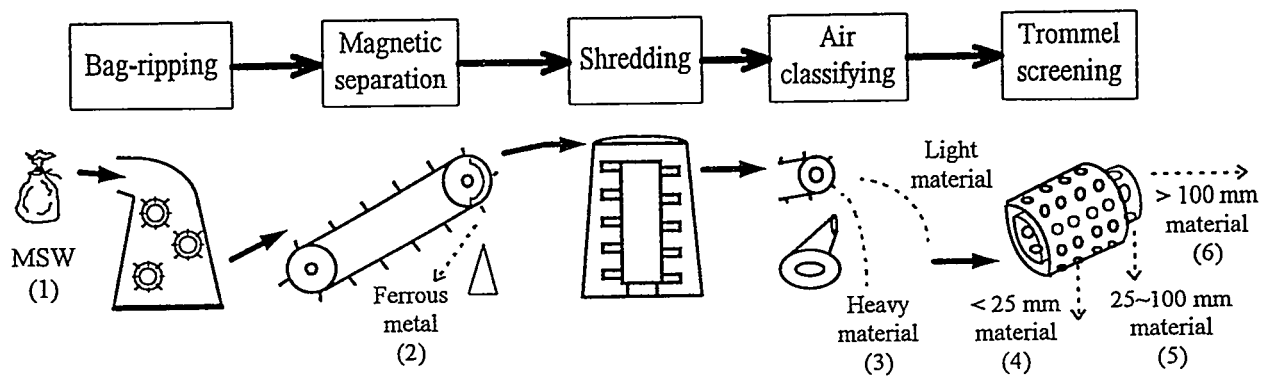


Figure 1: The system configuration of solid waste sorting process

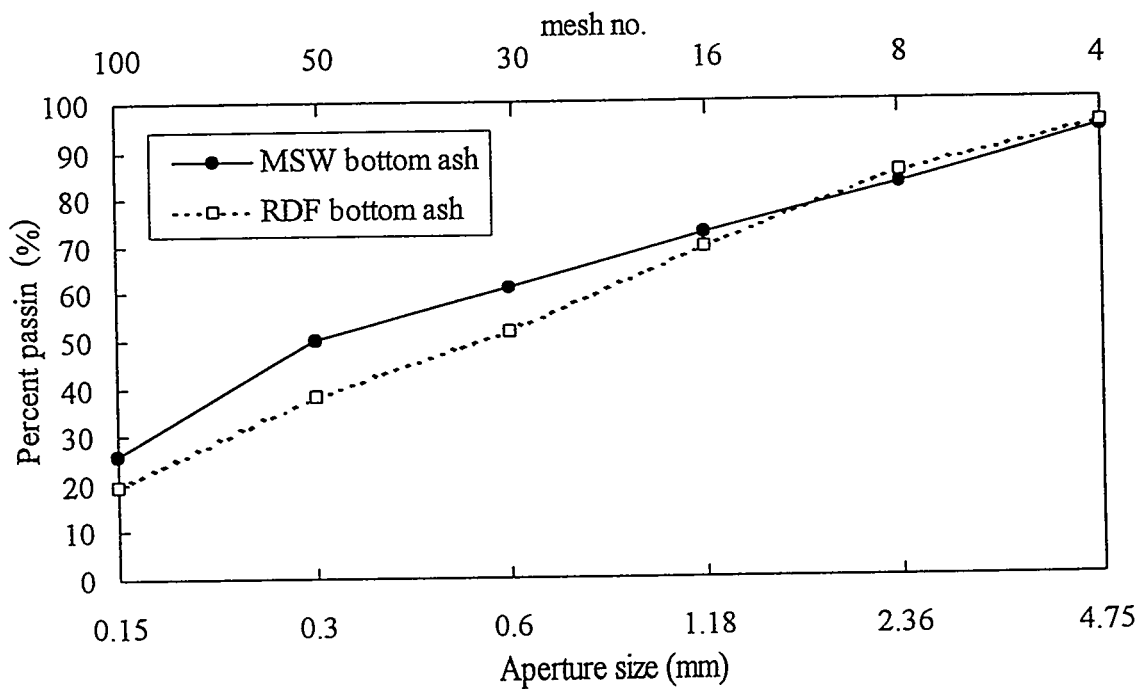


Figure 3: Grading of washed MSW and RDF bottom ash

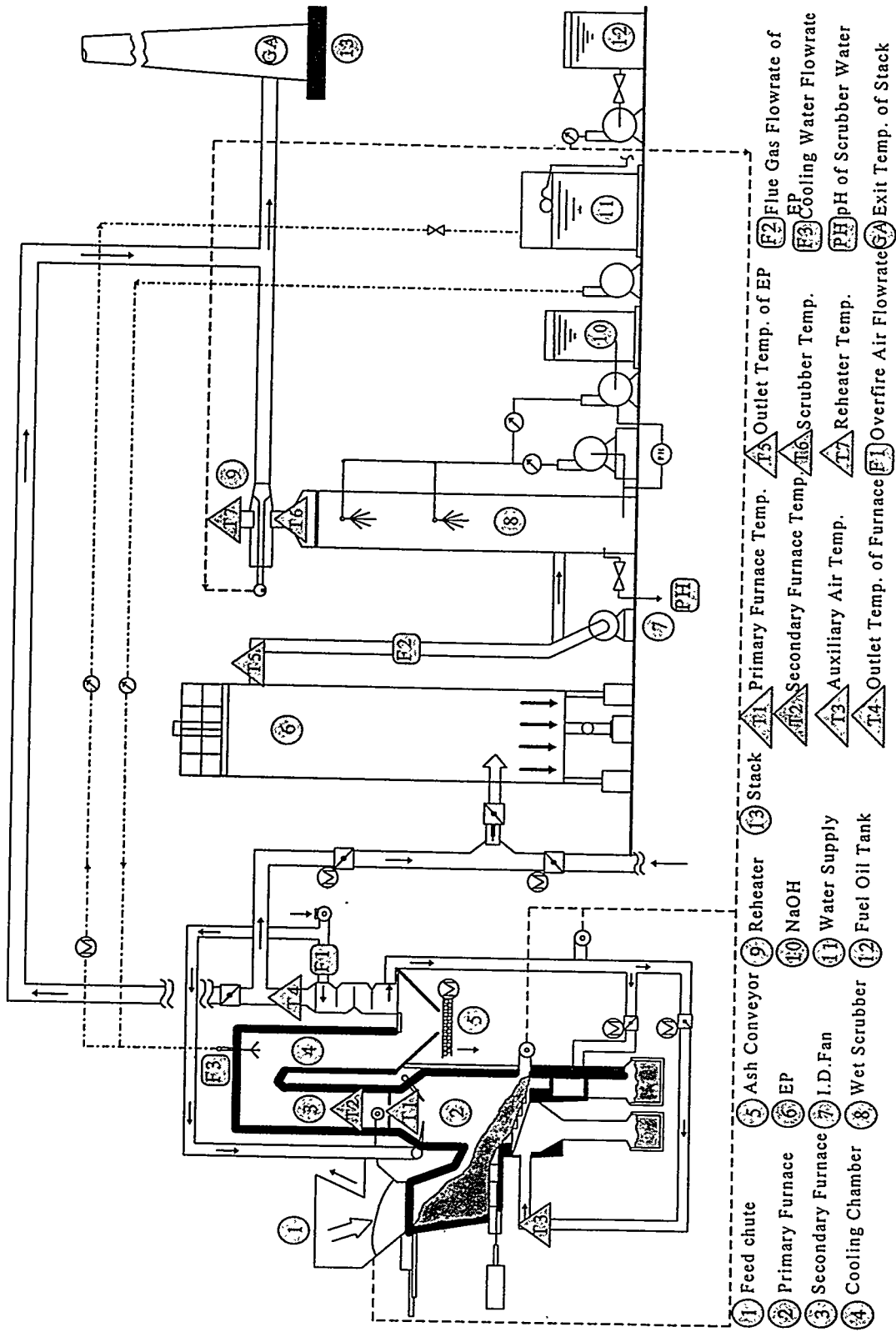


Figure 2: The system configuration of solid waste incineration process

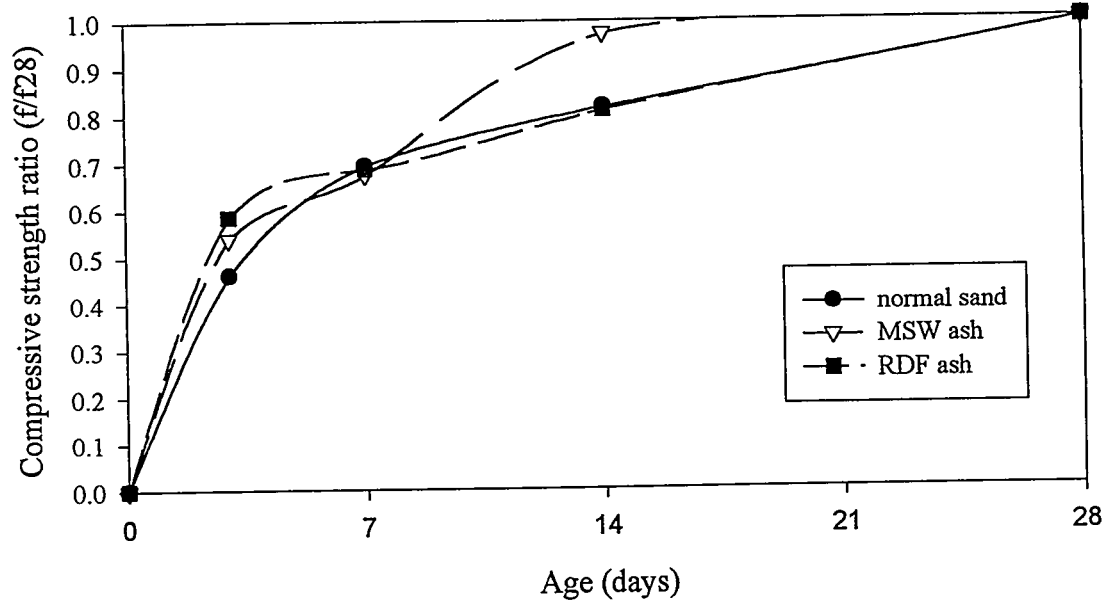


Figure 4: Compressive strength ratio versus age for different conditions of concrete mixing

Investigation into Seasonal Differences of Municipal Solid Waste Combustion Ash Leachate

Thomas Kusterer
Montgomery County, Maryland
Division of Solid Waste Services
101 Monroe Street
Rockville, Maryland 20850

James Reynolds, Aron Trombka, Robert Willson
Montgomery County, Maryland
Division of Solid Waste Services
101 Monroe Street
Rockville, Maryland 20850

INTRODUCTION

Interests in the reuse and recycling of municipal solid waste (MSW) combustion ash have increased as practical uses for this material improve. Among factors that warrant further investigation as interests rise for ash reuse is the variability of ash and ash leachate characteristics due to seasonal variations in the composition of the waste stream combusted. Since the constituents of MSW can vary by season, ⁽¹⁾ a logical assumption is that ash from the combustion of such waste also varies. Montgomery County, Maryland investigated the seasonal variations in the characterization of MSW ash and MSW ash landfill leachate from their Waste-to-Energy facility over a period of eighteen months.

BACKGROUND

Demographics

Montgomery County, Maryland, approximately 495 square miles in size, is located in the south-central portion of the state, northwest and immediately adjacent to Washington, DC. Population in 1996 was approximately 810,000 ⁽²⁾, the highest population of any Maryland jurisdiction and comparable to the population of Indianapolis or San Francisco. There are about 315,000 households in the County, with about 215,000 of those single-family households. There are approximately 20,000 businesses in the County. While the County is headquarters for companies such as Lockheed Martin and Marriott, most businesses are relatively small, with about 80 percent employing fewer than 100 individuals. There is very little manufacturing or heavy industry in the County. Most businesses are service oriented.

The Municipal Solid Waste Management System

Municipal solid waste generated in the County is managed through a comprehensive, integrated system that includes aggressive waste reduction measures, curbside and drop-off recycling services, waste-to-energy, composting and landfilling. The system employs five facilities including a materials recycling center for processing co-mingled recyclable material and newspapers; a yard waste composting facility; a transfer station complex that includes waste and recyclables drop-off by citizens, yard material grinding, small quantity hazardous waste drop-off, and MSW receiving and transfer to a rail transportation system; a waste-to-energy facility that receives waste only from the transfer station via the rail transportation system; and a landfill that provides disposal for non-processible waste and includes a separate ash monofill. All facilities are operated by the County or on their behalf through contracted operators.

The County generates approximately 900,000 tons per year of municipal solid waste, with about 540,000 tons from the residential sector and approximately 360,000 tons per year from the non-residential sector. Approximately 315,000 tons of waste -- a 35% recycling rate -- were recycled in 1995. Approximately 475,000 tons, are combusted in the County's waste-to-energy facility. The remainder, mostly from commercial generators, is exported from the County for disposal and/or recycling.

The County provides curbside recycling services for the collection of newspapers, mixed glass, aluminum and bi-metal cans, and High Density Polyethylene (HDPE) and Polyethylene Terephthalate (PET) plastic containers. The newspapers are kept separate from other materials during collection and are transferred to a private processing facility. The other materials are co-mingled during collection and are separated and processed at the County's Materials Recycling Center. The County intends to expand residential recycling and initiate a mixed paper collection program during the early part of 1998. County law also requires that commercial facilities and multi-family dwellings institute recycling programs. At a minimum, commercial facilities must recycle corrugated cardboard, office paper, newspaper,

aluminum and bi-metal cans, glass, plastic, and yard waste. The combination of residential, multi-family and commercial recycling programs has enabled Montgomery County to recycle approximately 35 percent of its waste stream. The County has a goal of achieving a 50 percent recycling rate by the year 2000.

WASTE COMPOSITION

A substantial portion of the current recycling rate is due to a yard waste ban which the County instituted in 1994. Yard waste is not accepted at disposal facilities and is now composted either by property owners, or is collected from residents and delivered to the County's yard waste compost facility. Therefore, the historic seasonal fluctuations previously associated with spring and summer surges of yard waste material have been largely removed from the disposal stream. County studies have shown that waste composition remains relatively consistent throughout the year, although volume decreases in winter months due to lower activity in general.

From 1994 through 1996, Montgomery County conducted quarterly characterization studies of municipal solid waste delivered to the County's Transfer Station. The intent of these studies was to generate data necessary to evaluate existing waste reduction, recycling and disposal programs, and to plan and implement new programs.

Waste sorters randomly selected 75 MSW samples during a one-week period in February, May, August and November. The minimum weight for each sample was 300 pounds, yielding a total weekly sample size of over 10 tons. Wastes were sorted by hand into over 50 categories for each of the three generating sectors: (1) single-family residential; (2) multi-family residential; and (3) non-residential.

Of the 75 samples taken each quarter, 30 were taken from vehicles delivering waste from the non-residential sector, 25 samples were taken from vehicles collecting from single-family residential homes, and 20 samples were taken from vehicles collecting from multi-family residential units exclusively. The County also calculated the aggregate composition of the full MSW disposal stream using weighted data from each of the three sectors.

Hazardous material segregated through the sampling included batteries, solvents, corrosives (typically cleaning fluids), fuels, and poisons (typically pesticides and herbicides). In each of the four seasonal samplings hazardous materials constituted less than one percent of the municipal solid waste processed by the County. Other major components of the waste stream also varied minimally from season to season.

Aggregated data for waste stream composition from calendar year 1995 is presented in Table 1. This is the only calendar year where sampling occurred in all four seasons.

LANDFILL LEACHATE

Landfill Design

The County is served by one active and permitted municipal solid waste landfill. The landfill became operational in June, 1982, and received approval for a vertical expansion in February, 1990. A separate area of the landfill was approved as a monofill for accepting ash from the waste-to-energy facility, and became operational with the waste-to-energy facility in May, 1995. The original landfill design included a

prepared floor with compacted soil that met a permeability of 6×10^{-6} cm/sec or less. A leachate collection system was constructed with a series of trenches filled with crushed stone and perforated lateral collection pipe. These pipes lead to trenches with perforated header pipes also embedded in crushed stone. The design for the vertical expansion incorporated this older design into a new perimeter collection system. Design of the vertical expansion consisted of geonet with filter fabric placed over an 80 mil HDPE liner that was placed predominately over the top of the original landfill. One foot of highly permeable rounded stone overlays the geonet.

Leachate flows by gravity to HDPE perforated collection pipes at the base of the new cells and then to lateral HDPE pipes. These lateral pipes subsequently direct leachate to manholes located outside the disposal area and then to a common leachate conveyance system that transports the material by gravity to a leachate lift-pump station. Leachate from the original area of the landfill and the vertical expansion are co-mingled in the header piping surrounding the fill area. However, leachate from the ash monofill remains separated until it intersects the primary conveyance system that directs the leachate to the leachate lift pump. At that intersection a manhole provides access for separate sampling of the ash leachate and the MSW leachate.

Leachate is then pumped into one of two double-lined open leachate storage lagoons that hold the leachate prior to on-site pre-treatment. A total of approximately 7,000,000 tons of MSW have been placed in the landfill since operations began in June, 1982 through December, 1996. Ash from the County's RRF, which began test burning in May, 1995, has been disposed in the dedicated ash disposal cell with approximately 200,000 tons of ash disposed to date. No daily or intermediate cover is required for the ash since litter and vector control are not of concern, and the ash moisture content is such that dusting of the ash is minimized.

The volume of leachate generated ranged from zero gallons per month to approximately 140,000 gallons per month before the landfill's expansion. The range of volume generated has been higher after the landfill's expansion because the new HDPE-lined cells are more effectively collecting leachate compared to the older soil-lined cells. For example, the amount of leachate generated at the landfill in 1996 has ranged from approximately 46,000 gallons in August to approximately 1,650,000 gallons in November, with a total leachate influent from the landfill of approximately 10,000,000 gallons in 1996.

The County pre-treats the leachate generated by the landfill before disposing of the liquid in a sanitary sewer. The County selected a biological process system that uses a fixed film process for reduction of the leachate's organic content. The selected system also incorporates elements of physical and chemical treatment. The process system selected, and now operational, is capable of processing up to 30,000 gpd at 1,500 mg/l BOD concentrations. The system has the hydraulic capacity of handling up to 60,000 gpd. Biological activity occurs in two 36 foot by 9 foot by 8.5 foot bioreactors. Each bioreactor has four cells where organic reduction occurs. Each of the eight cells currently uses aerobic treatment to decompose organic constituents, with the capability for conversion to anaerobic treatment if leachate conditions warrant. Reactors are made of coated carbon steel and enclose corrugated polyvinylchloride sheets laminated together at opposite angles so that a cross flow matrix occurs. This design creates almost 105,000 square feet of effective surface area media. The media is the site for organism attachment and growth.

Untreated leachate is pumped from one of the two synthetically double-lined open storage lagoons, through a feed line to centrifugal influent pumps. Gentle agitation via the flocculation mixer creates growth and aggregation of particles, including metals. As much as 90 percent removal of metals can occur through this

precipitation process. Clarified leachate from the precipitation process spills over a weir and flows by gravity to a splitter box. The splitter box directs equal liquid flow to the two bioreactors. Clarified effluent from the bioreactors flows by gravity to a 400 gallon effluent holding tank, where a horizontal centrifugal pump sends the pre-treated leachate to the synthetic double-lined storage lagoon. Pre-treated leachate is pumped into tanker trucks from the storage lagoon and hauled to a sanitary sewer where it is discharged for final treatment.

Sampling Protocol

Although the County is not required to sample ash leachate, it wanted to gather data regarding this material and began sampling in September, 1995. Samples of untreated ash leachate are taken monthly from a manhole that enables access for sampling the ash leachate separate from the other leachate. Sixteen constituents in the leachate are analyzed monthly (Table 2). Two constituents -- antimony and fats, oil and grease were detected in minimal concentrations, and are not included in Table 2. Grab samples are taken for fats, oil and grease analysis, while all other samples are composite samples. Samples are collected in 3.8 liter plastic containers, and then transported to a state-certified laboratory. Chain-of-custody controls are maintained through the conclusion of constituent analyses.

Ash Field Leachate Results and Discussion

Table 2 shows monthly sampling results for 14 constituents analyzed in the County's ash field leachate for the period between September, 1995 (when the ash leachate sampling program began) through December, 1996. There is no readily apparent pattern in constituent levels due to season or other factors. Most metals have been at non-detectable levels since April, 1996 (when the metal sampling program was broadened to include antimony, arsenic, cooper, chromium, mercury and nickel). Where there seems to be some evidence of possible seasonal effects -- total dissolved solids' levels are higher in October-December, 1995 than those in other months -- there is no replication of this phenomena in October-December, 1996. Levels for the latter period are similar to those of other months and seasons.

Values for the ash leachate constituents appear to be in the range reported in the literature (Table 3). County data presented in Table 3 is the mean for all observations of the particular constituent since the sampling program began for that particular constituent. Generally speaking, metal concentrations in the County's ash leachate appear to be in the lower part of the range reported in the literature. Table 4 displays 1996 data by season. The three month periods listed in the table are meant to correspond to the four seasons. The mean and standard deviation for these observations are also provided. No other statistical analyses were performed for these data because of the limited number of observations and the possibility that they might not provide an accurate representation of the actual situation. Indeed, there are some data where the standard deviation is larger than the mean (e.g., Biochemical Oxygen Demand) and other data where the standard deviation is comparable to the mean (e.g., Chemical Oxygen Demand (COD) and Total Suspended Solids (TSS)). Comparing the mean and standard deviation provides a casual method of finding changes in the constituents.

There are instances where constituents seem to vary significantly from the mean and from other seasonal concentrations. COD in July-September and in October-December is less concentrated than its mean concentration and also compared to concentrations in other season. There is a similar pattern in TSS concentrations. A comparison of these data with constituent levels in pretreated leachate shows similar patterns (Table 5). Whatever factors causing these concentration variations in the ash leachate seem to be affecting the general leachate population. Other factors besides potential seasonal variation in waste characteristics that might affect leachate concentrations are age of the landfill and its waste, types of waste

in the landfill, precipitation and volumes of raw leachate discharged from the landfill to the storage lagoons. It is difficult to ascertain a pattern of seasonal waste effects based on current landfill leachate data. More historical leachate data will help to clarify the question of possible seasonal effects from waste characteristics.

ASH CHARACTERIZATION

WTE Facility Design

Montgomery County's WTE facility is a mass-burn design with three 600 tpd units. The facility utilizes the Martin grate technology, and is operated by Ogden Martin Systems of Montgomery, Inc. The facility employs a semi-dry scrubber and reverse air baghouse as its principal air emissions control equipment. Fly ash is conveyed in enclosed augers from the baghouse, in reverse direction of the gas path, collecting spent scrubber residue and ash from various areas of the boiler. Fly ash and bottom ash are combined below the boiler and conveyed to a single ash storage pit before being removed for off-site disposal. In addition, dolomitic lime is introduced to the fly ash to help ensure that metals do not leach from the ash in unacceptable concentrations.

Acid gases are also controlled by injection of dry lime directly into the furnace area of the boiler. The furnace dry lime injection (FDLI) system operates in standby mode, and is secondary to the semi-dry scrubber. It functions in hand with the scrubber through a continuous emissions monitoring (CEM) system. The CEM reads the concentrations of SO_2 in the gas path at the scrubber exit. As acid gas concentrations rise in the scrubber exit, the feed mechanism of the scrubber is signaled and the system begins feeding additional lime into the scrubber. If the lime feed rate in the scrubber rises beyond a set point, the FDLI system is signaled and dry hydrated lime begins to feed into the boiler at a rate that is set to "catch" the rising concentrations and reduce them to a level managed only by the scrubber. Once controlled, the FDLI system is put back into a standby mode.

NO_x is controlled by a selective non-catalytic reaction (SNCR) which utilizes aqueous ammonia to reduce NO_x . Ammonia is injected into the furnace area of the boiler above the point of the FDLI nozzles.

Mercury and other organics and trace metals are controlled through the injection of dry activated carbon into the gas path before the scrubber inlet. The scrubber and baghouse help to control these parameters as well.

The CEM system reads seven parameters – CO , CO_2 , O_2 , NO_x , SO_2 , HCl , and opacity – on a continuous basis. Data is averaged over various time periods, depending on the permit requirements for that parameter. The CEM system continuously sends signals to the operating equipment and control mechanisms to actively influence the feed rates of all reagents in the air emission control system and related operations such as fuel feed rate and combustion air volumes.

Sampling Protocol

In accordance with the requirements of the Maryland Department of the Environment (MDE), an ash characterization program was implemented at the facility. Discussions with MDE and USEPA staff, and the use of their guidance documents, formed the basis of the County's sampling protocol that was developed before the facility came on line in 1995. The program follows the widely used protocol

identified in USEPA documentation.⁽³⁾⁽⁴⁾⁽⁵⁾ Sampling has been conducted every calendar quarter since the facility became operational. In each sampling event the full complement of TCLP metal and organics testing was performed.

Combined ash is sampled across the width of a vibrating conveyor just before it is fed into containers for transport off site. This location is consistent with USEPA's January 1995 decision regarding the point of generation at WTE facilities, and properly represents the ash that leaves the site for disposal. The facility stores its ash in a pit before it is processed for ferrous metal recovery and containerized for transport. Because the pit can be excavated faster than the ash enters it, a determination was made as to how frequently ash is to be sampled to ensure a representative sample over an operating shift of the boilers. Sampling is scheduled to provide fourteen grab samples for each operating shift, based on the excavation rate of the pit. Because operations are based on a 12-hour shift, sampling represents a 24-hour operating period.

The grab samples that represent a single shift are combined to form a shift composite sample. Collecting for two shifts per day, fourteen shift composite samples are collected over the course of seven days of sampling. Each shift composite sample is derived by properly mixing, and quartering the grab samples for that shift. Four sub-samples are created from each shift composite sample. The sub-samples are mixed, screened for sizing material $-3/8''$ and $+3/8 -2''$, crushed where required and screened again, and weighed. Sample aliquots for TCLP extraction are prepared by mixing proportional amounts from both sizes of material.

All samples are labeled and protected throughout the process using chain of custody procedures. Laboratory procedures follow established protocol for TCLP testing and reporting.

TCLP Results and Discussion

Ash from Montgomery County's WTE facility continues to test as a non-hazardous material. As expected, organic compounds, herbicides and pesticides are non-detectable. The test results of the metals analyses are summarized in Table 6. Montgomery County has chosen to report and use all test data for calculation of the upper confidence interval (UCI) – including statistical outliers that are determined based on Chauvenet's Criterion. Their inclusion in the data raise the respective UCI for that analyte and that test event.

A review of the data suggests that three metals (Arsenic, Selenium and Silver) have not been detected in any test. One metal (Barium) has been detected twice, and Chromium has been detected once, all at levels that were approximately one-half of one percent or less of their regulatory thresholds.

Cadmium and Lead, generally the most closely observed analytes, were both detected. However it is worth noting that Lead was reportable in only two events (29%), and at only 6.4% to 8.8% of its regulatory threshold. Statistical outliers, based on Chauvenet's Criterion, are included in the data for Lead in both test events where it was detected. Cadmium was reportable in all seven events at levels that ranged from 1.9% to 46.6% of its regulatory threshold. Statistical outliers are included in the data for Cadmium in all but the May and August test events.

Mercury was detected in four of seven test events, but at levels that range from 0.3% to 1.9% of its regulatory threshold. It appears that capturing Mercury from the gas stream has indeed resulted in its deposit in the ash. However, because Mercury control technology is not operating on many WTE plants with a scrubber and baghouse, additional data is needed to substantiate this observation.

Because most tests did not result in consistent detection of analytes, Cadmium is the only analyte that can be compared seasonally. As with landfill leachate data, it is difficult to ascertain a pattern of seasonal effects on ash leachate by comparing the Cadmium results.

CONCLUSIONS

Data collected to date from the Montgomery County waste-to-energy facility do not clearly indicate seasonal affects on the leachate from the ash or leachate from the ash disposal cell, at least with respect to the parameters of regulatory concern which have been reviewed herein. One reason for this may be that the output of a waste disposal facility is in good measure a function of the input to that facility. The composition of waste entering Montgomery County facilities has not demonstrated marked seasonal variations. Given the consistency of the waste stream and the effect that lime has in stabilizing ash from the combustion process, the lack of hazardous constituents in ash leachate, and the general lack of definable seasonal variations is not necessarily surprising.

Montgomery County will continue periodic testing of ash residue and landfill leachate. A more substantial database will evolve over the next few years which will enable review of these findings.

References

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2. Maryland National-Capital Park and Planning Commission, Washington, DC, personal communications, December 11, 1995.
3. Sampling and Analysis of Municipal Refuse Incinerator Ash, US Environmental Protection Agency, May 1994.
4. Guidance for the Sampling and Analysis of Municipal Waste Combustion Ash for the Toxicity Characteristic, EPA 530-R-95-306, US Environmental Protection Agency, June 1995.
5. Manual SW-946 - Test Methods for Evaluating Solid Waste - Physical/Chemical Methods, US Environmental Protection Agency, March 1992.
6. Introduction to Environmental Statistics, Environmental Protection Agency.

Table 1. Waste Stream Composition. ⁽¹⁾

Material Type	Percent by Weight
Paper Products	44
Organics	30
Plastics	10
Glass	4
Ferrous Metals	3
Wood	3
Inert Materials	3
Yard Waste	2
Non-ferrous Metals	1
Hazardous Materials	<1

(1) Aggregated data from 1995. Paper, plastics, metals, glass and yard waste result from portions of the waste stream not captured by recycling programs.

Table 2. Montgomery County (MD) Landfill Ash Leachate Analytical Results (mg/L).

Month	pH	BOD	COD	TDS	TSS	Sulfates	Chlorides	Cadmium	Lead	Arsenic	Chromium	Copper	Mercury	Nickel
1995														
September	6.0	40	870	20,000	37	220	9,800	0.02	0.04	NS	NS	NS	NS	NS
October	6.2	16	1,200	37,000	66	520	20,000	0.05	0.86	NS	NS	NS	NS	NS
November	6.2	780	1,800	48,000	96	530	23,000	0.02	0.50	NS	NS	NS	NS	NS
December	6.7	110	2,000	80,000	48	860	42,000	0.05	0.60	NS	NS	NS	NS	NS
1996														
January	8.3	240	550	21,000	270	320	14,000	ND	0.30	NS	NS	NS	NS	NS
February	6.1	1,200	1,700	82,000	950	780	47,000	ND	1.00	NS	NS	NS	NS	NS
March	6.3	320	2,100	40,000	370	470	35,000	ND	ND	NS	NS	NS	NS	NS
April	6.0	160	1,100	32,000	310	450	16,000	ND	0.10	ND	ND	0.01	ND	0.14
May	6.1	75	620	21,000	33	290	12,000	ND	ND	ND	0.02	ND	ND	0.07
June	5.9	72	500	28,000	530	220	13,000	ND	ND	ND	ND	ND	ND	ND
July	6.2	70	340	38,000	160	500	19,000	ND	ND	ND	ND	ND	ND	ND
August	6.5	ND	200	23,000	70	240	13,000	ND	ND	ND	ND	0.06	ND	ND
September	6.5	15	140	20,000	240	240	10,000	ND	ND	ND	0.02	0.02	ND	ND
October	6.5	5	280	23,000	37	600	12,000	ND	ND	ND	ND	0.02	ND	ND
November	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
December	7.3	100	260	23,000	76	150	10,000	ND	ND	ND	ND	ND	ND	ND

NS- Not Sampled

ND- Not Detected within Methodology Limits

Table 3. Comparison of Montgomery County (MD) Landfill Ash Leachate Inorganic Constituents for 1996 with Literature Reported Results for Ash Leachate (mg/L).

Source	pH	Chloride	Sulfate	Arsenic	Cadmium	Chromium	Copper	Lead	Mercury	Nickel
Montgomery County	6.45	19,720	426	0	ND	0.003	0.007	0.227	ND	0.014
Bagchi-a	8.47-9.94	33-305	105-1,440	<0.2	0.004-0.3	0.01-0.044	.026-0.103	0.15-0.6	<0.0002	0.01-0.03
CORRE Study-b	6.41	NA	1,259	ND-0.4	ND-0.004	ND-0.032	ND-0.012	ND-0.054	ND	NA

NA-Not Analyzed

ND- Not Detected within Methodology Limits

a-"Design, Construction and Monitoring of Sanitary Landfill," A. Bagchi, John Wiley and Sons, 1990, p. 41.

b- "Characterization of Municipal Waste Combustion Ash, Ash Extracts and Leachates," U.S. Environmental Protection Agency, EPA 530-SW-90-029A, March 1990, p. 7-21

Table 4. Seasonal Average of Ash Leachate Inorganic Constituents, 1996 (mg/L).

Season	pH	BOD	COD	TDS	TSS	Sulfates	Chlorides	Cadmium	Lead	Arsenic	Chromium	Copper	Mercury	Nickel
January-March	6.9	587	1,450	47,667	530	523	32,000	ND	0.43	0	NS	NS	NS	NS
April-June	6	102	740	27,000	291	320	13,667	ND	0.03	ND	0.01	0	ND	0.07
July-September	6.4	28	227	27,000	157	327	14,000	ND	ND	ND	0.01	0.03	ND	0
October-December	6.9	53	270	23,000	57	375	11,000	ND	ND	ND	0	0.01	ND	0
Mean	6.6	192	672	31,167	259	386	17,667	ND	0.12	0	0	0.01	0	0.02
Standard Deviation	0.34	205	440	8,645	159	73	7,474	ND	0.16	0	0	0.01	0	0.03

Table 5. Comparison of Select Inorganic Constituents by Season, Ash Leachate and Pretreated Leachate, 1996 (mg/L).

Season	ash leachate pH	pretreated pH	ash leachate COD	pretreated COD	ash leachate TDS	pretreated TDS	ash leachate TSS	pretreated TSS	ash leachate Cadmium	pretreated Cadmium	ash leachate Lead	pretreated Lead
January-March	6.9	7.1	1,450	287	47,667	4,933	530	85	ND	0.02	0.43	ND
April-June	6.0	7.5	740	213	27,000	6,567	291	73	ND	ND	0.03	ND
July-September	6.4	7.3	227	153	27,000	7,233	157	28	ND	ND	ND	ND
October-December	6.6	6.9	270	143	23,000	6,033	57	61	ND	ND	ND	ND
Mean	8.6	7.2	672	199	31,167	6,192	259	62	ND	0.01	0.12	ND
Standard Deviation	0.33	0.22	440	51	8,645	753	159	19	ND	0.01	0.17	ND

ND - Not Detected within Methodology Limits

Table 6. Montgomery County, Maryland MWC Ash Characterization Comparison of TCLP Statistical Results for Metal Analytes (1)

Analyte	90% UCI(2) Jul 95	90% UCI(2) Dec 95	90% UCI(2) Feb 96	90% UCI(2) May 96	90% UCI(2)(3) Aug 96	90% UCI(2) Nov 96	90% UCI(2) Feb 97	Regulatory Threshold
Arsenic	ND/0.06	ND/0.06	ND/0.5	ND/0.5	ND/0.5	ND/0.5	ND/0.5	5.0
Barium	ND/0.5	0.47	ND/10	ND/10	ND/10	ND/10	0.55	100.0
Cadmium	0.019	0.122	0.166	0.414	0.434	0.125	0.466	1.0
Chromium	0.018	ND/0.2	ND/0.5	ND/0.5	ND/0.5	ND/0.5	ND/0.5	5.0
Lead	ND/0.1	0.32	ND/0.5	ND/0.5	0.44	ND/0.5	ND/0.5	5.0
Mercury	0.0038	ND/0.0006	0.0012	0.0006	0.0006	ND/0.0005	ND/0.0005	0.2
Selenium	ND/0.06	ND/0.06	ND/0.1	ND/0.1	ND/0.1	ND/0.1	ND/0.1	1.0
Silver	ND/0.04	ND/0.04	ND/0.5	ND/0.5	ND/0.5	ND/0.5	ND/0.5	5.0

All units expressed as milligrams per liter (mg/l)
ND = Non-Detectable

(1) All other analytes were non-detectable. Statistical outliers (based upon Chauvenet's Criterion) are included in the data, resulting in higher UCI levels. Laboratory detection levels for non-detectable results are reported after the ND/.

(2) 90% Upper Confidence Interval as a single-tailed distribution is equivalent to an 80% Upper Confidence Interval as a two-tailed distribution, i.e., there is only a ten percent chance that the result could be higher.

(3) Testing of archived split sample for Lead showed lower concentrations. Worse case results are reported.

**Removal and Recovery of Heavy Metals From
Incinerator Ash Residues**

**Keith E. Forrester, P.E., M.S.Env.Eng.
President
Forrester Environmental Services, Inc.
P.O. BOX 2008
Hampton, NH 03843-2008**

Peer Review

INTRODUCTION

This paper presents results of a novel and state-of-the-art patent-pending processes developed jointly by Forrester Environmental Services Inc. ("FESI") and Brookhaven National Laboratories ("BNL") for the extraction and recovery of lead (Pb), Cadmium (Cd), Copper (Cu), Zinc (Zn) and other heavy metals from heavy metal bearing wastes including but not limited to solid waste incinerator bottom ash, flyash and combined ash.

The heavy metal extraction and recovery processes were found to be capable of high percentage of heavy metals extraction and recovery at a relatively low cost under bench scale and full-scale refuse incinerator facility conditions. This paper presents empirical data from bench scale studies only, as the full-scale data is currently under review. The ash product remaining after extraction passed all TCLP regulatory limits and retained only minimal Pb, Cd, Cu, and Zn content and other water insoluble heavy metal compounds.

The extraction efficiency of the processes exceeded expectations for Pb, Zn and other key heavy metals at 90%+ levels, thus yielding post-extracted ash heavy metal contents well within current USEPA and state allowable levels in residential soils. The process capital and operating expenses were also determined to be highly cost competitive against conventional and currently used ash stabilization methods. The FESI/BNL Heavy Metal Extraction and Recovery Process is currently under contract for use at industrial applications throughout the world including waste incinerators and is expected to enhance the acceptance of incinerator ash use by significantly reducing the content, solubility and availability of heavy metals therein.

Results of heavy metals recovery and low cost from ongoing field applications of this technology are consistent with the bench scale data presented within this paper.

BACKGROUND

Waste-to-Energy Ash Production and Type

Waste-To-Energy ("WTE") facilities employ a form of recycling, involving the use of solid waste as a fuel to produce steam which in turn is used to produce electricity. In the combustion process the total volume of solid waste is reduced by 90%, resulting in an ash generation of nearly 10% by volume and 30% by weight. In most modern WTE facilities, refuse is combusted at temperatures approaching 1800 to 2500 degrees Fahrenheit. Most organic materials in

the solid waste are reduced to base elements such as Carbon, Oxygen and Nitrogen. Inorganic materials such as iron, aluminum, calcium, sodium and silicates make up the major components of ash residue, along with much smaller weight fractions such as Pb, Cd and Zn which are regulated due to their relative toxicity and potential threat to the environment.

The ash residues are collected at various points throughout the system, producing three distinctive types -- bottom ash (BA), fly ash (FA), and flyash scrubber residue (FASR). As the words imply, bottom ash is collected at the bottom of the furnace grates following the combustion process. Flyash is composed of small particles which are carried by the combustion flue gas and then captured by the air pollution control devices or drop-out hoppers. Bottom ash typically represents roughly 85 to 90 percent by weight of the total ash produced in a mass burn facility, with flyash and scrubber residues comprising the remaining 10 to 15 percent ("scrubbers" are combustion gas cleaning systems that neutralize acid gases). The BA/FA+FASR ratio for Refuse-Derived Fuel ("RDF") combustion facilities which remove a fraction of ferrous, non-ferrous and certain non-combustible wastes prior to combustion has been measured by FESI at full-scale operations at 50/50.

The use of lime scrubbers can significantly alter the leachability of FA by increasing or decreasing Pb solubility and decreasing Cd solubility based upon the pH-log solubility characteristics of those elements and compounds thereof. The water solubility of FA without lime scrubbing is often relatively low due to the neutral pH condition of FA, yet as lime scrubbing products and unreacted lime as hydroxide are added, the water solubility of the Pb in the newly produced FASR can greatly increase ... this due to the amphoteric nature of Pb that remains water soluble under low and high pH conditions.

The use of the acidic TCLP #2 test to measure the leachability of FASR under an assumed acid leaching condition actually lowers the pH of the FASR in solution with dilute acetic acid, and now presents FASR Pb solubility at a semi-neutral pH condition, as compared to the more probable high pH condition likely to occur in the field under much less acidic leaching conditions. Consequently the TCLP test can greatly under-predict the leaching potential of FASR.

Current Ash Management

Most commonly, FA/FASR and BA are combined at the WTE

facility and transported to permanent disposal sites. BA is usually wetted in a water quench system to allow for a boiler air seal and to cool the 1800 to 2500 degree F mass of silica and non-combustibles. The larger fractions of BA such as slag often fractures upon wetting due to sudden cooling in the water quenching tank.

FA and FASR are bone dry as generated from air pollution control devices after dry scrubbing towers, and are collected in enclosed hoppers due to their dust-like fugitive nature and human exposure risk. These FA/FASR residues are often wetted to control dusting, and thereafter added to the BA for disposal, thus producing a combined ash ("CA").

Landfill disposal remains the simplest and most cost effective method of disposing both BA and FA/FASR. The preferred practice is to dispose of the residue at the residue-only landfill, referred to as an ash "monofill".

Various concerns have been raised by regulators, public interest groups and scientists alike regarding the safe handling, disposal and possible use of ash residues. One of the most common concerns raised relates to the total compositional content of Pb and Cd in ash the fate of those elements over the long-term use and handling of ash products in the open environment.

Some opponents to ash use argue that: (a) heavy metals contained in residue are concentrated at unacceptable levels and (b) the metals are "leachable components" which have the potential to reach groundwater supplies. "Leachable components" are those elements or compounds which have the potential to dissolve in water. Ash use critics often also claim that as rainfall percolates through ash, it has the potential to leach these heavy metals and transport them into the water supply.

However, scientific tests throughout the international community have demonstrated that ash residues from modern WTE facilities, when properly managed at ash landfills do not leach contaminants at significant risk levels. In fact, CA leachate closely resembles seawater. As a matter of extra safety, these CA leachates are often collected and stabilized prior to disposal in accordance with strict federal and state environmental standards.

THE NEED FOR METALS CONTENT REDUCTION

In addition to the above mentioned leaching of heavy metal

bearing wastes, human and biological exposure to heavy metal content has long been of concern to environmental regulators and waste producers. Under the Resource Conservation and Recovery Act (RCRA) solid waste is classified by the U.S. Environmental Protection Agency (USEPA) as hazardous waste if excessive amounts of heavy metals leach from the waste when tested under the Toxicity Characteristic Leaching Procedure (TCLP). EPA also regulates the land disposal of certain heavy metal bearing wastes depending on the content of the heavy metals regardless of the leaching potential. In addition, several state governments require solid wastes with elevated levels of heavy metals be disposed of as a hazardous waste. Disposal of waste at a hazardous waste landfill is typically more expensive than disposal at non-hazardous waste landfills.

In an attempt to reduce the expenses associated with the landfill disposal of heavy metal leachable waste, particularly lead bearing waste, various methods to control heavy metal leaching and reduce heavy metals have been developed. These methods include the stabilization of lead bearing waste with, for example, portland cement, silicates, sulfates, phosphates and combinations thereof as well as acid digestion and metals recovery. However, these methods are often expensive and involve complex handling equipment and operations. Additionally, some of these methods use chemicals, such as strong acids, which in the amounts used, are hazardous to workers and corrosive to the waste handling and treatment equipment.

The stabilization methods most commonly used do not reduce compositional level or bioavailability of Pb and other regulated metals, and thus fail to reduce the risks of direct exposure to the waste after treatment. Given that many states now require limitation of heavy metal content for use or RCRA Subtitle D solid waste disposal of industrial wastes, the stabilization methods fail to provide the required technology for waste reuse or local landfilling.

Accordingly, a need exists for means of reducing lead content beyond leachable fractions, particularly when considering reuse of the ash outside of a landfill where environmental sensitivity to newly introduced heavy metals such as Pb and Cu can be extreme.

FESI/BNL PROCESS

In late 1993 FESI and BNL entered in the first of two Cooperative Research Agreements (CRADA) for development of a

safe, simple and inexpensive method of extracting and recovering inorganic compounds from industrial wastes. The process method is not disclosed herein given its pending patent status, although key results are presented.

The materials evaluated by FESI/BNL to date have included various heavy metal bearing wastes and materials, firstly bottom ash from solid waste combustion and the ferrous and non-ferrous metals normally produced along with the bottom ash, leaded paint contaminated soils, metal finishing sludges, foundry sands, K061 waste, Pb bearing soils and industrial site wastes. Such wastes, materials and residues often contain high levels of lead and cadmium which can be leached at levels in excess of 5 ppm (5 mg/l) and 1 ppm (1 mg/l) as determined by the USEPA TCLP leaching test and copper and zinc in excess of 25 ppm and 200 ppm as determined by the California state leaching test method. Such wastes also often contain total compositional heavy metals such as lead, cadmium, barium, chromium, copper, magnesium, manganese, nickel, strontium, tin, and zinc at levels which are higher than those allowed by the USEPA, state regulators and local officials for ash use in engineered products such as cement blocks and/or application to the environment such as roadbase aggregate.

Incinerator Bottom Ash Evaluation

Water quenched bottom ash from a solid waste combustion facility was first subjected to ten (10) separate composited baseline total metals and TCLP analyses in order to define the character of the ash prior to extraction. Total metal content in the ash was determined by acid digestion after grinding of an ash composite sample of 0.5 grams with a mortar and pestle.

Analytical Method: The composited bottom ash sample was placed in a 30-ml platinum crucible. Five ml of concentrated HNO₃ was added to each crucible. The mixture was then heated on a hot plate to almost dryness. An additional 3 ml of HNO₃ plus 2 ml of HClO₄ was added to the crucible. The mixture was then heated until fumes of HClO₄ appeared. The crucibles were cooled and then 5 ml of 30% HF was added. The mixture was then reheated and evaporated to dryness. Finally, 5 ml of concentrated HNO₃ and 5 ml of deionized water was added, heated until the solution boiled gently, transferred into volumetric flasks, and diluted to 100-ml with deionized water. Metals were then analyzed by ICP-MS.

The bottom ash baseline sample was also subject to the Toxicity Characteristic Leaching Procedure (TCLP) as set

forth in the Federal Register Vol. 55, No. 61 (Mar. 29, 1990) which corresponds in pertinent part to the procedure set forth in Federal Register, Vol. 55, No. 126, pp 26985-26998 (June 29, 1990). This test procedure is also referenced in EPA SW 846, 3rd Edition. The TCLP test produces an aliquot of filtered solution containing soluble metals which were analyzed by ICP-MS.

Extraction Method: In this first study, 100 grams of <3/4" size reduced BA was subjected to three separate solutions of a FESI patent-pending Modified Complexing Agent ("MCA") at an ash to solution ratio of 1:20 for 48 hours using a wrist action shaker to maintain mixing contact. During extraction, 5 ml aliquot samples were taken in order to assess the time variance of the extraction efficiency. After the 48 hour extraction period, the ash was dewatered via centrifuge (12,000 rpm, 20 min.) and then subjected to a post-extraction TCLP and total metals analyses. Extractions were conducted at 25 degree C and 85 degree C in order to assess the impact of temperature on the extraction of metals, given that the bottom ash incinerators often quench the bottom ash at elevated temperatures.

The use of an ash centrifuge for dewatering and removal of residual MCA solution from the ash solid matrix, 48 hour batch mixing of the ash with the MCA solution and contact with varied solutions were all considered by FESI to define certain upper boundaries of removal efficiencies of metals under aggressive mixing, dewatering and contact conditions. Field and laboratory evaluations of less aggressive and more likely full-scale applications of the technology including press dewatering, extraction in a semi-mixed batch reactor, contact times of 5 to 60 minutes and lower MCA concentration extract conditions were also conducted. These more probable field operating conditions don't preclude the use of one or more of the aggressive methods described if needed to achieve target removal percentages.

The chemical constituents of the extract remaining after the removal of ash from the extraction vessel was of great interest during the research effort. The recovery and management of complexed metals and free MCA in solution after contact with the ash through biodegradation and/or precipitation are an important aspect of commercialization of the process.

In order to define the ability to control residual MCA and soluble metal complexes in the ash porosity after extraction as well as define a possible supporting wastewater treatment scheme, the MCA extract was subjected to biological

treatment to recover the metals from solution. For this purpose, a FESI patent-pending Engineered Bacteria ("EB"), was developed to consume MCA as a sole carbon source. A series of tests using EB were conducted to establish degradation efficiencies and rates.

After treatment, the extract samples were centrifuged (12,000 rpm, 20 min) to separate the solids biomass and metal precipitates from the solution which resulted in complete recovery. The solid phase was dried overnight at 70 degree C then weighed. The solid was dissolved in 5 ml concentrated Ultrex HNO₃ diluted to 200 ml with deionized water and analyzed for metals by ICP-MS. Metal recovery was calculated as a percentage of the initial metal concentration of the extract correlated for relative mass.

Extraction Results

Metals Extraction. The ash baseline and post-48 hour extracted heavy metals concentrations and percent metal extracted are presented in Table 1 in rounded average values. The results clearly confirm the MCA extractability of major metals Aluminum, Iron and Magnesium as well as trace metals such as Cadmium and Lead in all solutions evaluated. The measurement of extract metals concentration over time indicated that a majority of the metals from ash were recovered in the first 5 hours with a classical inflection of diffusion rate from surface to bulk mobility occurring at 5 to 10 hours with a gradual transition to flat slope of extraction after 20 hours.

Total Pb was 85% extracted at only 5 hours ... having a very steep extraction rate from 0 to 5 hours, 100% of total extractable amount at 25 hours with a 10 degree slope from 5 to 25 hours and a flat extract-to-time relationship after 25 hours. This time-effect observation was important, as long-term extractions such as 48 hours would likely require separate ash handling facilities due to the high tonnage production of ash and the need to store 48 hours production of ash while waiting on batch baths, or the need to have a higher batch production system to handle batch reaction times. Shorter extraction periods would allow for extraction and ash processing in-line or along side existing ash production facilities.

Temperature Effects. The ash extractions were also found to vary with temperature. Most metals showed an increase in extraction efficiency at 85 degree C as compared to 25 degree C, with the exception of Fe, Sr and Ti. This temperature effect could prove useful when applying the MCA

to ash quenching tanks or when timing the bath reactor loading such that hot ash is subjected to extraction. A hot batch extraction process may also prove very useful in post-combustion ferrous and non-ferrous scrap metal polishing and cleaning prior to sale, as the removal of surface oxidized metals and contaminants from the combustion process such as bottom ash or ash fines will increase the value of the scrap metal. Table 2 presents results of temperature effect on ash metals extraction. Extraction results were somewhat different from previous extraction testing due to sample variability common with incinerator ashes.

TCLP Control. The ash TCLP baseline and post-extraction, post-centrifuge dewatering results presented in Table 3 also confirm that the MCA removes the more readily soluble forms of metals as determined under the TCLP extraction method, thus reducing the residual metals available after ash dewatering for leaching within the buffered acetic acid solution used within the TCLP-1 test for BA.

Biodegradation. Biodegradation of residual MCA remaining in the extract after ash contact was found to occur rapidly and at a somewhat linear rate within 43 hours. The initial degradation rate of MCA was 80 mg per liter per hour. The removal of metals from solution and conversion of such to a precipitate was observed to be very high for metals as shown in Table 4.

The rate of metals removal varied, yet generally remained linear during the 48 hour period up to the point of reduction to levels less than 0.5 ppm where the metal concentration to time relationship flattened. Lead removal rates of 0.045 mg per liter per hour were observed. These results confirm that the residual metals in solution, and/or within the pores and on surfaces of the processed ash remaining after the ash MCA extraction, can be converted through biodegradation to insoluble precipitates within a liquid or solid ash matrix by addition of EB.

It is further possible that addition of common heavy metal precipitating agents could reduce the remaining soluble metals within the ash, yet such methods would not enhance the reduction of available MCA within the ash and thus would allow the residual MCA to remain available and possibly continue to allow for reduction and conversion of metals to soluble complexes. It is thus desired to reduce the MCA residual to a low level within the ash, as remaining MCA in solution will possibly increase the potential for metals to become water soluble at some time in the future, thus increasing the potential of metals release.

MCA Recycling. The use of EB for degradation of MCA in solution and/or within ash void liquids will provide useful for control of residual MCA and reduction of soluble metals when recycling of MCA to the primary extraction vessel is not considered necessary. As an alternative method, recycling of MCA from the ash batch reactor, ash drainage or ash rinsing solutions may be considered valuable to operators using high concentrated solutions of MCA.

Several evaluations of post-batch extractions revealed only 0.5 to 1.0 percent reduction of available MCA for bath durations of 5 minutes to 48 hours. Such a low consumption rate presents the opportunity to include MCA recycling in a process where loss of MCA by solution biodegradation is not desirable. Consequently, the heavy metal precipitating agents sodium sulfide and hydroxylapatite were evaluated in order to determine their capability to recover heavy metals from MCA recycle wastewaters and ability to return free MCA in solution to the reactor tank.

Both sodium sulfide and hydroxylapatite were found to precipitate over 99% of Pb out of solution within several minutes of contact. The recovery of MCA after addition of 1% sodium sulfide to extract of ash was found to be 98.7%. The comparison of fresh MCA against recycled MCA in the batch ash reactor as shown in Table 5 also supports that recycled MCA provides similar and often superior metal extraction efficiencies.

Process Costs

The process chemical costs for a full-scale extraction and recovery operation are less than \$0.50 per US ton of waste processed. The scale-up process application can vary in cost from \$150,000.00 capital and \$60,000.00 operating and maintenance for a 100 ton per day extraction facility to \$700,000.00 capital and \$270,000.00 operating and maintenance for a 500 ton per day facility as determined by FESI at several ongoing industrial waste extraction projects. The amortized capital and operating cost is less than \$2.50 per US ton, resulting in a net \$3.00 per ton of waste processed operating and installation cost.

Given \$60.00+ per ton landfill disposal costs in the Northeast, the \$3.00 extraction to enhance ash reuse and consequently avoiding landfilling is highly attractive. The estimated \$3.00 per ton processing cost is also competitive with existing TCLP stabilization methods and is often less expensive given that the extraction process reduces ash weight required for haul and disposal.

CONCLUSION

FESI and BNL researched and demonstrated a novel method for extraction and recovery of heavy metals from industrial wastes and materials. The projects primary objective of defining a safe, simple, cost effective method of extracting and recovering Pb from incinerator ash was achieved through use of a Modified Complexing Agent ("MCA") for single stage ambient temperature extraction of Pb in combination with an Engineered Bacteria ("EB") which targeted and consumed remaining MCA in the wetted ash and bioconverted MCA complexed lead in extract solution to insoluble Pb bioprecipitates.

Although the process method and application rates remain proprietary at this time pending patent issuance, the results of the extraction at 96% + for Pb, 90% (+) recovery rates by biodegradation, TCLP metals control to less than required by the USEPA and simple ambient temperature application confirm the method as beneficial for incinerator ash processing and production into a more reusable nature than baseline.

Table 1. Total Metals Extraction Results

Metal	Baseline (ppm)	Percent Metals Extracted		
		A	B	C
Aluminum	33,700	40	51	52
Barium	873	25	28	26
Cadmium	31	14	18	16
Chromium	309	16	17	20
Copper	558	54	74	90
Iron	47,300	9	22	29
Lead	600	61	74	96
Magnesium	4,200	91	94	94
Manganese	534	46	73	97
Nickel	1,090	21	26	24
Strontium	324	43	60	60
Tin	120	39	41	47
Titanium	6,280	13	14	17
Zinc	3,170	61	83	87

Table 2. Temperature effects on extraction

Metal	Percent Metal Extracted	
	25 C	85 C
Aluminum	25	53
Cadmium	7	13
Chromium	8	21
Iron	23	20
Lead	>99	>99
Magnesium	95	>99
Manganese	75	>99
Nickel	18	68
Strontium	34	43
Tin	37	>99
Titanium	13	23
Zinc	>99	>99

Table 3. TCLP results pre and post-extraction

Metal	Baseline TCLP	Extracted TCLP
Cadmium	0.068	0.007
Chromium	0.050	0.001
Lead	3.2	0.50
Zinc	110	44

Table 4. Biodegradation recovery of heavy metals

Metal	Percent Metal Recovered from Extract
Barium	99
Cadmium	88
Iron	99
Lead	93-99
Magnesium	99
Nickel	87-91
Strontium	99
Tin	89-98
Zinc	99

Table 5. Recycled versus fresh MCA extraction

Metal	Baseline (ppm)	Percent Metal Extracted	
		Fresh MCA	Recycled MCA
Aluminum	35,200	44.9	52.8
Cadmium	22	63.2	67.7
Chromium	148	39.9	46.3
Lead	1010	70.2	76.1
Magnesium	7140	64.6	70.2
Manganese	578	58.3	63.7
Nickel	72	56	51.2
Zinc	4740	74.7	78.1

Benefit/Cost Analysis of RDF Process in Taiwan

Ni-Bin Chang* and Y. H. Chang**

presented to

Fifth North American Waste-to-Energy Conference

Research Triangle Park, NC

April 21-25, 1997

* Associate Professor, Department of Environmental Engineering, National Cheng-Kung University, Tainan, Taiwan, R.O.C.

** Graduate Student, Department of Environmental Engineering, National Cheng-Kung University, Tainan, Taiwan, R.O.C.

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Ni-Bin Chang and Y. H. Chang

Department of Environmental Engineering
National Cheng-Kung University
Tainan, Taiwan, Republic of China

ABSTRACT

Reducing the waste stream through incineration is very important to minimize the use of landfills and to maximize the recovery of energy. The technology of mass burn waterwall incineration was widely used in the past two decades for solving the problems of solid waste disposal. In recent years, the sorting process is considered as an essential pretreatment unit prior to the incineration process. However, many engineering and economic disciplines are involved in the integration of refuse-derived fuel and waste-to-energy processes. This paper illustrates the related benefit/cost analysis issues during selecting an appropriate sorting process for Pa-Li municipal incinerator in Taipei metropolitan region of Taiwan.

INTRODUCTION

RDF (Refuse-derived Fuel) technology was developed in the US in the early 1970's. The first RDF facilities were based on firing RDF in coal-fired utility boilers. The initial reason for processing municipal solid waste prior to incineration was to remove a large fraction of the non-combustibles and to size the RDF so that some of it could more readily burn in suspension. The coupling of RDF preparation with new incineration systems designed exclusively for firing RDF is not an easy work. There were many technical and economic problems that had to be overcome. However, the RDF technology evolved slowly to where it is today has been a proven and reliable technology.

The original economic trade-off of RDF technology was primarily based on the capital and O&M cost savings of smaller boiler and air pollution control systems versus the added capital and O&M cost of the processing equipment. Also, RDF offered potential benefits for recycling part of the secondary materials, providing lower pollutant emissions, resulting in environmentally secure disposal of residues, and increasing energy recovery efficiency. Hence, cost-benefit or cost-effectiveness analysis is therefore an important indicator for the application of

such a technology. The current focus of economic aspects using RDF technology as an auxiliary component in the solid waste management system is how to fully identify the related benefits while traditional costs become more apparent. These benefits may relate to the resale income from secondary material market, the improvement of recycling potential, the achievement of lower pollutant emissions, and the production of a clean bottom ash amenable to reuse. However, economics does not always adequately reflect direct benefits from waste sorting. The saving of management expenditure from a regional sense and the scarcity of physical resources from a national sense should be considered to a reasonable extent in order to justify the investment of large scale sorting and recycling programs. Hence, this analysis also tries to cover the intangible benefits and indirect costs associated with waste sorting and recycling activities.

Overall, the purpose of this paper is to present an integrated evaluation framework and summarize the profile of both tangible and intangible benefits as well as direct and indirect costs. Such information would facilitate a thorough evaluation of economic viability of burning RDF as fuels in the future. The case study conducts a series of description of the general situation of solid waste management in Taipei metropolitan region. A typical refuse-derived fuel system, developed by a local engineering firm in Taiwan, which consists of standard unit operations of shredding, magnetic separation, trommel screening, and air classifying is fully described. The benefit/cost analysis to characterize the economic feasibility of adding such a sorting process to Pa-Li incinerator is then discussed as the related management issues become more clear. Final integrated evaluation of MRF and RDF based on the entire Taipei metropolitan region is proposed as well.

LITERATURE REVIEW

The engineering efficiency using RDF process prior to incineration has been well known. While sorting process prior to incinerators has won public concern over the years, its economic viability has not developed as quickly due to the lack of front-end planning information of related benefit/cost. In recent years, Derks and Hadfield [1] presented an innovative method to figure out the price of RDF according to the discounted cost of fuel displaced by burning RDF and the discounted revenue received for excess energy recovery by allocating the boiler output energy to steam and electrical generation. Zach [2] developed a computer

model for examining recycling system life cycle economic costs. Gershman [3] further discussed the factors affecting the costs of solid waste management from a broader sense. Hartman and Smith [4] emphasized the beneficial use of RDF technology with recycling and environmental protection goals. Lea and Kowalewski [5] tried to apply a computer model to evaluate the cost structure of an integrated solid waste management system in south Louisiana. The model has been used to predict the future cost of twelve waste management options available to local government. The articles written by Porter and Robert [6] in the book "Energy Savings from Waste Recycling" presented a thorough survey of the indirect benefit of recycling which further characterizes many intangible issues in solid waste management.

ANALYTICAL BACKGROUND OF CASE STUDY

Taipei City, located at the central part of Taipei County, is the largest city in Taiwan. The geographical location of this region is illustrated in Figure 1. The City of Taipei is divided into 12 administrative districts where each has its own garbage collection team in charge of individual clean-up work. However, 29 administrative districts are organized in Taipei County, and a single garbage collection team is also organized within each district in charge of waste shipping and disposal. The Taipei City and County Government handle their solid waste streams independently, although the resident's activities in both areas have amalgamated to form a unique metropolitan region. The 1995 population of Taipei City and County were about 2,600,000 and 3,500,000, respectively. This large metropolitan region with a total population over 6 million and an area of over 2,000 sq.km., requires solid waste management on a regional basis.

The Taipei metropolitan region currently generates over 6,500 tonnes of solid waste which is collected daily using a labor force of 6,741 and 1,008 collection vehicles. Six administrative districts have promoted their household recycling programs in Taipei City. Shan-Chu-Ku regional sanitary landfill is the only existing landfill, located at the eastern boundary of the city. In addition, two municipal incinerators (Nei-Hu and Mu-Cha) are currently in operation with the design capacity 900 TPD and 1,500 TPD, respectively, and the construction of a third (Pei-Tou) with the design capacity 1,800 TPD is in progress. Municipal solid waste streams in Taipei County are transported to two existing incinerators -- Shu-Lin and Hsin-Tein with the design capacity 1,350 TPD and 900 TPD,

respectively -- or to the only regional sanitary landfill (San-Hsia) for waste treatment and disposal. The shaded areas indicated in Figure 1 represent the service region originally assigned for Shu-Lin and Hsin-Tein incinerators. Although a number of small landfills are operated by local public or private agencies in several administrative districts of Taipei County, they will be out of capacity very soon. New incinerator and landfill, both located at the Pa-Li area, are being constructed now. The design capacity of Pa-Li incinerator is 1,350 TPD, that is to be started up in the year 2000. No MRF or RDF facilities exists in the current solid waste management system.

Some observations about an apparently significant trend in the solid waste management system has developed due to rapid economic development in this region and the uncertain need for waste treatment and disposal in the long run. Tables 1 and 2 describe the quantity and quality information of MSW in Taipei County. It is estimated that about 40% of the waste streams can be recovered as the secondary materials. While the source separation programs was not so successful in the last few years, the need of MRFs or IPCs, and/or RDF plants in the existing system configuration is phenomenal. The RDF technology would help make recycling compatible with waste incineration. Figure 4 illustrates the current and future solid waste management system configuration using RDF and MRF as new components.

In addition, the increase of heat values of waste streams results in a lower throughput in Shu-Lin and Hsin-Tein incinerators, which is almost one-third below the original design capacity. However, the heat value of MSW used to design Pa-Li incinerator is 8,000 KJ/Kg that is almost 50% higher than the existing average heat value of MSW in Taipei County. This will result in a possibility of siting RDF as a pretreatment unit in Pa-Li incinerator in the future. The first benefit in favor of the use of a sorting process in Pa-Li incinerator may be the increase of heat value of RDF destined for incineration. This would indirectly achieve higher energy recovery efficiency from a local sense and handle higher amount of waste flow at Pa-Li incinerator than originally planned level from a regional sense. Concurrent with attempts to impose a sorting process prior to Pa-Li incinerator, the Environmental Protection Bureau began effort to think about the idea of redistribution of waste flow according to the heat value of waste flow generated in different administrative districts so that the design capacity of these incinerators can be fully utilized.

Several economic-oriented issues encountered in this system include: (a) Is it necessary to build RDF process in this system to meet the growing demand of solid waste generation? (b) What are the impacts from the economic aspects through the use of such a RDF process? (c) Would the considerations of benefit/cost profile become different with respect to the scale of planning area? and (d) What is the possible incentives for the private sectors to perform BOT (Build, Operation and Transfer) or BOO (Build, Operation and Own) projects? These questions can be analyzed using the benefit/cost analytical framework in this paper.

RDF PROCESS DESCRIPTION

Various equipment are available for processing mixed or source-separated solid waste feedstocks for the recovery of secondary materials. The selection of the appropriate unit operations in a RDF or MRF system is a function of the characteristics of the feedstock, the specifications for the recovered products. The designed process of the first refuse-derived fuel process in Taiwan, as described in Figure 2, consists of three major subsystems: shredding, air classification, and screening. The impacts from the engineering aspects through the use of such a RDF process has been fully characterized by Chang, et al. ([7]-[10]). These engineering factors include throughput capacity, composition of the feedstocks, product specifications, and available technologies. Mass balance diagram can be made as illustrated in Figure 3. Table 3 lists the average energy requirements in this RDF process during two test runs in 1996.

BENEFIT/COST ANALYSIS

Benefits of Sorting prior to Incinerator

System economic benefits can accrue from the sale of recovered materials, which is itself a function of market demand, processing efficiency and separation efficiency. Revenues from the sale of materials can be estimated using information derived in a formal market investigation, as indicated in Table 4. Other funding sources may include tipping fees, subsidy, and even landfill diversion credits (or avoided cost). Direct avoided costs are calculated using the procedure corresponding to the saved shipping cost from incinerator to landfill and the disposal cost in landfill. But the indirect avoided cost might involve the

calculation of the social value of nonrenewable resource (i.e., landfill space) conservation. The other indirect benefits might relate to improving the processing of waste prior to combustion so that greater amounts of energy are conserved during the reuse of those recyclables, achieving lower pollutant emissions, increasing the energy recovery efficiency, and producing a clean bottom ash amenable to reuse. Hence, they are summarized as below:

♦ Direct Benefits:

- Revenues from the sale of materials
- Revenues from tipping fees
- Revenues from governmental subsidy
- Revenues from the sale of compostables
- Revenues from the sale of RDF as fuels to boiler utility or incinerator
- Avoided costs from the saving of shipping and disposal expenditure

♦ Indirect Benefits:

- Social value of nonrenewable resource (landfill space) conservation
- Energy conservation due to the reuse of those recyclables
- Lower pollutant emissions during incineration
- Clean bottom ash amenable to reuse
- Increase of energy recovery efficiency in boiler utility or incinerator

Costs of Sorting prior to Incinerator

Costs associated with RDF process include siting, building, and operation, process residue disposal, and material storage and shipping. The information of cost data, using the first pilot RDF process in Taiwan, becomes available in this study that is the first test run in this country. The essential items of cost analysis are summarized as below:

♦ Direct Costs:

- Costs for siting
- Costs for construction
- Costs for operation and maintenance
- Costs for process residue disposal
- Costs for material storage and shipping

♦ Indirect Costs:

- Costs for possible subsidy to the residents due to environmental impacts
- Costs for possible payment for waste inflow due to unexpected flow control

- Costs for shipping the recyclables for disposal due to instability of secondary material market

THE DIFFERENCE BASED ON PLANNING SCALE

From Private Sector Point of View

The evaluation of using sorting plant as a pretreatment unit associated with incinerator might not be based on too broad profile of benefits and costs terms in engineering analysis. Direct benefit/cost with limited extent might be more helpful for the alternative selection. Since the stability of secondary material market is quite unstable, the designer of such a sorting system must fully grasp the characteristics of the waste feedstock and the end product property required by the recycling sectors. The unit cost of processing solid waste may include debt service, taxes, insurance, labor, fringes, administrative, parts, supplies, utilities, and other costs incurred for the operation and maintenance of the system. The debt service is basically the amortization of the initial capital investment. These costs are conveniently divided into fixed costs (debt service, taxes, insurance, etc.) and operating and maintenance costs. On the other hand, the benefit terms could be characterized by the resale income of recyclables from secondary material market as well as tipping fees charged for those users.

In this analysis, the determination of the level of debt service is based on a uniform interest rate of 7% within operational period of 20 years that would result in a yearly capital recovery factor of 0.09439. The value of 0.9 is assumed as the system availability rate and a yearly throughput of 78,000 tons is chosen as a operational basis. According to the power consumption profile and other information, the long-term operating cost can be estimated as approximately 800 NT\$/ton (29 US\$/ton) in average, including the amortization of the initial capital investment. On the other hand, the income by selling the ferrous metals in the secondary material market is about 125 NT\$/ton (4.5 US\$/ton). Therefore, the tipping fee required for a profitable operation is equal to 675 NT\$/ton (25 US\$/ton). However, the true benefit of such a sorting plant could be further justified from its indirect contribution (i.e., avoided cost) in a solid waste management system.

From Regional Point of View

Cost and benefit redistributions through the use of sorting or recycling process are the major concerns in system planning of solid waste management in the metropolitan region. It obviously shows that the income from electricity sale is the largest direct benefit and the cost spent for waste transportation is the major expenditure in many cases. Hence, an optimization analysis to reorganize the waste flow to those three incinerators such that the average heat value of waste inflow destined for each incinerator might be consistent with its original design level. To clearly understand such a methodology, Chang, and et al. have delineated the comparative structure of cost and benefit distributions for many different planning scenarios ([11]-[12]). The program calculates avoided labor, equipment and overhead costs, then integrates these values to produce an overall value for avoided cost. A simulated run was initialized by Chang, et al. to estimate the avoided cost by recycling according to the net benefit difference, recycling cost, and the corresponding electricity loss. It shows that the avoided cost per unit of material recycled is 963NT\$/tonne (36US\$/tonne). Hence, the indirect benefit of waste recycling might include such an avoided cost as well. Overall, the systematic evaluation methodology used for the regional analysis can be presented in Figure 5 for the purpose of demonstration. Costs and benefits which are directly or indirectly associated with either collection or processing must be considered in any economic life cycle analysis.

From National Point of View

Advanced considerations in the development of benefit/cost scheme might rest upon the possible extent to which the energy saving from waste recycling can be estimated from a broader point of view. Consumer motivation of waste recycling probably not only based on the direct income but also from resources conservation. The contribution which resource recovery from waste streams makes to the conservation of energy and materials may be measured conveniently by its implications for primary energy use. Hence, the appreciation of the environmental and conservation benefits which accrue should be emphasized. Direct energy recovery from MSW can be achieved through direct incineration methods. However, energy savings result from waste recycling if the energy used in collecting, separating and treating reclaimed wastes, and subsequent processing, is less than the energy used in originating and processing primary materials and disposing of wastes. There are considerable variations in material production processes both within and between countries. Also the age of plant

and purity and form of the primary and secondary materials affects the energy consumption of manufacturing processes. Comparison of unit energy savings by appropriate recycling of secondary material were summarized as follow [6]: 1) aluminum: 222×10^9 Joules/ton; 2) waste paper: 7×10^9 Joules/ton; 3) glass: 17×10^9 Joules/ton; and 4) rubber: 44×10^9 Joules/ton. These values can be used as representative indicators when assessing a national policy related to the waste recycling or sorting actions.

INTEGRATED EVALUATION

Taipei metropolitan region is a highly populated area in Taiwan. Various non-hazardous types of waste disposal issues, such as the construction debris and scrape tire, can be handled together as part of the MSW streams. However, the need of material recovery facilities (MRFs) or intermediate processing centers (IPCs) to facilitate all types of recycling activities becomes at least equally important in the integrated solid waste management programs today. How to manage such an adapting change in the system become more and more critical. Since the Solid Waste Clean-up Law in Taiwan was just amended by the members of Legislative Yen in 1996. Multi-channel recycling programs are emerging in this country such that the MRFs would be an innovative technology to be used in the solid waste management alternatives. A new system configuration, as described in Figure 6, can be proposed, in which the MRFs and RDF plants are incorporated together to achieve a higher value of partnership. While RDF technology assisits in the incineration process, the MRFs consolidate and improve the purity materials collected from all possible waste streams before they are sent to markets.

CONCLUSIONS

Mixed waste processing, though apparently well established in Europe and USA, has a much less well established track record in Taiwan. Benefit/cost profile is an effective indicator for the justification of waste sorting or recycling programs. However, only part of those benefits and costs can be easily characterized and quantified for comparative analysis. The objective of this study was designed to assess the scope of acquired benefits and costs from waste sorting by a more broader point of view although some of them are difficult to be quantified for detailed assessment. It shows that additional benefits, such as

avoided costs and energy savings, resulting from sorting and recycling program must be finally attractive. Compared to alternative disposal options, the tax reduction or subsidy from the governmental agencies would be an essential policy to encourage the privatization for solid waste management in the metropolitan region.

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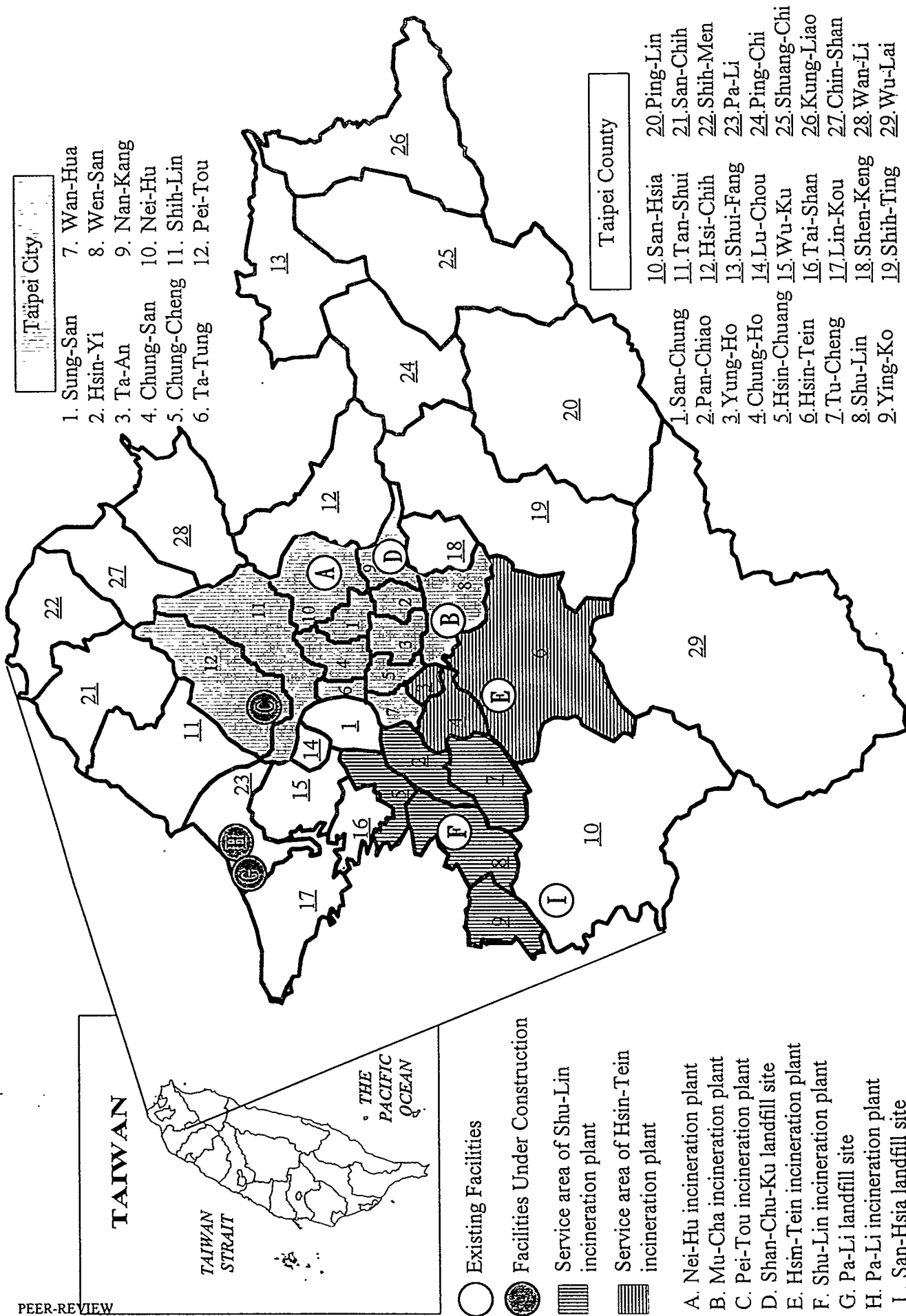


Figure. 1. The Planning Area, Incineration Plants and Landfill Sites

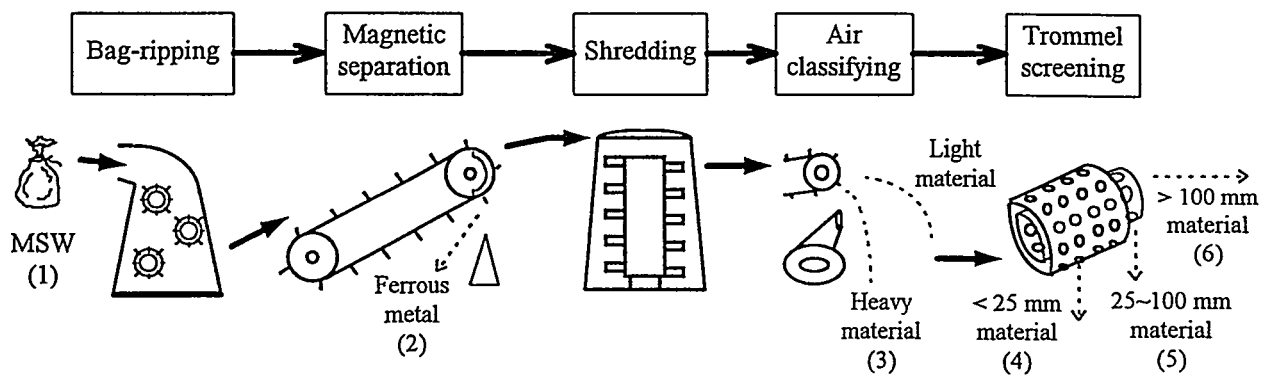


Figure 2. The system configuration of solid waste sorting process

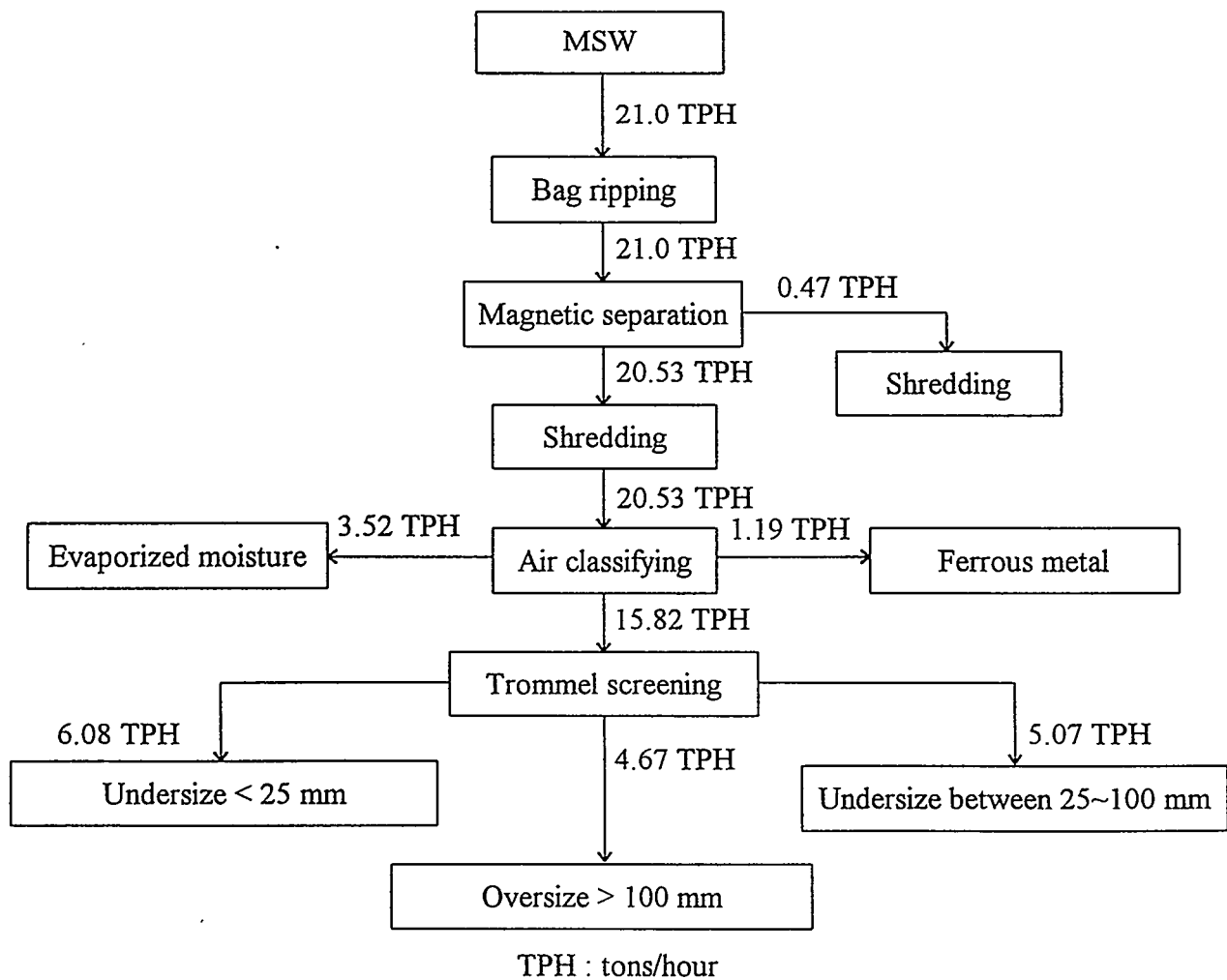


Figure 3. Mass flow diagram of sorting process

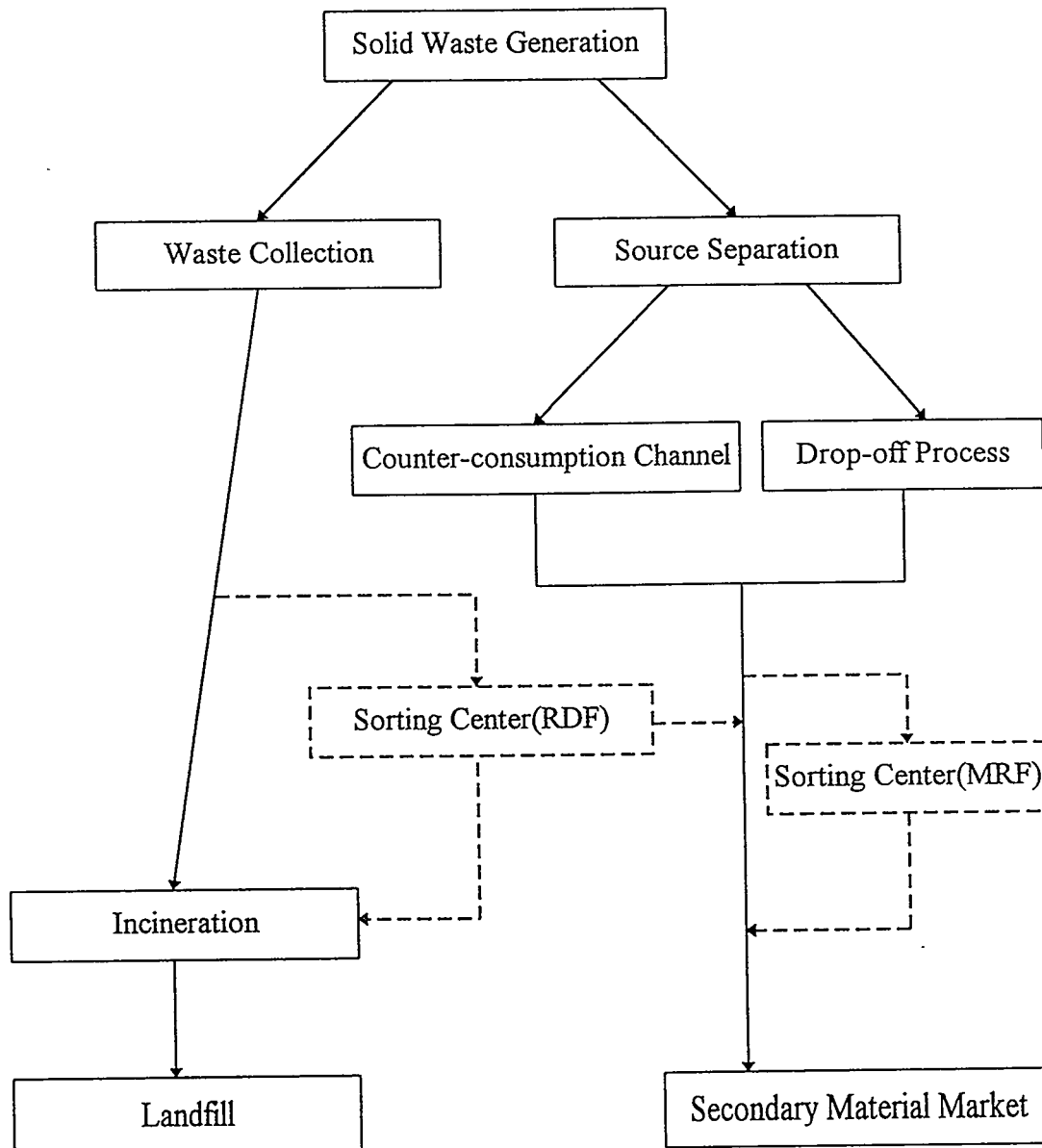


Figure 4. Schematic of solid waste management system in Taipei County

Table 1. The waste generation of areas in Taipei county

Area	Amount(tons/day)	Area	Amount(tons/day)
San-Chung	473.3	Tai-Shan	130
Pan-Chiao	565	Lin-Kou	34.2
Yung-Ho	250	Shen-Keng	24.6
Chung-Ho	391.7	Shih-Ting	9.8
Hsin-Chuang	323.3	Ping-Lin	17.5
Hsin-Tien	257.9	San-Chih	38.9
Tu-Cheng	235.9	Shih-Men	10
Shu-Lin	82.5	Pa-Li	61.4
Ying-Ko	65.4	Ping-Chi	21
San-Hsia	151.7	Shuang-Chi	13.1
Tan-Shui	162.5	Kung-Liao	21
Hsi-Chih	60	Chin-Shan	22.7
Shui-Fang	350.7	Wan-Li	42.5
Lu-Chou	150	Wu-Lai	9.8
Wu-Ku	82.9		

Total waste amount in Taipei county : 4059.2 tons/day

Table 2. Waste composition in Taipei County

Physical composition analysis(on dry base)	Percentage
Paper	37.99%
Textiles	6.11%
Garden trimmings	2.57%
Food waste	18.94%
Plastics	19.86%
Leather & rubber	1.24%
Metal	3.68%
Glass	7.28%
Ceramics & china	0.44%
Stone & sand	1.00%
Others	0.88%

Table 3. The specification of major equipments

Equipment	Capacity	Energy requirement (hp)
Bag-ripper	30 (tons/hr)	5
Magnetic separator	30 (tons/hr)	3
Shredder	30 (tons/hr)	500
Air classifier	200 (m ³ -air/min)	20
Trommel	30 (tons/hr)	7.5
Cyclone	400 (m ³ -air/min)	40
Conveyors	--	1~10

Table 4. The price of secondary materials in Taipei area

Item	Price	Item	Price
Waste paper	7.5 NT\$/kg	Waste green glass	1.87 NT\$/kg
Ferrous metal	3.9 NT\$/kg	Waste dark glass	1.3 NT\$/kg
Aluminar can	2.8 NT\$/kg	Coke plastic bottle	2.8 NT\$/item
Waste textile	25.3 NT\$/kg	Plastic bottle for mineral water	0.5 NT\$/item
Waste white glass	4.1 NT\$/kg		

*The currency ratio is 27.5 NT\$/1US\$ in 1997

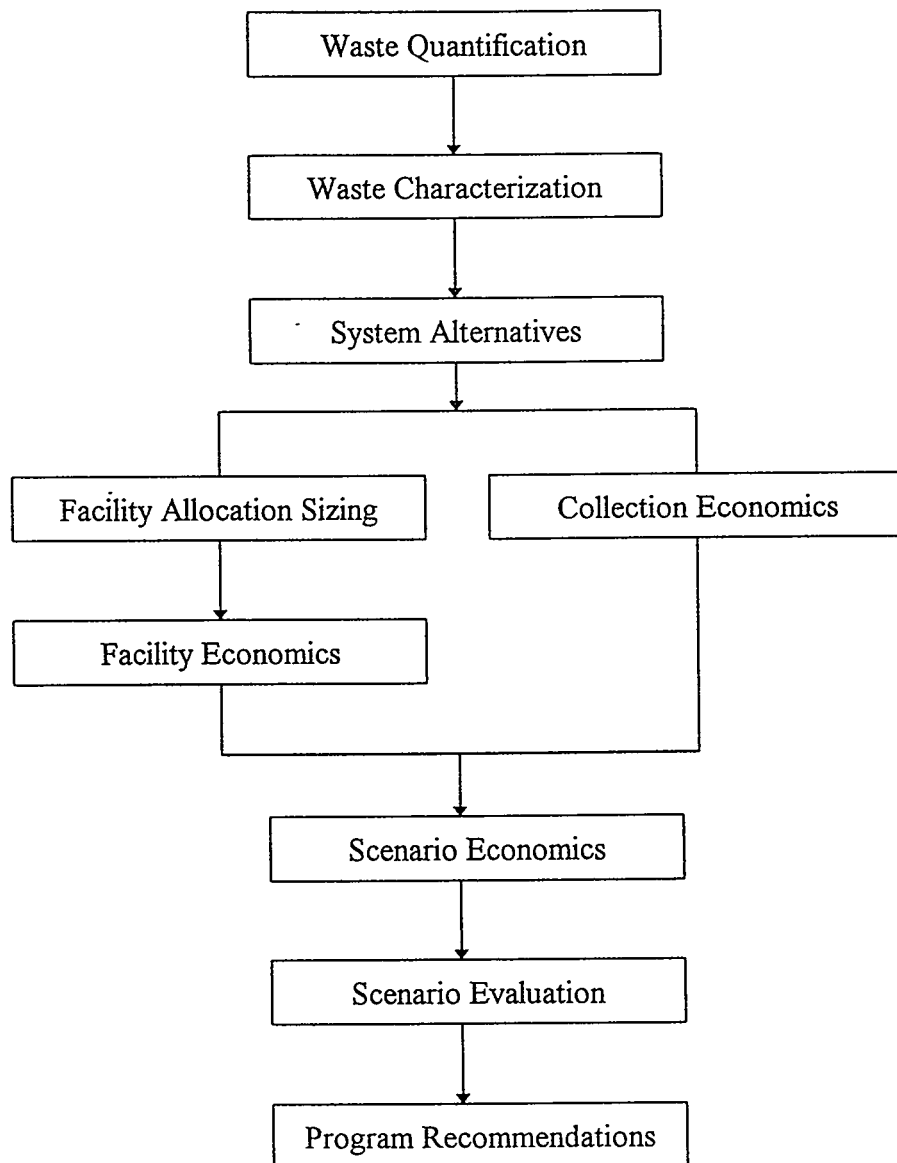


Figure 5. Integrated evaluation model for benefit/cost characterization

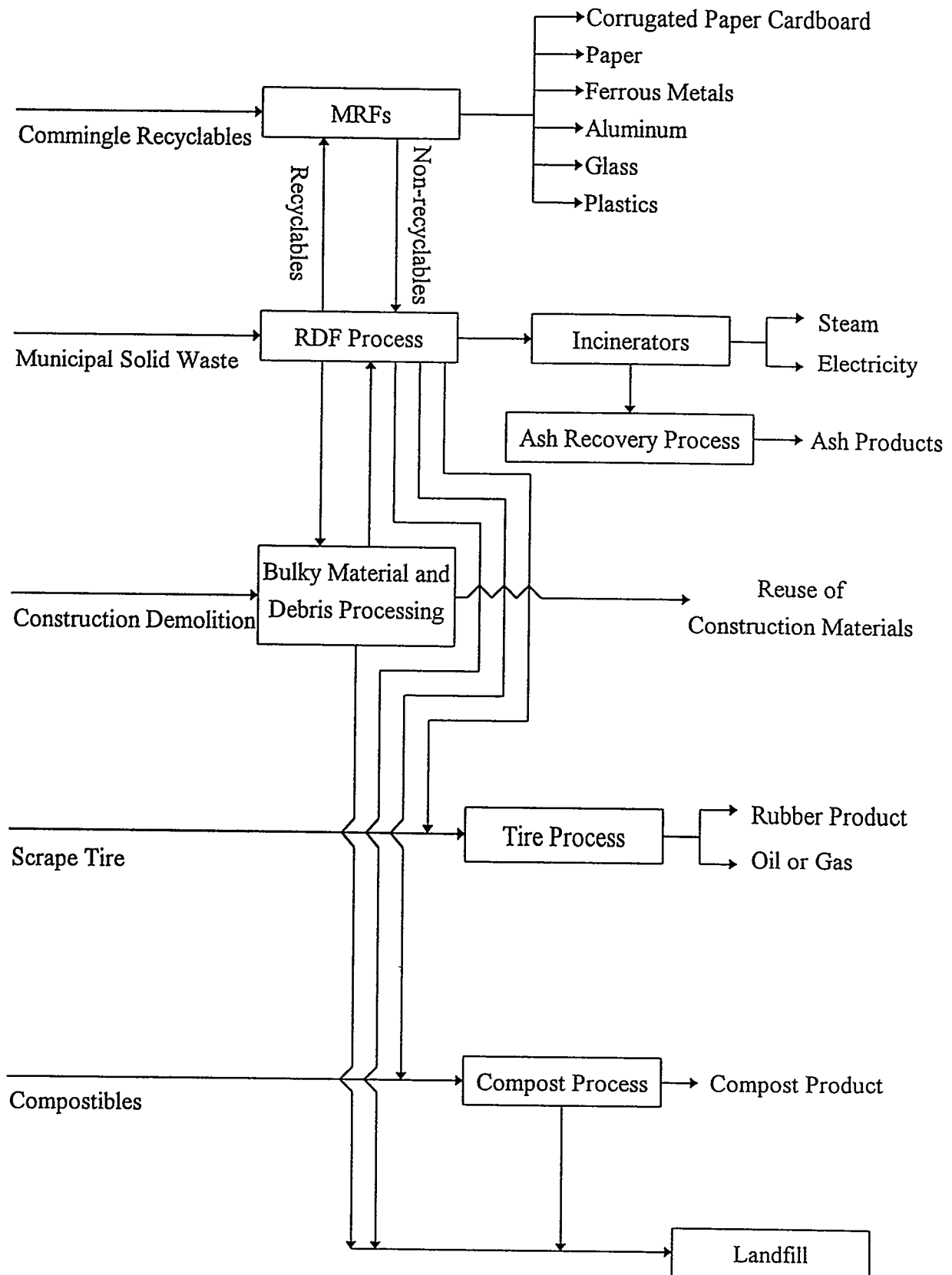


Figure 6. Future integrated system of MRF and RDF

TECHNICAL SESSION V

Emissions Control

Update of Dry Scrubbing Experience on European Waste-to-Energy Facilities

Karsten Felsvang

Niro A/S
305, Gladsaxevej
DK-2860 Soeborg
Denmark

Niels Jacobsen

NiroA/S
305, Gladsaxevej
DK-2860 Soeborg
Denmark

Guy Morvan

ABB France
5 bis, Place de la Défense
F-92974 Paris-La Défense Cedex
France

Niels Møller Pedersen

I/S Amagerforbrænding
Kraftvaerksvej 32
DK-2300 Copenhagen S
Denmark

INTRODUCTION

Disposal of municipal solid waste by incineration is a well established technology in Europe. Over the past decades emission requirements from these waste-to-energy facilities have gradually been tightened (1). The most stringent requirements in Europe are in the Central European countries like Germany, Holland, Switzerland and Austria. In these countries the latest, most stringent regulations, i.e. the German 17th Federal Immission Control Regulation (17th BImSchV) is setting the emission standard. In contrary, the emission standards set currently by the European Union (EU) are less stringent, but are expected to be tightened in the future, see Table 1.

Based on the difference in the emission requirements locally and presumably also based on the difference in attitude, countries like Denmark, Sweden, Finland, England, France, Spain, Portugal and Italy have chosen to comply with the emission standards by using less complicated and less expensive air pollution control equipment compared to the Central European countries. Air pollution control equipment in Central Europe has over the last decade advanced to such complexity and costs that the price of the air pollution control equipment far exceeds the incinerator per se (1,2). As prices for air pollution control equipment have sky-rocketed, the societies in Central Europe have realized that this is not a sustainable development and the trend has now reversed such that simpler and more cost-effective solutions are considered, while at the same time still fulfilling the 17th BImSchV-regulation.

One of the cost-effective options being considered is the spray dryer absorption technology, including a spray dryer and fabric filter. The paper describes four commercial spray absorption systems in different countries. They include various design modification, however they all are able to meet the most stringent European regulations.

DESCRIPTION OF PLANTS

The waste-to-energy plants in question are the following:

1. Amager - Denmark
2. Turku - Finland
3. IBW - Belgium
4. Mallorca - Spain

These facilities are geographically located far apart from the far North (Turku) to the Southern part of Europe (Mallorca). Design data for the waste-to-energy facility per se is given in Table 2.

The spray dryer absorption systems were all built by ABB under a license agreement with Niro. Of the four plants in question the Amager and Turku plants are designed as a traditional spray dryer absorption (SDA) process. The SDA process combines spray drying technology with efficient particulate collection in a down-stream filter, which usually is a fabric filter. The system is designed to removed acid gases and particulates from flue gases without saturating the flue gas and therefore producing a dry product for disposal. Figure 1 is showing a simplified diagram of the four SDA systems incorporating the general design features for the Niro system:

- Use of a single spray dryer per incinerator unit.
- Use of a single rotary atomizer per spray dryer producing a cloud of fine reagent droplets.
- Use of a single gas disperser to control the shape of the droplet cloud and achieve intimate mixing in the flue gas and the reagent slurry.
- Inclusion of a 2-point product discharge designed to ensure an open gas passage.
- Sufficient spray dryer residence time to ensure adequate drying of disposal product.

The SDA system consists of a reagent preparation system, a spray dryer absorber, a dust collector and an ash transport system. Most commonly the SDA system is designed for single-pass operation.

Quicklime is delivered by truck and conveyed pneumatically to a storage silo. From the silo, the lime is transferred to a paste or detention slaker, where an approx. 20% lime slurry is prepared. The lime slurry is transferred via a grid screen to a feed tank with final dilution of the lime slurry accomplished either in a small dilution head tank located above the spray dryer absorber, or in the rotary atomizer itself utilizing a dual-liquid distributor. By using the latter method, lime slurry and water are mixed directly in the atomizer wheel. The degree of dilution is controlled by a signal from an HCl or SO₂ analyzer located in the stack; the total liquid flow to the rotary atomizer is controlled to maintain a constant spray dryer absorber outlet temperature.

The atomized lime slurry enters the spray dryer, where it is mixed with the hot incoming flue gas; simultaneously lime reacts with the acid gases present and the reaction product is dried into free-flowing powder. A portion of the dried product is removed from the base of the spray dryer, while the majority is entrained with the off-gases and recovered in the particulate collector. Additional acid gas absorption takes place in the particulate collector, while the dust is being removed from the flue gas. The dried product from the spray dryer absorber and the particulate collector is conveyed either mechanically or pneumatically to a waste disposal silo. Normally, this product is hygroscopic due to the content of chlorides. The spray dryer outlet gas temperature is controlled as low as possible to give a high efficiency of acid gas removal, while simultaneously ensuring a dry product. Factors which influence the selection of spray dryer outlet temperature include: level of chlorides in the disposal product, water vapor content of the flue gas leaving the spray dryer absorber, solids content of the feed slurry and whether the system is operating in single-pass or recycle mode.

For additional control of vapor phase emissions such as mercury and dioxins, the SDA system can be augmented with an activated carbon injection system. This consists of a patented, dry additive system for injection of activated carbon, either up-stream, in or down-stream of the spray dryer, depending on the temperature level throughout the SDA system. The activated carbon injection technology for mercury control was developed and patented by Niro. It seems like this technology is the preferred technology for mercury control on waste-to-energy plants, and as a consequence Niro has through its licensee, the Babcock & Wilcox Co., and previously through Joy Technologies granted sub-licensees to main contractors of waste-to-energy plants, operators of waste-to-energy plants as well as vendors of air pollution control equipment. It is Niro's policy to continue this sub-licensing of the patented mercury control technology to any interested party.

The above description of the generic SDA system used at Amager and Turku applies for more than 65 waste-to-energy trains having installed the Niro SDA system.

Further development of the basis SDA system has been made at the IBW and the Mallorca plant. The basic layout of those two plants are shown in Figure 1.

The system at IBW is the so-called High-Performance Spray Dryer Absorber (HPSDA). The HPSDA-system consists of a normal spray dryer absorber system which at IBW includes a spray dryer absorber with down-stream electrostatic precipitator. In addition, the HPSDA-system further includes a fabric filter installed down-stream of the electrostatic precipitator. The flue gas between the two filters can optionally be cooled in a heat-exchanger to a lower and for the process more optimum temperature. In the fabric filter, hydrated lime is introduced by dry injection in the duct up-stream of the fabric filter. The spent and partially reacted hydrated lime from the second fabric filter may then be used for dry injection up-stream of the electrostatic precipitator. By this method, the overall disposal quantities are reduced to a level comparable to disposed quantities from the wet scrubbing system. The advantages of cooling the flue gas in a heat-exchanger is twofold. First of all heat is recovered and secondly mercury removal in the fabric filter is improved, even without active carbon injection. Thus mercury emission requirements can be met with no or very little active carbon injection.

The Mallorca incinerator plant is a completely new facility consisting of two 450 TPD incinerator trains each equipped with identical dry scrubbing units. The Mallorca dry scrubbers are designed with dry recycle to enhance the performance. The recycle system is designed as follows: Dry scrubber waste with excess lime from the fabric filter is transported pneumatically to an intermediate silo. Next to this silo is a silo with activated carbon. The alkaline dry scrubber waste is then mixed with activated carbon and pneumatically injected into the duct between the spray dryer and fabric filter. This process modification is increasing the alkalinity ratio into the fabric filter and thereby improving the absorption performance. The recycle rate of dry scrubber waste is set to 5 times the amount of solids being introduced via the rotary atomizer. The amount of active carbon injected is relatively high, i.e. 240 mg/Nm^3 . This is due to the fact that the system has been designed for an outlet spray dryer temperature of 160°C , at which temperature mercury removal is more difficult than at the normal dry scrubber outlet temperatures for incinerators ($130\text{-}140^\circ\text{C}$).

The plant is designed for emission limits according to the Spanish legislation, i.e. HCl emissions of 50 mg/Nm^3 , and SO_2 emissions of 300 mg/Nm^3 , both at 11% O_2 dry, so today the dry scrubber systems are fulfilling the present EU legislation.

Design data for the four air pollution control systems are shown in Table 3.

TEST RESULTS

Amager

The Amager incinerator plant has four 288 TPD incinerator trains, each equipped with identical dry scrubbing units. The plant was originally designed for emission limits according to the Danish 1986 legislation, i.e. HCl emissions of 100 mg/Nm^3 and SO_2 emissions of 300 mg/Nm^3 both at 10% O_2 dry. Today the dry scrubber systems are operated with a lower set-point for the HCl emission, fulfilling the present EU legislation, i.e. HCl emission equal to 50 mg/Nm^3 and SO_2 emissions of 300 mg/Nm^3 both at 11% O_2 dry.

In the winter and spring of 1995, the Amager incinerator plant decided to enter into a test program with the purpose of demonstrating that the Niro dry scrubbing system was capable of meeting the 17th BImSchV emission limits regarding HCl and SO₂ and at the same time to estimate the corresponding lime consumption. The test program was carried out jointly by I/S Amagerforbrænding (Amager Incinerator), Kemp & Lauritzen A/S, MILJØKEMI Dansk Miljøcenter A/S and Niro A/S. The companies Kemp & Lauritzen A/S and MILJØKEMI Dansk Miljøcenter A/S were supplying a multi-component FT-IR gas analyzer type KL2000 developed by Kemp & Lauritzen A/S. I/S Amagerforbrænding was responsible for the daily operation, and Niro A/S was responsible for temporarily installed gas analyzers on the inlet and outlet side of the dry scrubbing system, calibration of analyzers and plant instrumentation using reference methods, data-logging and reporting of measurements. Hence, during the tests continuous emission monitors were installed both at the inlet of the dry scrubber and in the stack measuring HCl, SO₂, H₂O and O₂.

During the tests, the only modification to normal operation of the plant was the lowering of the spray dryer absorber outlet temperature to 135°C and an adjustment of the HCl emission set-point from 50 mg/Nm³ down to 10 and 5 mg/Nm³ respectively. The HCl emission signal was utilized to control the lime feed.

All measurements from the plant instrumentation or temporarily installed instruments were logged in a temporarily installed data-logging system. The data were logged as 1 minute, 5 minutes or one half hour averages. The test program was carried out without any major operational problems although the set-point for the spray dryer outlet temperature was lowered to 135°C and 130°C respectively. No drying problems or product handling problems were encountered.

The inlet HCl distribution during the test is shown in Figure 2. As can be seen most values are in the range from 600 - 1000 mg/Nm³. The half-hour emission average with a HCl set-point of 10 mg/Nm³ is shown in Figure 3, and the half-hour average using a set-point of 5 mg/Nm³ is shown in Figure 4. From these results it can be seen that the dry scrubber without problems can meet the German 17th Federal Emission Control Regulation of 10 mg/Nm³ and that it is further possible to meet half this emission standard.

During the test program also the inlet SO₂ concentration was measured as shown in Figure 5. The corresponding SO₂ outlet emissions on a half-hour averaging basis for a HCl set-point of 10 mg/Nm³ and 5 mg/Nm³ are shown in Figure 6 and 7 respectively. As it can be seen, the SO₂ emission can be kept way below the 50 mg/Nm³ specified in the German 17th Federal Immission Control Regulation.

Turku

As mentioned before, the Turku plant consists of two 120 TPD incinerator lines originally built by Von Roll in 1975. The dry scrubber system that was retrofitted in 1995 was designed to treat the flue gas from the two existing incinerators plus a future 3rd train of 240 TPD.

The dry scrubbing system is characterized by having a 1-field electrostatic precipitator as a pre-collector, a spray dryer absorber and a downstream fabric filter. The dry scrubber system is equipped with an activated carbon injection system for mercury control.

This dry scrubber system is unique in the sense that this is the first Niro dry scrubbing system in which the German 17th BImSchV regulation of $10 \text{ mg/Nm}^3 \text{ HCl}$ was guaranteed.

The active carbon injection system is used for control of heavy metals like mercury and dioxins. The very small amount of active carbon is continuously injected into the flue gas duct between the absorber and the bagfilter. A static mixer is installed for distribution of the active carbon.

The Turku retrofit dry scrubbing system was started-up and tested in 1996. Responsible for the test program was the engineering company IVO International Oy.

The performance test data for acid gases and particulate are shown in Table 4. The particulate concentration into the SDA is low due to the use of an electrostatic precipitator as precollector. As can be seen from the performance test results, the plant clearly met the German 17th BImSchV regulation.

Results of the performance testing for heavy metals and dioxins are shown in Table 5. During the test, activated carbon was injected in a rate of approx. 40 mg/Nm^3 . The flue gas flow during the performance testing was between 40,000 and 47,000 Nm^3/h .

IBW

The performance test of the IBW dry scrubbing system was accomplished in September 1996. The company SGS Ecocare Analytical Services was in charge of the measurements. Results of the testing are shown in Table 6, 7 and 8. As it can be seen from the results, the High-Performance SDA system is achieving very good emission values. The sulfur dioxide is the most difficult to remove in the spray dryer, but with the additional fabric filter, very low outlet emissions can be achieved.

The results from the IWB plant show that the dry scrubber system can achieve emission values corresponding to half the German 17th Immission Control Regulation.

Mallorca

The Mallorca incinerator system was started-up in the fall of 1996 and preliminary performance tests were made in late November 1996. At this point, the final performance tests have been made, but the data are not yet available.

As it appears from the preliminary performance test results in Table 9, the dry scrubber at Mallorca was easily able to meet the present EU legislation of $50 \text{ mg/Nm}^3 \text{ HCl}$ and $300 \text{ mg/Nm}^3 \text{ SO}_2$.

CONCLUSION

Results from testing of four commercial dry scrubber units in Europe have proven that dry scrubbing technology today can meet the performance required by the most stringent European regulation enacted in the German 17th Federal Immission Control Regulation. The paper further documents that half the

German emission standards can be obtained with dry scrubbing technology. These emission values are comparable to what can be achieved with more complex systems using wet scrubber technology.

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1. Karsten Felsvang et al, Recent Experience with Air Pollution Control on Sewage Sludge, Municipal Solid Waste and Industrial Incinerators, 4th International Symposium on Solid Waste Management: Thermal Treatment and Waste-to-Energy Technology, April 18-21, 1995, Washington, D.C., USA
2. Georg Schaub, Rauchgasreinigung mit Reststoffbehandlung und Wertstoffgewinnung in der Abfallverbrennung - Stand und Tendenzen, Chemie Ingenieurtechnik (68), 11/96

Table 1: Emission requirements for European waste-to-energy facilities

Pollutant	German 17th BImSchV	EU 1989 -	EU Future expected
HCl	10	50	10
SO ₂	50	300	50
Hg	0.05	0.2*)	0.05
Particulate	10	30	10

mg/Nm³ at 11% O₂ *) Hg + Cd

Table 2: Design data for waste-to-energy facilities

Plant	Amager	Turku	IBW	Mallorca
Capacity, TPD	4 x 288	2 x 120	1 x 120 1 x 240	2 x 450
Incinerator manufacturer	Vølund	Von Roll	B&S Bartholomeis	DBA
Type of kiln	Travelling grate + rotary	Travelling grate	Travelling grate	Travelling grate
Economizer	Yes	Yes	Yes	Yes
Type of waste	Household & hospital waste	Household	Household	Household
Plant start-up	1989/91	1994	1995 1997	1996

Table 3: Design data for air pollution control systems

Plant	Amager	Turku	IBW	Mallorca
Flue gas flow, Nm ³ /h	95,500	77,000	35,000 60,000	110,000
Flue gas temp. °C	180-228	180-250	210-300	190-260
<u>Pollutants</u>				
<u>Concentration</u>				
HCl, mg/Nm ³ d, 11% O ₂	≤ 1,636	1000-1500	≤ 2000	≤ 1800
HF, mg/Nm ³ d, 11% O ₂	≤ 14	≤ 7	≤ 8	≤
SO ₂ , mg/Nm ³ d, 11% O ₂	≤ 364	≤ 400	≤ 500	≤ 1200
Hg, mg/Nm ³ d, 11% O ₂	0.35	0.1	-	1.0
Particulate, g/Nm ³ d	≤ 7	≤ 7	≤ 1	≤ 4
<u>Emission requirements</u>				
HCl, mg/Nm ³ d, 11% O ₂	≤ 100	≤ 10	≤ 5	50
SO ₂ , mg/Nm ³ d, 11% O ₂	≤ 300	≤ 150	≤ 25	300
HF, mg/Nm ³ d, 11% O ₂	2	≤ 1	≤ 1	2
Hg, mg/Nm ³ d, 11% O ₂	≤ 0.20	≤ 0.05	≤ 0.05	< 0.20
PCDD/PCDF, ng TE/Nm ³ d, 11% O ₂	-	≤ 0.1	≤ 0.1	≤ 0.1

Table 4: Performance test results - Turku
Acid gas and particulate removal

Component		System Inlet	System Outlet
HCl	mg/Nm ³	420	9.6
HF	mg/Nm ³	2.1	0.1
SO ₂	mg/Nm ³	200	43
Particulate	mg/Nm ³	9	2

Table 5: Performance test results - Turku
Heavy metal and dioxin removal

Component		System Inlet	System Outlet
Pb + Cr + Cu + Mn	mg/Nm ³	2.2	0.74
Ni +As,	mg/Nm ³	-	0.007
Cd	mg/Nm ³	0.008	0.00006
Hg	mg/Nm ³	0.023	0.002
PCDD/PCDF	Eadon eqv. (ng/Nm ³)	17.5	0.007

Table 6: Performance test results - IBW
SO₂ removal - SO₂ concentration in mg/Nm³

Date	Raw gas	Downstream electro-static precipitator	Downstream fabric filter
September 12, 1996	164	43	< 25
September 13, 1996	370	54	< 24

Table 7: Performance test results - IBW
HF removal - HF concentration in mg/Nm³

	Raw gas	Downstream electro-static precipitator	Downstream fabric filter
September 10, 1996	0.1 - 1.5	< 0.1	< 0.1
September 11, 1996	0.1 - 0.8	< 0.1	< 0.1
September 12, 1996	0.1 - 3.4	< 0.1	< 0.1
September 13, 1996	0.1 - 0.4	< 0.1	< 0.1

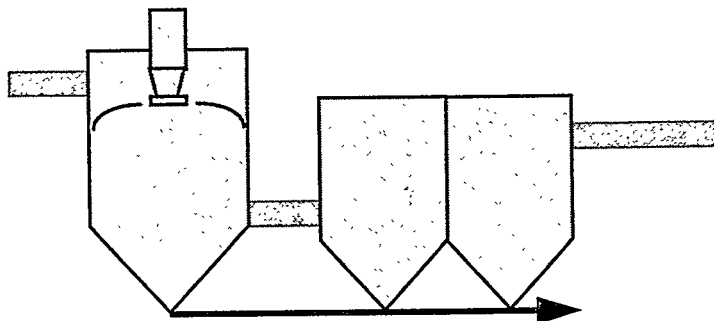
Table 8: Performance test results - IBW
HCl removal - HCl concentration in mg/Nm³

	Raw gas	Downstream electro- static precipitator	Downstream fabric filter
September 10, 1996	138 - 907	2.6	-
September 11, 1996	493 - 771	3.0	-
September 12, 1996	210 - 393	1.8	<1
September 13, 1996	1382 - 3618	<1	<1

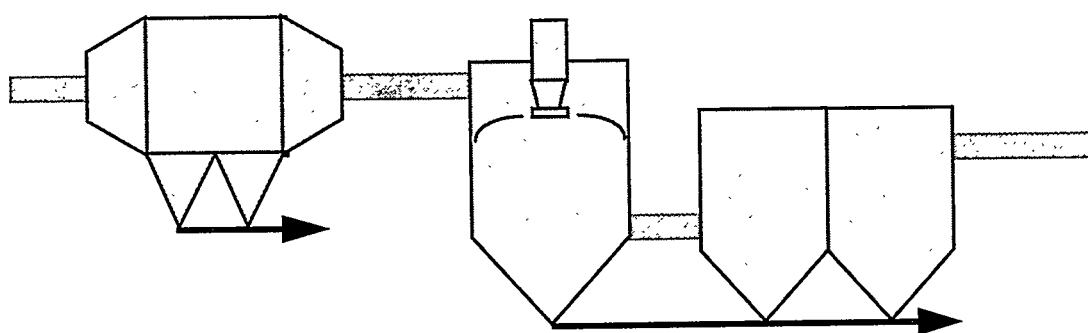
Table 9: Preliminary performance
Test results - Mallorca

Component		System inlet	System outlet
HCl	mg/Nm ³	753	33
SO ₂	mg/Nm ³	97	38

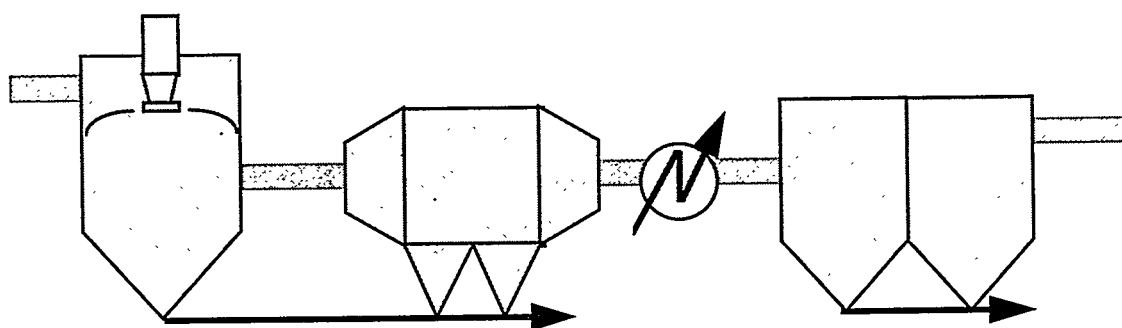
Amager



Turku



IBW



Mallorca

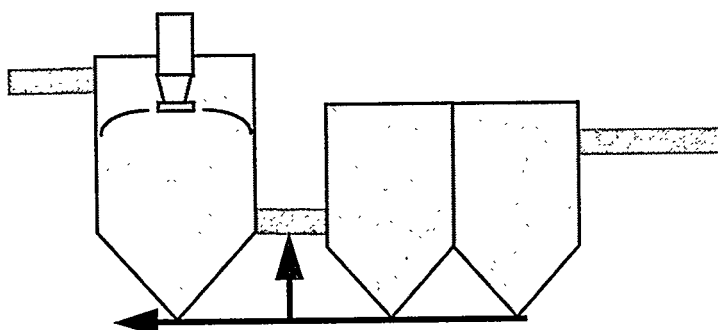


Figure 1: Design of air pollution control equipment

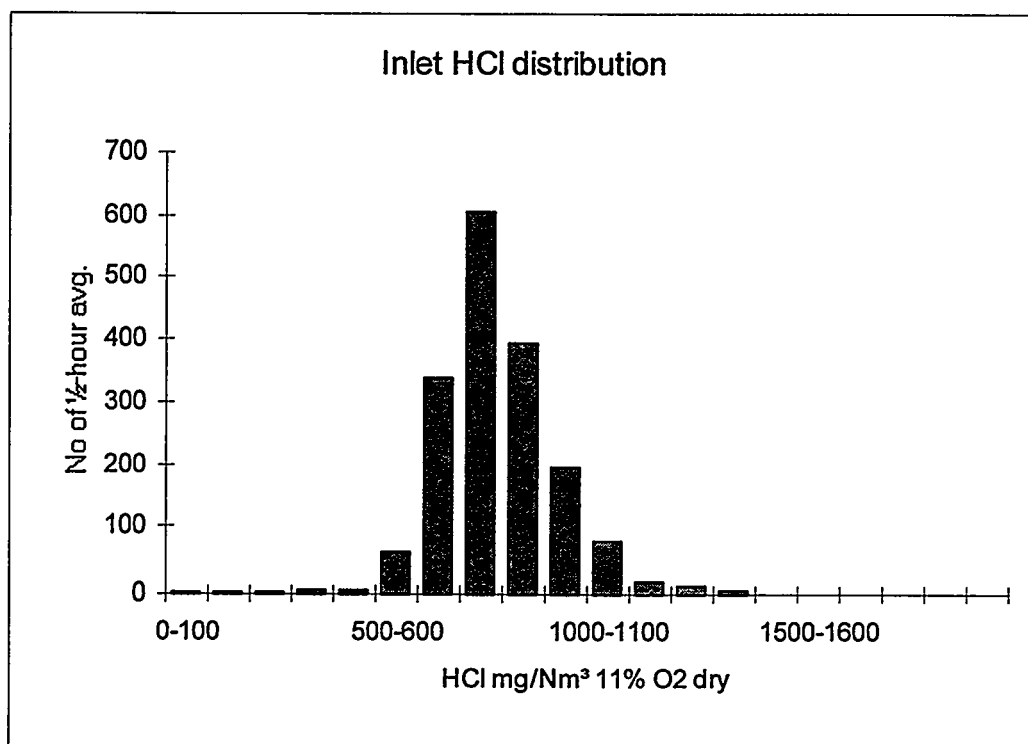


Figure 2: Inlet HCl distribution

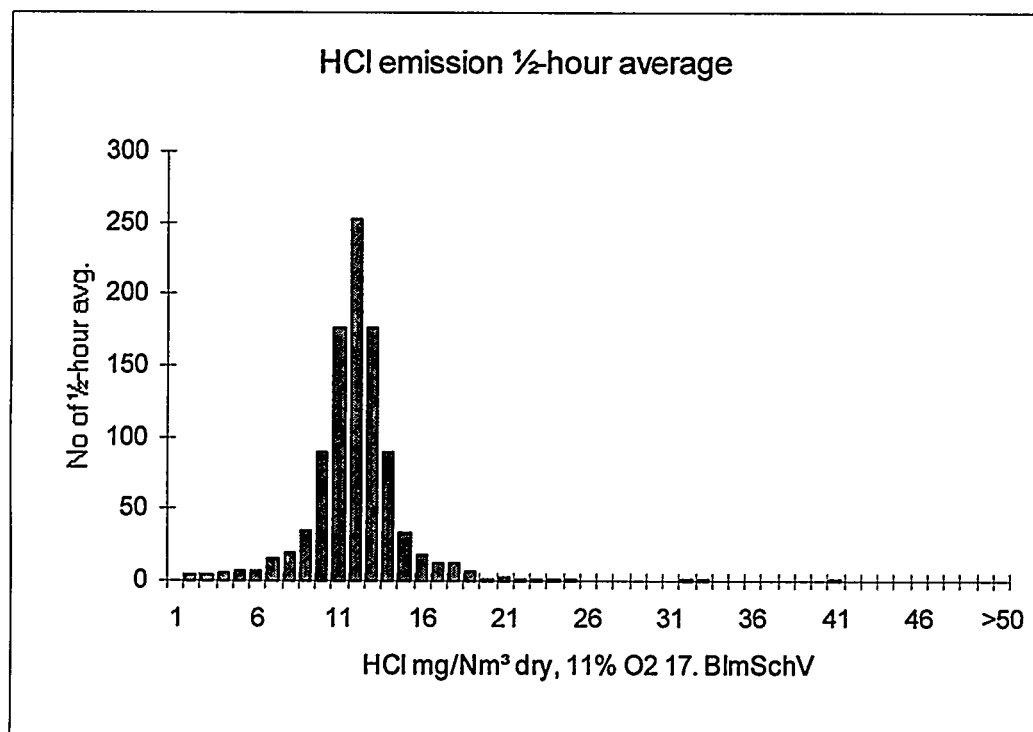


Figure 3: HCl emission 1/2 hour average
 Temp. SDA outlet 130-140°C, Set Point HCl 10 mg/Nm³ wet
 at actual O₂

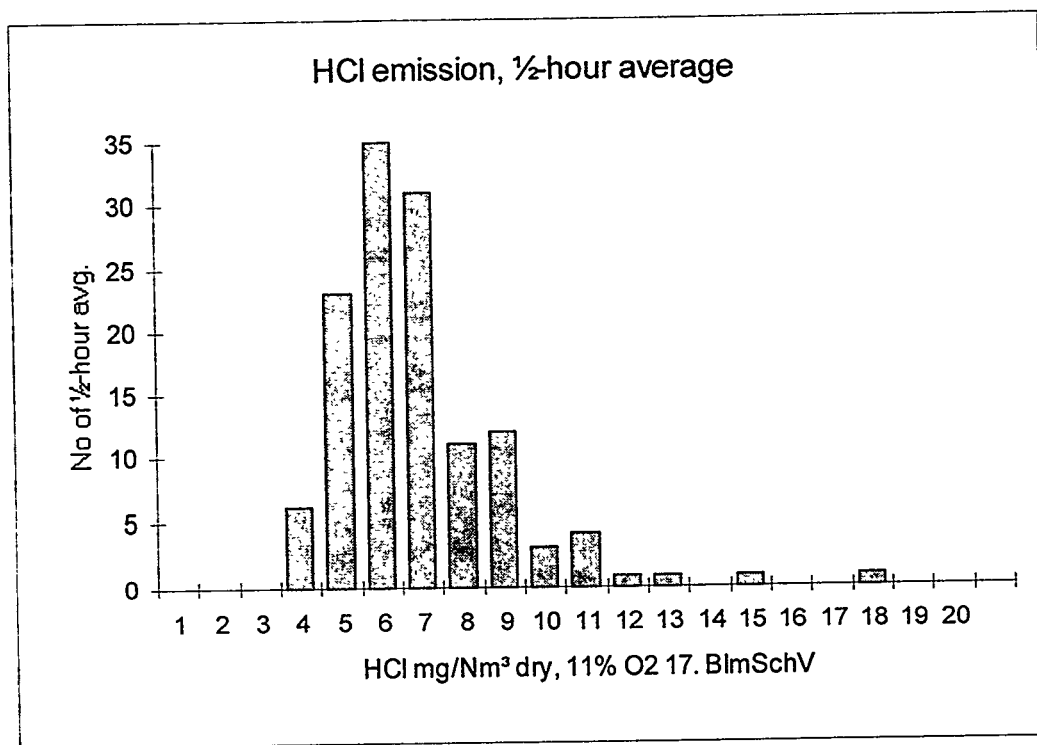


Fig 4: HCl emission 1/2 hour average
Temp. SDA outlet 130-140°C , Set Point HCl 5 mg/Nm³ wet
at actual O₂

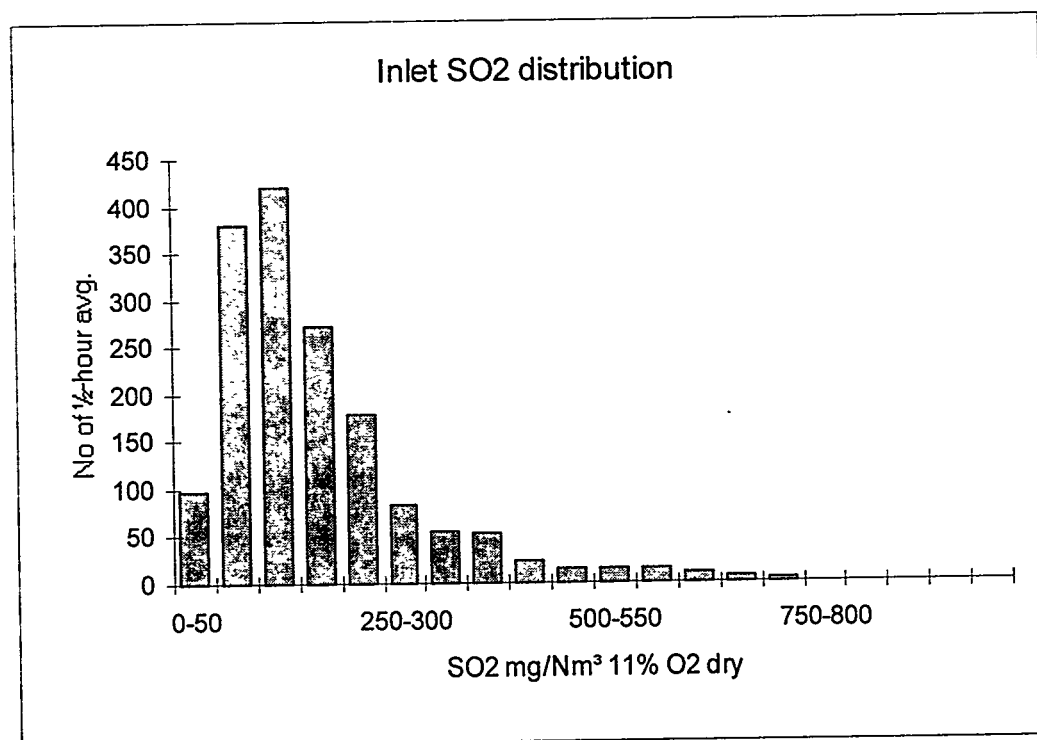


Figure 5: Inlet SO₂ distribution

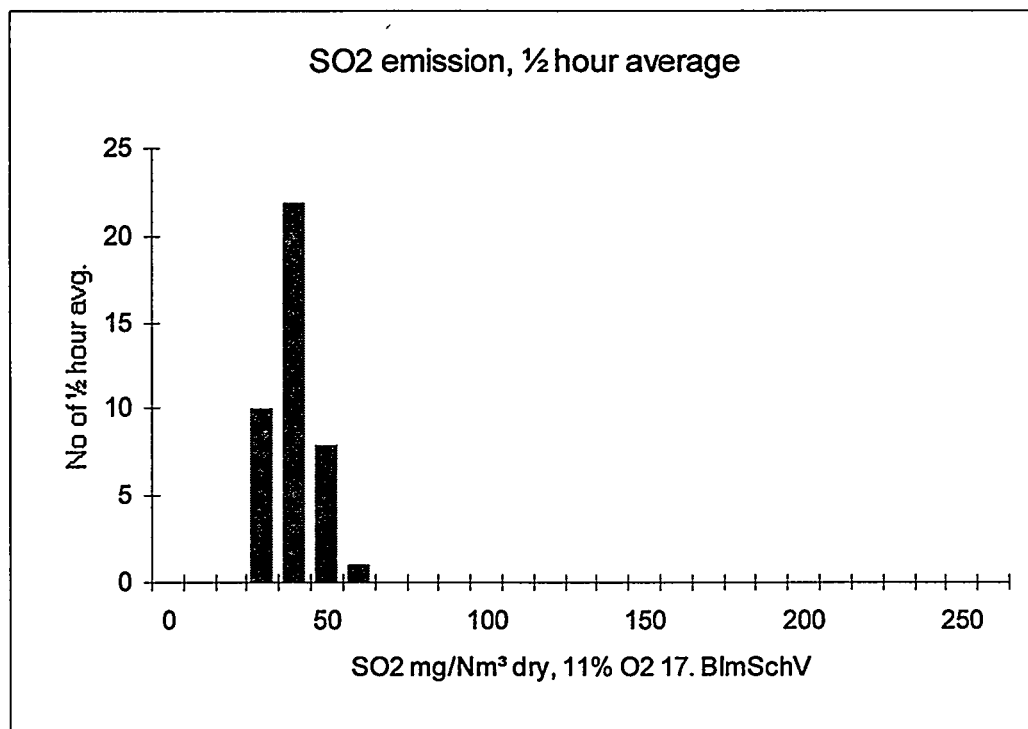


Figure 6: SO₂ emission, 1/2 hour average
Temp. SDA outlet 130-135°C, Set Point HCl 10 mg/Nm³
at actual O₂

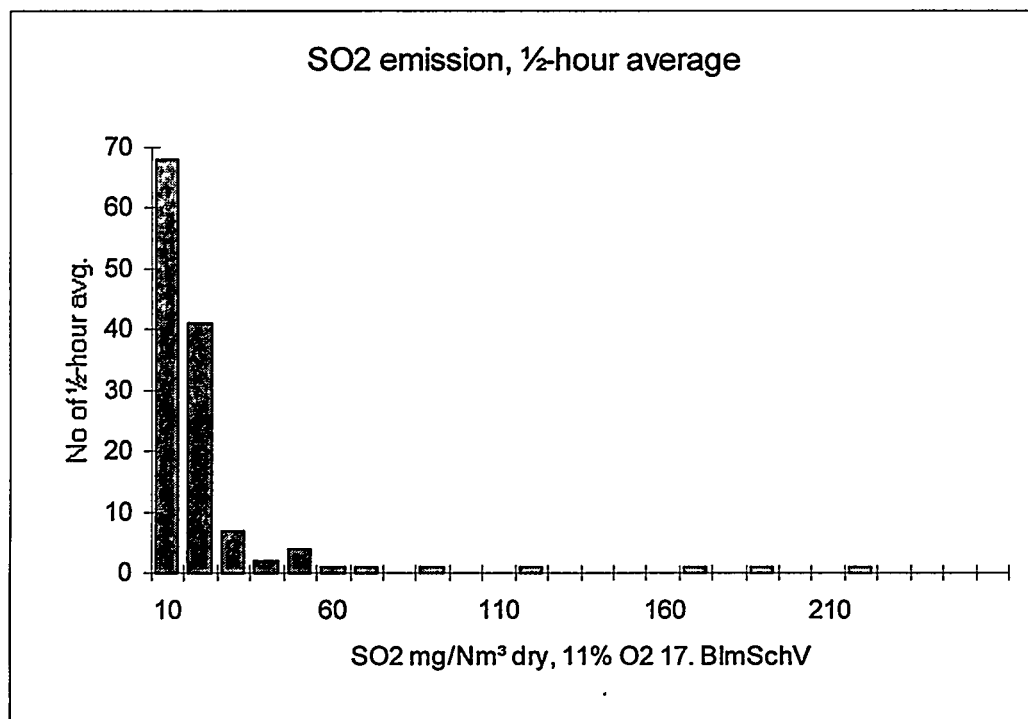


Figure 7 SO₂ emission, 1/2 hour average
Temp. SDA outlet 130-140°C, Set Point HCl 5 mg/Nm³
at actual O₂

Experience with a Carbon Injection System at a
Spray Dryer/Electrostatic Precipitator Equipped Waste-to-Energy Facility

Thomas S. Honeycheck
American Ref-Fuel Company
777 N. Eldridge Parkway
Houston, TX 77079

Kenneth E. Armellino
American Ref-Fuel Company
333 Earle Ovington Boulevard, Suite 302
Uniondale, NY 11553

Greg Gesell
American Ref-Fuel Company
777 N. Eldridge Parkway
Houston, TX 77079

Joseph Kozlowski
American Ref-Fuel Company of Essex County
183 Raymond Boulevard
Newark, NJ 07105

INTRODUCTION

American Ref-Fuel Company of Essex County obtained an air permit to construct the Essex County Resource Recovery Facility (ECRRF), a municipal solid waste resource recovery facility, in December 1985 from the New Jersey Department of Environmental Protection (NJDEP). Permit condition A.9.a. states that the emission rate of mercury from each unit shall not exceed 0.053 pounds per hour, based on the average value of three runs using EPA Method 101A. Testing for mercury was required to be performed on a quarterly basis during the facility's first year of operation. This emission requirement was met by the spray dryer adsorber (SDA)/electrostatic precipitator (ESP) equipped facility. Subsequently, the NJDEP chartered a task force to investigate the setting of a new statewide mercury emission standard for municipal solid waste (MSW) combustors. The task force in July of 1993 recommended a more stringent two phase emission standard requiring all facilities to achieve 65 ug/dscm at 7% oxygen dry volume or 80 % reduction by January 1, 1996, and to achieve 28 ug/dscm at 7% oxygen dry volume or 80% reduction by January 1, 2000. These recommendations and a requirement for installing a mercury control system were codified into a regulation in November 22, 1994. In order to comply with the new regulation the facility proceeded with a retrofit mercury control system.

FACILITY DESCRIPTION

The Essex County Waste-to-Energy Facility is New Jersey's largest waste-to energy plant, owned and operated by American Ref-Fuel of Essex County in Newark. In operation since late 1990, it serves the refuse disposal needs of 22 municipalities in Essex County and the surrounding region. The plant has three combustors which operate 24 hours per day, 365 days per year, and processes approximately 2,500 tons of municipal solid waste per day. The plant also produces, via two steam turbine-generators, about 70 megawatts of electricity for sale to Public Service Electric and Gas, New Jersey's largest utility.

Each incinerator utilizes the proprietary mass burn technology developed by the German firm of Deutsche Babcock Anlagen (DBA), which since 1961 has been installed in more than 60 facilities worldwide. Each unit at the Essex plant has six Duesseldorf roller grates, each with a width of 6.5 meters. The heat generated by the refuse combustion is used in a four pass boiler to produce steam of 650 psia and 750F. The flue gas generated by the combustion leaves the final economizer section of the boiler at a temperature between 432F to 520F, depending upon the degree of boiler surface fouling.

Each incinerator has a dedicated flue gas cleaning system, composed of two spray dryer absorbers (SDAs), or "dry scrubbers", in parallel, followed by an electrostatic precipitator (ESP). The system was supplied by Deutsche Babcock Anlagen. The flue gas flow from the economizer outlet, approximately 110,000 to 150,000 scfm wet, splits into two parallel streams that enter the SDAs at the bottom. In this inlet section, called the pre-cyclone, approximately 70% of the flyash is removed from the flue gas flow. The gas then flows upward through pipes which dampen the remaining turbulence into the main reactor vessel. Dual fluid nozzles deliver a lime slurry of approximately 15% concentration into the reactor vessel, using compressed air for atomization. The lime reacts with the acid gas components to form neutral salts of reaction that are collected in the SDAs and downstream in the electrostatic precipitator. The outlet concentration of SO₂ is the parameter that is used to determine the lime slurry feed rate. As the flue gas exits the SDAs at the top, the temperature is measured and additional dilution water is injected via the dual fluid nozzles to maintain the outlet temperature between 280°F to 325°F. Each

SDA is 105 feet tall with an internal diameter of 12 feet 2 inches. Upon exiting the SDAs, the two flue gas streams are combined and enter an ESP. These particulate collection devices used at the Essex Facility were supplied by DBA through subsupplier Flakt, Inc. Each ESP has three fields and has a particulate emission requirement of 0.015 grains per dry standard cubic foot at 7% O₂.

EMISSION HISTORY

The ECRRF was required as an initial permit condition to perform mercury testing, using Method 101A, along with a variety of other parameters on a quarterly basis during the first year of operation. Although the facility initially had one of the lowest mercury emission concentration rates in the state, it did not achieve the required emission rate of 0.053 pound per hour. As a result, additional monthly testing was mandated which demonstrated the facility's compliance with its mercury emission rate. In order to settle any claims related to prior compliance within the mercury emission rate, an Administrative Consent Order was entered into between the ECRRF and the NJDEP on January 14, 1994. This ACO required additional testing on a quarterly basis utilizing Method 29. Figure 1 presents the data from these test programs, all prior to any mercury control system being installed at the facility.

Before the NJDEP revised the statewide mercury emission requirements, the facility and the State of New Jersey had undertaken a number of actions to reduce mercury levels in the wasteshed. Some of these programs are discussed in greater detail in the two papers cited in the Reference section of this paper. The facility began a battery survey program designed to eliminate mercury batteries from the waste stream. Mercuric oxide batteries were commonly used in consumer items such as hearing aids, in institutional applications such as hospitals and in military applications. In addition, New Jersey passed the Dry Cell Battery Management Act which was intended to restrict mercury containing batteries in the state. Fluorescent light bulb recycling was also promoted by the facility and certain counties. As can be seen from the data presented in Figure 1, mercury emission rates were trending downward.

FACILITY MERCURY RETROFIT

In order to meet the new mercury requirements, bids were solicited from suppliers of systems that could inject carbon into the flue gas stream. Although a reduction in mercury concentration was the prime objective, a reduction in dioxin was also anticipated. Concerns were raised that performance would be more difficult to achieve with an ESP-equipped facility or that other emission concerns such as increased particulate might arise. Bids were accepted on a dry carbon injection system, on a carbon in water slurry system that mixes the carbon slurry with the lime slurry for injection through the existing dual fluid nozzles, and for a system in which carbon is added to the lime slurry tank and the combined lime/carbon slurry is injected via the existing dual fluid nozzles into the reactor vessel. The system chosen was a dry carbon injection system supplied by Norit Americas Inc. Some testing and data appear to indicate that a dry injection system is more efficient in carbon utilization, which is the major cost in a life cycle analysis of this system.

The Norit Americas Inc. powdered activated carbon, bulk storage and dosing system is composed of a bulk storage silo and three independently controlled dosing modules with associated carbon delivery piping. The system layout is shown in Figure 2. Fitting the system on the existing site posed numerous challenges. A decision was made to locate this system near the existing lime storage silos and lime slakers, and the phosphoric acid tank in order to keep bulk chemical storage in a centralized but accessible part of the plant. This decision, along with the required traffic patterns and access roads at

this operating plant led to the layout shown. Air is blown by the blowers from the auxiliary building to eductors in the silo skirt. There carbon is entrained within the air stream and subsequently is conveyed to the flue gas streams in the plant.

The total volume of the carbon silo is approximately 5,000 ft³, and can contain 2-1/2 truckloads (more than a month's usage) of carbon while maintaining 13 feet of freeboard. The silo is fed from road tankers carrying 40,000 pounds per truck. During silo filling, the carbon is pneumatically conveyed from the truck to the silo. The silo is equipped with three point level switches, and with one continuous level sensor. A bin vent filter is mounted atop the silo to minimize fugitive emissions during silo filling. In addition, the silo has two 39 inch x 40 inch blow-out panels based upon the National Fire Protection Association NFPA 68 requirements.

Figure 3 shows a schematic of the carbon dosing and supply systems. The silo skirt contains various components with the remainder located within the auxiliary building. Ten air fluidization nozzles are connected to each of the three discharge cones to promote the flow of carbon. For each of the three lines, carbon flows from the silo through a rotary valve to a volumetric feeder package. These packages contain a 6.0 ft³ feeder supply hopper with three level switches and volumetric feeders with a variable speed controller allowing a 50:1 turndown. Adjustments in carbon feed rate can be made over a range of 0 to 150 pounds per hour. The carbon discharges from the volumetric feeder into a pneumatic conveying eductor where carbon is entrained within the air stream. Low pressure air is used as the motive force to convey the carbon to the point of injection into the flue gas stream.

Figure 4 shows a layout of the auxiliary building, which was designed for easy access to components requiring maintenance. A monorail and hoist were subsequently added to aid in blower and motor removal and maintenance. Each positive displacement blower is equipped with a single speed motor, and delivers 160 scfm air at 12 psig. Other equipment located within the auxiliary building include an air receiver for system instrumentation, motor control centers, and a main control panel. The original design concept was to have PLCs to monitor and control all system functions. However, a change was made to control the system from the plant main distributed control system (DCS) with local indication provided by Norit.

After the carbon is entrained within the air stream by the eductors it is conveyed through a piping system composed of schedule 40 carbon steel pipe with ceramic backed, 24" centerline radius sweeping elbows to one of two possible injection points. A hand operated diverter valve in each conveying line allows the carbon flow to be directed to either the flue gas ducts upstream of the SDA pre-cyclone sections or to the SDA vessels after the precyclone. Because of the need to fit the system into the existing facility, field routing resulted in discharge piping distances of between approximately 530' to 580', depending upon the destination chosen. In either case the flow is divided between the pair of ducts entering the two SDAs or between the individual SDAs by ceramic backed wyes. These two locations were chosen to allow a determination of the best injection point relative to carbon consumption. Preliminary tests indicated that adding carbon in the duct upstream of the SDAs was more efficient. It is believed that the longer residence time of the carbon within the flue gas stream resulting from using this location was the reason for this result. Once delivered to the flue gas stream, the powdered carbon adsorbs various volatile forms of mercury including mercuric chloride and elemental mercury present within the gas stream. The carbon is then collected before discharge from the stack by the ESP and is removed with the other flyash.

The carbon used within this system is DARCO FGD, supplied by Norit Americas Inc. It is a lignite coal based activated carbon manufactured specifically for the removal of heavy metals and other contaminants typically found in incinerator flue gas emission streams. According to Norit, it has been proven to be highly effective for the removal of gaseous mercury, dioxins, and furans in numerous full scale operating facilities. Its open pore structure and fine grind permits rapid adsorption, which is critical in this application.

SYSTEM STARTUP

The system installation was completed in December, 1996. Construction was completed under a tight schedule and incurred some delays due to the installation of mercury control systems at the other New Jersey facilities and due to a few site specific issues. Initial startup problems were limited to a few pipe leaks which were quickly fixed.

During initial operation a plug of carbon feed was not maintained in the feed hopper. When this plug is not maintained, the eductor tends to draw the carbon from the silo directly resulting in very high feed rates. It was also found that the eductor vent line cap was too small. This caused the vacuum on the system to be higher than desired compounding the carbon feed rate problem. The vent cap was enlarged correcting the problem. Several other minor modifications were made to upgrade the system for the facility.

In the design of this system, Ref-Fuel adopted an approach relative to the handling of carbon that was deemed to be very conservative. Carbon was considered to be a flammable and explosive material. Dusting, which could lead to an explosion via various means of ignition, was the primary concern where carbon was present as a pure compound and was not diluted with either water or fly ash. As a result, the design included features such as explosion vents on the storage silo in accordance with the National Fire Protection Association Standard 68 (NFPA-68). In addition, all motors and associated electrical equipment, where dry activated carbon was to be handled, was specified to conform to the Electrical Code for Wiring and Motors Exposed to Carbonaceous Dusts (i.e. National Electrical Code, Class II, Division 2, Group F). Once again, this approach was considered to be overly conservative by the system supplier, who has extensive experience with carbon handling.

SYSTEM OPTIMIZATION

It was required by the NJDEP to determine the optimal carbon injection rate for the facility. A test program was constructed to collect data at a baseline condition, as well as three various setpoints centered around the manufacturer's expected setpoint of 20 pounds per hour. Norit determined this value based upon the Essex County historical mercury emission rates. On one unit, three 2-hour runs of USEPA Method 29 were performed at each of the following conditions:

- Baseline Condition (No carbon injection)
- Low Injection Rate (15 pounds per hour)
- Mid Injection Rate (30 pounds per hour)
- High Injection Rate (45 pounds per hour)

To ensure that these injection levels were being achieved, a calibration check of the carbon feed system was performed prior to each group of runs at each setpoint to determine the actual injection rates. For

the test program, injection rates of 14.5, 31, and 40 pounds per hour were achieved. Table 1 presents the data from this program.

To determine what the optimal injection rate was, the outlet concentrations of each carbon injection level were plotted, and the equation and slope of the trendline determined. This curve is included as Figure 5. Since the slope of the curve represents the change in mercury emission per unit of carbon used when no significant decrease in mercury emissions was gained when additional increments of carbon were added, this injection rate was determined to be the optimal setpoint. This calculation showed the optimal point to be about 21 pounds per hour. Since this agreed very well with the Norit Americas expected operating setpoint in their system proposal of 20 pounds per hour, the facility selected 21.5 pounds per hour as the operational setpoint.

ONGOING TESTING

Since the New Jersey regulations require quarterly testing for two years, with a provision to go annual thereafter should all results be in compliance, the ECRRF has been conducting inlet and outlet testing since January of 1996. These results are provided as Table 2. The facility, at the predetermined optimal injection rate of 21.5 pounds an hour, has been able to achieve compliance with the current regulation, as well as tentatively demonstrating the ability to achieve compliance with the January 1, 2000 standard. Limited dioxin emission testing has also been completed since the activated carbon system has been in operation. Test results were very favorable as presented in Table 3. The table also shows that particulate emissions were reasonable.

CONCLUSION

The mercury control system has performed very well since startup. Emission control is consistently within permit requirements and the system has been able to demonstrate the design performance objectives. Concerns of meeting the emission requirements for an ESP-equipped facility have not materialized and in fact, the additional dioxin control provided by the system is an extra bonus.

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Table 1. Essex County Mercury System Optimization Data.

Carbon Injection Setpoint (lb/hr)	Carbon Injection Actual (lb/hr)	Inlet Mercury Concentration (ug/dscm@7%O2)	Outlet Mercury Concentration (ug/dscm@7%O2)	Percent Removal (%)	Average Mercury Concentration (ug/dscm@7%O2)	Average Mercury Removal (%)
0	0		292	N/A		
0	0		176.6	N/A		
0	0		269.2	N/A	245.9	N/A
15	14.5	274.6	64.0	77%		
15	14.5	222.0	33.1	85%		
15	14.5	261.1	65.8	75%	54.3	81%
30	31	174.3	11.0	94%		
30	31	213.4	12.8	94%		
30	31	168.0	13.6	92%	12.5	93%
45	40	245.7	11.4	95%		
45	40	237.8	12.7	95%		
45	40	125.7	13.8	89%	12.6	93%

Table 2. Essex County Quarterly Mercury Emission Data for 1996.

Quarter	Boiler 1			Boiler 2			Boiler 3		
	Boiler Exit (ug/dscm@7%)	ESP Exit (ug/dscm@7%)	Removal (%)	Boiler Exit (ug/dscm@7%)	ESP Exit (ug/dscm@7%)	Removal (%)	Boiler Exit (ug/dscm@7%)	ESP Exit (ug/dscm@7%)	Removal (%)
1st	135.0	21.5	84%	140.0	20.4	85%	130.0	22.2	83%
2nd	173.0	42.4	75%	151.0	17.0	89%	156.0	35.0	78%
3rd	124.0	27.3	78%	124.0	25.2	80%	140.0	32.1	77%
4th	116.0	16.0	86%	180.0	25.0	86%	109.0	18.0	83%
Average	137.0	26.8	81%	148.8	21.9	85%	133.8	26.8	80%

Table 3. Essex County Dioxin Emission Data with Mercury Control System Retrofit.

Parameter	Facility Average Corrected to 7% O ₂		
	Unit 1	Unit 2	Unit 3
Total Dioxins①, ng/dscm	3.0	1.5	2.0
Particulate	0.0025	0.0010	0.0010

① Total dioxins is inclusive of tetra-octa polychlorinated dibenzo-p-dioxins and tetraocta polychlorinated dibenzo furans reported on a total

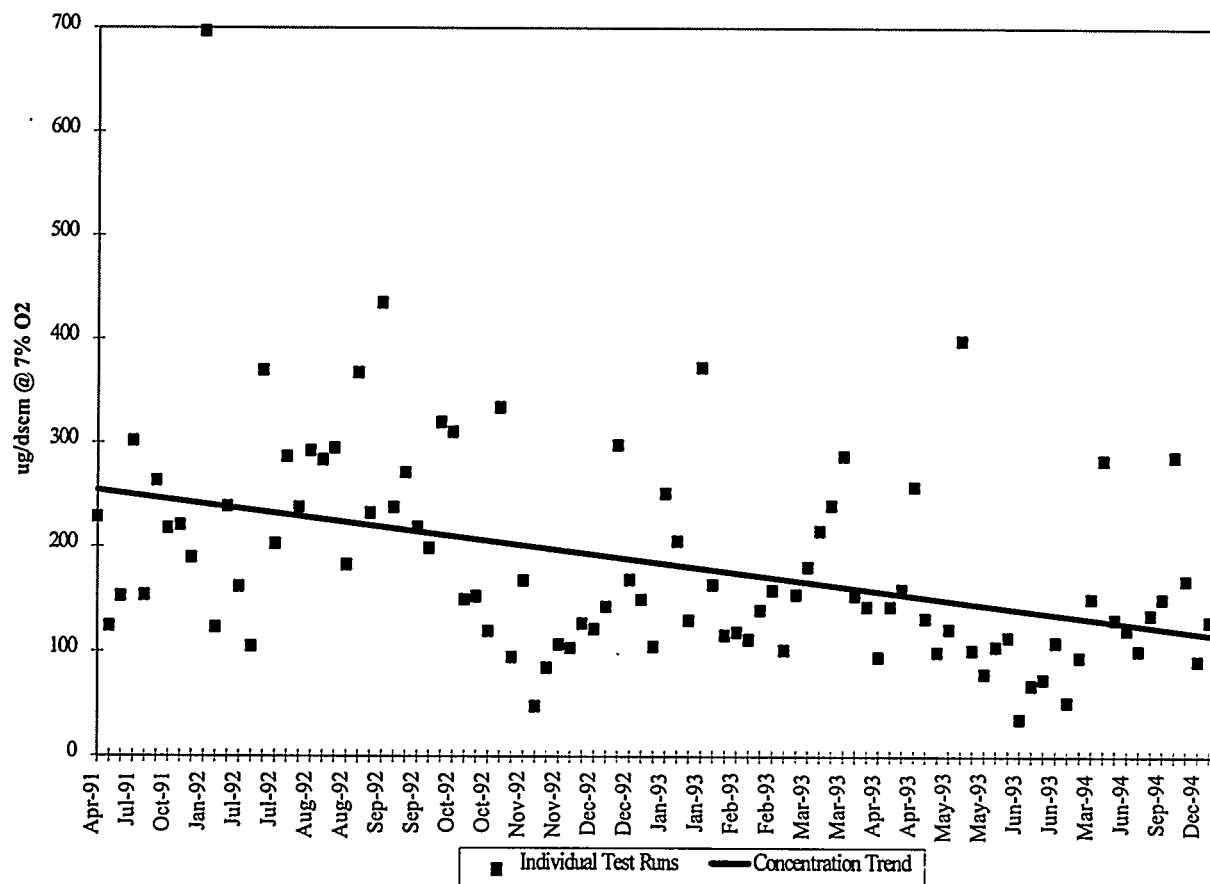


Figure 1. Essex County historical mercury concentrations.

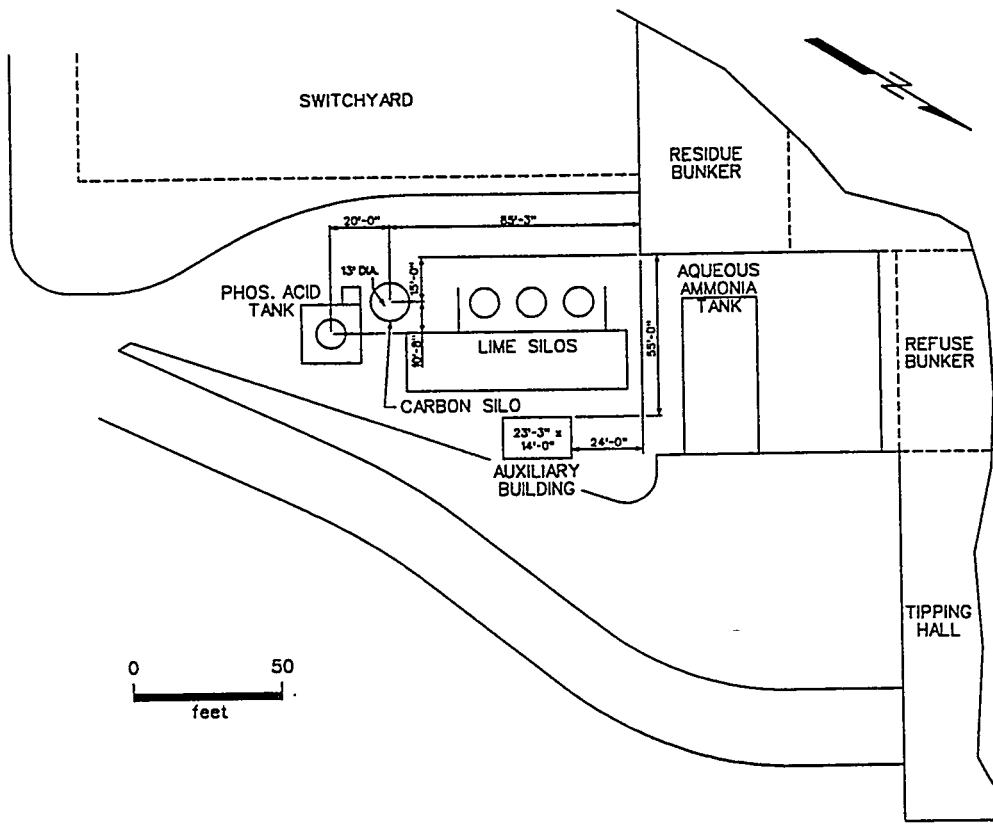


Figure 2. Essex County Resource Recovery Facility
Dry Activated Carbon Injection System Layout

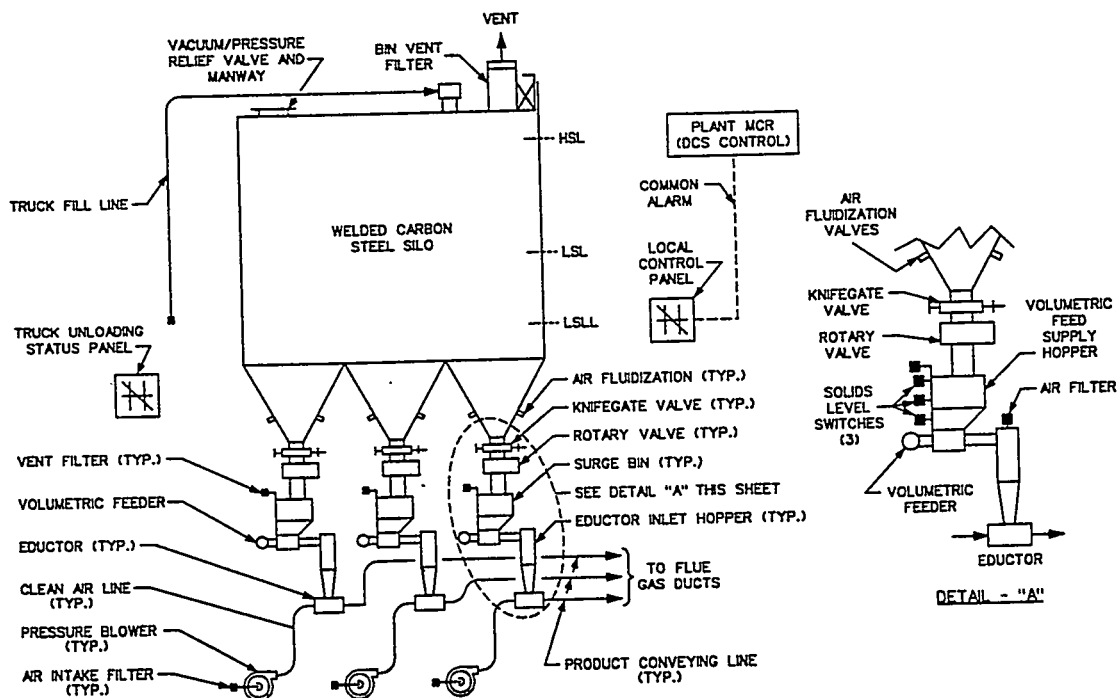


Figure 3. Essex County Resource Recovery Facility
Dry Activated Carbon Injection System
Simplified Process Floor Diagram

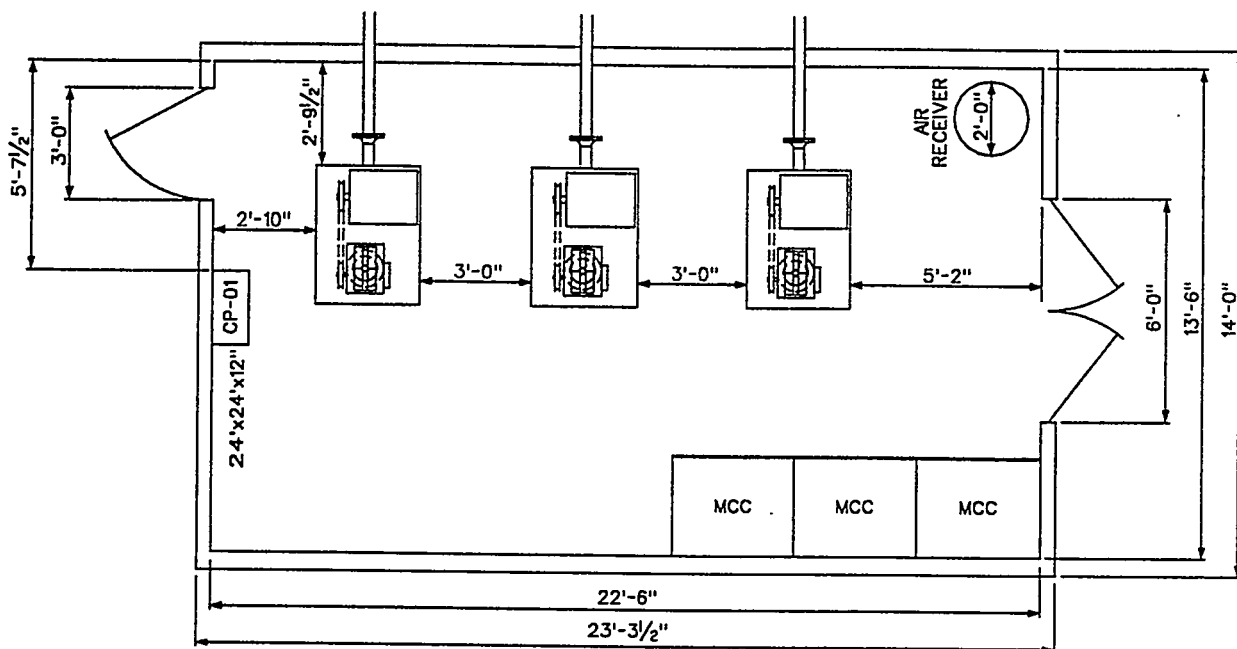


Figure 4. Essex County Resource Recovery Facility Dry Activated Carbon Injection System Auxiliary Building Layout.

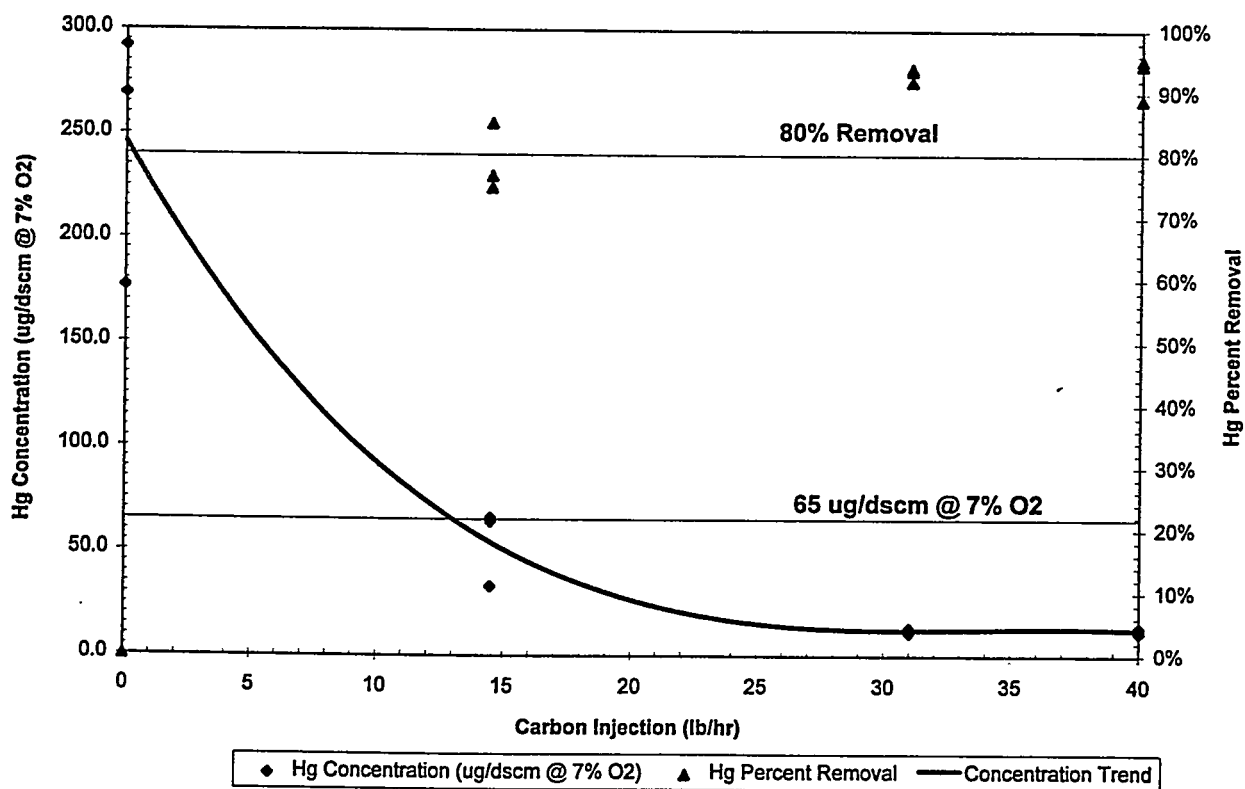


Figure 5. Essex County Resource Recovery Facility Mercury Control Optimization Curve.

Stack Emissions and Ash Characterization Data
from a
State of the Art Municipal Waste Resource Recovery Facility

Ramana K. Rao
Montgomery County Department of Public Works and Transportation
Division of Solid Waste Services
101 Monroe Street, 6th Floor, Rockville, Maryland 20850

INTRODUCTION

Montgomery County, Maryland, is located outside of Washington, D.C. In 1987, the County implemented an Integrated Solid Waste Management Program which provided for a Waste-to-Energy municipal solid waste Resource Recovery Facility (RRF) as the County's central disposal facility for municipal waste. On February 12, 1993, the Maryland Department of Environment (MDE) issued a Permit to Construct (PTC) the RRF. Construction of the facility started in March 1993 and was completed in May, 1995. The RRF, which is constructed adjacent to a coal-fired power plant near Dickerson Maryland, consists of three units. Each unit is designed to combust 600 tons of refuse per day and generate approximately 20 megawatts (MW) of electricity.

Northeast Maryland Waste Disposal Authority (NEA) is the legal owner of the facility. Ogden Martin Systems of New Jersey (Ogden) is the full service vendor, who designed, constructed and operates the facility.

Waste is transported to the RRF by rail from the County's Waste transfer station located in Rockville, approximately 20 miles away. The County's residential, commercial and office waste as well as yard waste and recyclables are brought to the Transfer Station daily by trucks. The trucks are checked by County staff for potential hazardous substances. If any hazardous materials are found, the waste is not accepted by the County. The accepted waste is unloaded into the pit at the Transfer Station. The waste in the pit is again inspected for any hazardous substances. If any household hazardous substances are found, they are sent to the County's Household Hazardous Waste Collection Center. The recyclables are sent to the County's Material Recycling Facility (MRF) located adjacent to the Transfer Station. Non-processibles are sent to the Oaks landfill by truck. The non-recyclable and burnable waste is loaded in to specially designed balers that compact the waste in to 30-ton 37-foot logs. These logs are slid into 40-foot long intermodal containers. The containers are sealed with internal air bladders to prevent leakage, and loaded on to specially designed trailers and transported to the railyard approximately 500 feet from the Transfer Station. Although the RRF is designed to burn 1800 tons of waste per day, only 1200 tons of waste currently arrives at the Transfer station. Each rail carriage holds two 30-ton containers. Therefore, twenty carriages are needed to transport the 1200 tons of waste per day from the Transfer Station to the RRF.

When the loaded rail units arrive at the rail yard adjacent to the RRF every morning, the containers are lifted by an overhead MiJack crane and lowered on to specially designed trucks with tipping chases. The trucks take the containers to the RRF tipping floor. The waste is dumped into the 205-foot long, 65-foot wide and 30-foot deep pit by inclining the containers at a 70-degree angle.

After combustion of the waste, the residue is again loaded into the intermodal containers and taken

to the rail yard for transporting back to the County's Transfer Station. The ash-containers are then trucked approximately 10 miles to a landfill for disposal in a monofill.

Only two of the three units of the RRF are generally operating on any given day to combust the approximately 1200 tons of waste currently being shipped to the RRF.

The facility consists of three water wall boiler units, each unit combusting approximately 600 tons of waste per day (TPD) and generating approximately 20 megawatts (MW) of electricity. The facility is equipped with the state of the art Air Pollution Control (APC) System that consists of a reverse air fabric filter baghouse, spray dryer and activated carbon injection system for the control of organics, trace metals, acid gases, and mercury. A selective non-catalytic reactive system (SNCR) is installed for the control of nitrogen oxides (NO_x). In addition, direct lime injection system in to the boiler further controls the acid gases, and addition of dolomitic lime to the ash minimizes leaching of metals from the ash when it is deposited in a landfill. Atmospheric discharge is through a 275-foot tri-flue stack (Figure 1). Technical information pertaining to the facility is presented in Tables 1, 2 and 3.

A Service Agreement signed by NEA and Ogden requires Ogden to conduct several engineering and environmental compliance tests to demonstrate that the facility can operate within the prescribed conditions in the Service Agreement before the facility can be accepted by the County and the Authority. The emission guarantees in the Service Agreement are based on stack test results from the vendor's best performing facilities. On May 5, 1995, the Maryland Department of Environment (MDE) issued a temporary Permit to Operate that required the vendor to conduct compliance tests within 180 days of start-up to demonstrate that the facility can operate in compliance with the permits issued by the Agency.

The facility commenced temporary operations on May 9, 1995. Compliance tests were conducted from July 24, 1995 to August 4, 1995. These tests included stack emissions and ash characterization programs. The facility passed all compliance tests that were required by NEA's Service Agreement and MDE's temporary operation permit. On November 8, 1995, the RRF received an Air Permit to Operate and a Waste Disposal Permit from MDE. The Air Permit to Operate is valid until October 31, 2000, and the Waste Disposal Permit is valid until February 9 1998.

MDE's Air Permit to Operate requires that stack emission tests for certain pollutants be conducted quarterly for each combustion train for the first year of operation after initial compliance testing, and annually thereafter. The pollutants to be tested are: particulates, nitrogen oxides, sulfur dioxide, carbon monoxide, hydrogen chloride, sulfuric acid mist, non-methane hydrocarbons, fluorides, mercury, cadmium, beryllium, lead and total dioxins and furans. For certain other pollutants, stack emissions testing are conducted on one combustion train rotated quarterly for the first three years of operation. These pollutants are: chlorophenols, polychlorinated biphenyls, chlorobenzenes,

ammonia, total chromium, chromium_{VI}, copper, zinc, antimony, arsenic, barium, cobalt and selenium. MDE's Waste Disposal Permit required ash characterization prior to the startup of commercial operations of the facility. However, the County required quarterly ash testing during the first year of operation.

As required by MDE's air permit, compliance tests were conducted in August 1995 and quarterly tests during the first year of operation in December 1995, February 1996, May 1996 and August 1996. During the second year of operation, quarterly stack testing for one combustion train (Unit 2) was conducted in November 1996.

SAMPLING AND ANALYTICAL METHODS

Stack Air Emissions

As required by MDE's Air Permit to Operate, emissions tests were conducted for each unit in accordance with the protocol approved by MDE. The test methods are listed in Table 4.

Combustion Residue Characterization.

Fly ash from the baghouse is carried via ash conveyors and is combined with residue from the scrubber and bottom ash from the boiler ash dischargers. Dolomitic lime is added to the ash between the scrubber and the baghouse to stabilize the ash to bind the metals. Combined ash samples are collected at a location after the ferrous material has been removed so that the sample represents the ash as it leaves the site. In accordance with the requirements of MDE's Waste Disposal Permit, an ash residue characterization program was conducted within 90 days of startup of the RRF. The program was designed in accordance with USEPA's draft guideline document entitled "Sampling and Analysis of Municipal Refuse Incinerator Ash", "Guidance for Sampling and Analysis of Municipal Waste Combustion Ash for the Toxicity Characteristics", and other supporting documents. The ash sampling methods are listed in Table 9. The ash testing program was repeated quarterly after the initial compliance test. A total of six quarterly tests have been conducted over the last eighteen months.

DISCUSSION OF RESULTS

Stack Emissions

A total of five stack tests were conducted on units 1 and 3, and six tests on unit 2. Of the six tests, five were conducted by Clean Air Engineering and one test was conducted by Entropy. The County screened these consultants for their compliance record. The results are reported by Ogden in Environmental Test Reports^{1,2,3,4,5,6}. MDE's permit limits for organics and acid gases are standardized

to 7% O₂ and for particulates and metals to 12% CO₂. EPA's requirements for organics as well as metals are standardized to 7% O₂. Therefore two sets of stack emission test results were reported, one standardized to 7% O₂ and the other to 12% CO₂. However, the difference between the two sets of results is generally less than five percent. These results are summarized in Tables 5 to 8. The emission limits required by MDE's Permits, the NEA's Service Agreement and the USEPA are also listed in these Tables. The results for selected compounds are discussed below.

Organics.

A total of 16 samples of dioxins and furans were collected between August 1995 and November 1996. The overall maximum and minimum concentrations of total dioxins in the flue gas are 7.06 and 0.26 ng/dscm @ 7% O₂ respectively. MDE's Permit limit is 30 ng/dscm @ 7% O₂. The overall maximum and minimum dioxin concentrations expressed as 2-3-7-8TCDD (EPA 89 TEF or ITEF) are 0.004 ng/dscm @ 7% O₂ and 0.0142 ng/dscm @ 7% O₂, compared to the NEA's Service Agreement requirement of 1 ng/dscm @ 7% O₂. The results of total dioxins obtained in the quarterly tests from each of the three units are shown in Figure 2. The results indicate that no specific data point is consistently highest or any test series consistently the highest. This means that the variations from test to test or unit to unit may be nothing more than random noise. Flue gas concentrations of PCBs, PAHs, Chlorophenols and Chlorobenzenes were below laboratory detection limits. These detection limits are shown in Table 4.

Particulates and Trace Metals.

From the data obtained in the six stack tests conducted so far, the range of particulate concentrations in the flue gas is from 0.00016 to 0.0018 gr/dscf @ 12% CO₂ compared to MDE's permit limit of 0.01 gr/dscf @ 12% CO₂. In all six stack tests, mercury was found above detection limits. The overall maximum and minimum concentrations of mercury in the flue gas are 76.9 and 1.8 microg/dscm @ 7% O₂ respectively compared to EPA's requirement of 80 microg/dscm @ 7% O₂. The results of mercury flue gas concentrations in the quarterly tests from each of the three units are shown in Figure 3. In three stack tests, cadmium was below laboratory detection limits of 0.06 microg/dscm @ 7% O₂. The range of detected concentrations of cadmium in the flue gas is 0.2 to 0.63 microg/dscm @ 7% O₂ compared to EPA's requirement of 40 microg/dscm @ 7% O₂. In three stack tests, lead was below laboratory detection limits of 0.1 microg/dscm @ 7% O₂. The range of detected concentrations of lead in the flue gas is 0.17 to 13.8 microg/dscm @ 7% O₂ compared to EPA's requirement of 490 microg/dscm @ 7% O₂. The results indicate that there is no seasonal trend in the metals.

Acid Gases and Nitrogen Oxides.

The range of detected 3-hour average concentrations of sulfur dioxide (SO₂) in the flue gas is 0.1 to

15.2 ppmv @ 7% O₂ compared to MDE's permit limit of 30 ppmv @ 7% O₂. The removal efficiencies ranged from a maximum of 99.9% to a minimum of 92.4% compared to MDE's permit requirement of 85% removal efficiency. The range of 1-hour average concentrations of hydrogen chloride (HCl) in the flue gas is 8.0 to 21.8 ppmv @ 7% O₂ compared to MDE's permit limit of 25 ppmv @ 7% O₂. The removal efficiencies ranged from a maximum of 98.1% to a minimum of 95.9% compared to MDE's permit requirement of 95% removal efficiency. The range of 24-hour average concentrations of nitrogen oxides (NO_x) in the flue gas is 151 to 177 ppmv @ 7% O₂ compared to MDE's permit limit of 180 ppmv @ 7% O₂.

Combustion Residue Characterization

A total of six quarterly ash characterizations have been done over the last eighteen months. The results are reported by Ogden in Environmental Test Reports^{7,8,9,10,11,12}. In all six quarterly ash characterization programs conducted so far, volatile/semivolatile organics, herbicides and pesticides were below detection limits. Therefore, only trace metal results are presented in Table 10, and are discussed below.

Trace Metals.

In all six quarterly ash characterization programs, arsenic, selenium and silver were below laboratory detection limits. These detection limits are shown in Table 10. Cadmium was found in all six tests but lead was only detected in three of the six tests while mercury was detected in four of the six tests. Barium and chromium were detected in only one test. The sampling results and regulatory thresholds are presented in Table 8. The range of 90% upper confidence interval concentration of cadmium in the ash was 0.019 to 0.434 mg/liter compared to the regulatory threshold value of 1.0 mg/liter. The range of detected 90% upper confidence interval concentration of lead in the ash was 0.051 to 0.44 mg/liter compared to the regulatory threshold value of 5.0 mg/liter. The range of detected 90% upper confidence interval concentration of mercury in the ash was 0.0006 to 0.0038 mg/liter compared to the regulatory threshold value of 0.2 mg/liter.

SUMMARY AND CONCLUSIONS

This paper summarizes stack emissions and ash characterization data obtained in six quarterly tests conducted over an eighteen month period for the Montgomery County Waste-to-Energy Resource Recovery facility (RRF) located near Dickerson, Maryland. The facility started testing and temporary operations in May 1995. The first stack test was a compliance test conducted in August 1995 to demonstrate to the County, NEA and the Maryland State that the facility can comply with all applicable permit conditions prior to the issuance of an operation permit by the Maryland Department of Environment (MDE). In November 1995, MDE issued the operation permit. Subsequent to this date, five quarterly tests have been conducted. The last quarterly test reported in

this paper was conducted in November 1996. Of all the stack emissions, dioxin and mercury levels in the flue gas are of focal interest both from a regulatory compliance perspective and public perception.

Of the sixteen samples obtained in the six stack tests conducted for the three units, nine samples of total dioxins in the flue gas were less than 1 ng/dscm @ 7% O₂. Four samples were between 1 and 2 ng/dscm @ 7% O₂ and two samples were between 3 and 4 ng/dscm @ 7% O₂. The remaining sample, the maximum reported in this paper is 7.06 ng/dscm @ 7% O₂. A comparison of these values with the data obtained from other facilities that have similar air pollution control equipment, indicate that the dioxin levels recorded in the stack tests of Montgomery County Facility are the lowest values recorded by any other currently operating modern facility in the United States. Activated carbon injection system proved to be effective not only for mercury control, but also for dioxin and trace metal control.

Of the sixteen mercury samples obtained in the six stack tests conducted for the three units, fifteen samples were less than 51 microg/dscm @ 7% O₂. Only one sample (76.9 microg/dscm @ 7% O₂), the maximum reported in this paper came close to the EPA's requirement of 80 microg/dscm @ 7% O₂. Of the fifteen samples which were below 51 microg/dscm @ 7% O₂, eight samples were less than 20 microg/dscm @ 7% O₂ and the remaining seven samples were between 20 and 51 microg/dscm @ 7% O₂. Mercury removal efficiencies exceeded 93% compared to EPA's requirement of 80% removal efficiency.

The results of ash characterization programs indicate that all organics are below detection limits. Of the trace metals, cadmium, lead and mercury are present in detectable quantities. However, the maximum lead concentrations were less than 10% of the regulatory threshold and the maximum mercury concentrations were less than 2% of the regulatory threshold. The maximum concentrations of cadmium were less than 50% of the regulatory threshold. Most recent tests indicated that cadmium is the only metal that is present in detectable quantities.

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**TABLE 1. Technical Information for the Montgomery County
Waste-to-Energy Resource Recovery Facility**

Waste-to-Energy System	Three 600 tons-per-day (TPD) mass-burning waterwall furnaces with Martin reverse-reciprocating grates and ash handling system
Waste Type	Municipal residential, commercial and office waste
Guaranteed Throughput	558,450 tons per year (1530 TPD)
Boiler Design	865 psig/830 deg F superheater outlet conditions
Air Pollution Control Equipment	Dry flue gas scrubbers, direct lime injection system into boilers, reverse air fabric filter baghouses, nitrogen oxide control with Selective Non Catalytic Reactive (SNCR) system and mercury control with activated carbon injection system. Scrubber Inlet Temp: 440 deg F Scrubber Outlet Temp: 295 deg F
Gross Energy Generation at Rated Capacity	54 MW
Net Energy Generation at Rated Capacity	48 MW
Customer	Potomac Electric Power Company (PEPCO)
Special Features	Waste is transported by rail in closed containers. Combustion residue, after ferrous materials recovery is also transported by rail in closed containers

Table 2. Reagents used in the Air Pollution Control and Ash Leaching in 1996

(Average Amounts in Pounds per Ton of Refuse Burned)				
Pebble Lime	Hydrated Lime	Dolomitic Lime	Ammonia	Carbon
15.0	3.1	12.8	1.8	1.7

Table 3. Combustion Residue and Ferrous Materials generated in 1996

Percent by Weight of Refuse Burned	
Combustion Residue	Ferrous
26.1	3.0

PEER-REVIEW

TABLE 4. Stack Emissions Test Methods

Parameter	Test Method	Location
Particulate Matter (PM)	EPA Method 5	Stack
Particulate Matter <10 micr. (PM10)	EPA Method 201A	Stack
Sulfur Dioxide (SO ₂)	EPA Method 6C	Inlet/Stack
Hydrogen Chloride (HCl)	EPA Method 26	Inlet/Stack
Total Fluorides (HF)	EPA Method 13B	Stack
Carbon Monoxide (CO)	EPA Method 10	Inlet
Sulfuric Acid Mist	EPA Method 8	Stack
Nitrogen Oxides (NO _x)	EPA Method 7E	Stack
Mercury (Hg)	EPA Method 101A	Inlet/Stack
Dioxins/Furans (PCDD/PCDF)	EPA Method 23	Stack
Polychlorinated Biphenyls (PCBs), Polycyclic Aromatic Hydrocarbons (PAHs), Chlorophenols, Chlorobenzenes	SW846 - 0010	Stack
Ammonia (NH ₃)	EPA Method 26	Stack
Carbon Dioxide (CO ₂)	EPA Method 3A	Inlet/Stack
Oxygen (O ₂)	EPA Method 3A	Inlet/Stack
Multi Metals: Antimony (Sb), Arsenic (As), Barium (Ba), Beryllium (Be), Cadmium (Cd), Total Chromium (Cr), Cobalt (Co), Copper (Cu), Lead (Pb), Nickel (Ni), Selenium (Se), Zinc (Zn)	EPA Method 29	Stack
Non-Methane Hydrocarbons (NMHC)	EPA Method 25A	Stack
Hexavalent Chromium (Cr ₆)	BIF Cr ₆	Stack
Opacity	EPA Method 9	Stack

TABLE 5. Stack Emissions Test Results - Organics

Flue Gas Concentration in nanograms per dry standard cubic meter (ng/dscm @ 7% O ₂)	Unit 1	Unit 2	Unit 3	MDE Operating Permit Standards	EPA's Standards promulgated on 10/31/95	NEA Service Agreement Requirements
Dioxins (Total)	0.29 - 1.41	0.294 - 7.06	0.26 - 3.51	30 (4-hr)	30	None
EPA 89 TEF	0.004	0.012	0.014	None	None	1.0 ^a 0.9 ^b
PCBs	<2661	<4454	<2300			
Total PAHs	<3959	<4575	<6445			13,400
Chlorophenols	<3673	<15,431	<18,069			
Chlorobenzenes	<3670	<6976	<8148			

TABLE 6. Stack Emissions Test Results - Trace Metals

Flue Gas Concentration, microg/dscm @ 12% CO ₂ or 7% O ₂	Unit 1	Unit 2	Unit 3	MDE's Operation Permit Standards @ 12% CO ₂	EPA's Standards promulgated on 10/31/95 @ 7% O ₂	NEA Service Agreement Requirements @ 12% CO ₂
Arsenic (As)	<0.21 - 0.23	0.15 - <0.2	<0.19 - 0.37	None	None	26 ^b
Beryllium (Be)	<0.05 - <0.06	<0.04 - <0.06	<0.04 - <0.06	0.36	None	0.88 ^a 0.82 ^b
Cadmium (Cd)	0.06 - 0.63	0.06 - 0.25	0.04 - 0.12	None	40	64.4 ^b
Chromium (Cr)	<0.16 - 0.83	<0.17 - <0.5	<0.2 - 6.0	None	None	465 ^b
Cr _{VI}	0.11 - <0.32	0.13 - <0.46	0.15 - <0.40	None	None	None
Nickel (Ni)	<0.16	<0.15	0.26			444 ^b
Lead (Pb)	<0.1 - <1.07	<0.2 - <3.3	<0.4 - 13.8		490	2702 ^a 537 ₆
Mercury (Hg)	5.0 - 77.0	12.4 - 47.0	1.8 - 51.0		80 85% removal	130 80% Removal ^{ab}

EPA 89 TEF: EPA's 1989 Toxicity Equivalent Factors for dioxins/furans

a: NEA Service Agreement Compliance Test Requirement

b: NEA Service Agreement Annual Average Requirement

7% O₂: adjusted to 7% oxygen in dry gas at standard conditions

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TABLE 7. Stack Emissions Test Results - Acid Gases, NO_x, CO & NH₃

Flue Gas Concentration ppmv @ 7% O ₂	Unit 1	Unit 2	Unit 3	MDE's Operation Permit Standards	EPA's Standards promulgated on 10/31/95	NEA Service Agreement Requirements
Sulfur Dioxide (SO ₂)	1.4 - 15.2	0.14 - 7.03	2.1 - 10.2	30	31	30
Removal Efficiency %	95.5 - 98.8	92.4 - 99.9	93.8 - 97.5	85	75	85
Hydrogen Chloride (HCl)	8.0 - 16.7	9.9 - 21.8	8.2 - 19.1	25	31	30 ^a 25 ^b
Removal Efficiency %	97.1 - 98.1	96.1 - 97.5	95.9 - 97.9	95	95	90 ^b
Nitrogen Oxides (NO _x)	151 - 168	154 - 168	153 - 177	180 (24h)	200	180 ^b
Carbon Monoxide (CO)	16.8 - 31.2	11.4 - 25.6	18.0 - 31.8	200 (1h) 50 (24h)	100 (4h)	50 ^b
Ammonia (NH ₃)	1.4 - 8.7	<0.11 - 4.7	2.2 - 4.7	None	None	None

TABLE 8. Stack Emissions Test Results - Fluorides, NMHC, H₂SO₄ Mist, Particulates and PM₁₀

Flue Gas Concentration in grains per dry standard cubic foot (gr/dscf @ 12% CO ₂)	Unit 1	Unit 2	Unit 3	MDE's Operation Permit Standards	EPA's Standards promulgated on 10/31/95	NEA's Service Agreement
Fluorides	<0.02 - <0.283	<0.02 - <0.207	<0.02 - <0.220	3.1	None	None
Nonmethane Hydrocarbons (NMHC)	0.1 - <1.2	0.1 - <1.2	0.2 - <1.2	4.4 (3h)	None	None
Sulfuric Acid Mist	0.0184 - 2.51	0.0507 - 2.85	0.0484 - 2.75	20 (3h)	None	None
Particulates	0.00016 - 0.0018	0.00024 - 0.0012	0.00024 - 0.00074	0.01	None	0.01
PM ₁₀	<0.0007	<0.0007	<0.0007	0.01 (3h)	0.012	0.01 ^{ab}

a: Service Agreement Compliance Test Requirement,

b: Service Agreement Annual Average Requirement

TABLE 9. Ash Testing Methods

Parameter	Analytical Method ^b
<u>TCLP Metals^a</u>	
Arsenic	3010 and 6010A (ICP)
Barium	3010 and 6010A (ICP)
Cadmium	3010 and 6010A (ICP)
Chromium	3010 and 6010A (ICP)
Lead	3010 and 6010A (ICP)
Mercury	7471 (CVAA)
Selenium	3010 and 6010A (ICP)
Silver	3010 and 6010A (ICP)
<u>Other TCLP Constituents</u>	
Volatiles	8260 (GC/MS)
Semi volatiles	8270 (GC/MS)
Pesticides & Herbicides	8080 and 8150 (GC)
2.0 Moisture	160.3
(a) EPA Method 1311, Toxic Characterization Leaching Procedure (b) ICP: Inductively Coupled Plasma Spectroscopy CVAA : Cold Vapor Atomic Absorption GC: Gas Chromatograph GC/MS: Gas Chromatograph and Mass Spectroscopy	

Table 10. Ash Characterization Results from Six Quarterly Tests - Metals

Metals	Lowest Detection Limit	90% Upper Conf. Interval* (milligrams per liter)	Regulatory Threshold** (Milligrams per Liter)
Arsenic	0.028	ND	5.0
Barium	0.26	0.47 (1)	100
Cadmium	0.001	0.019 - 0.434 (6)	1.0
Chromium	0.001	0.018 (1)	5.0
Mercury	0.0003	0.0006 - 0.0038 (4)	0.2
Lead	0.003	0.051 - 0.44 (3)	5.0
Selenium	0.03	ND	1.0
Silver	0.019	ND	5.0
*: SW-846 (b) **: 40 CFR Part 261 ND: Not Detected (--): Number of Tests in which the metal is detected			

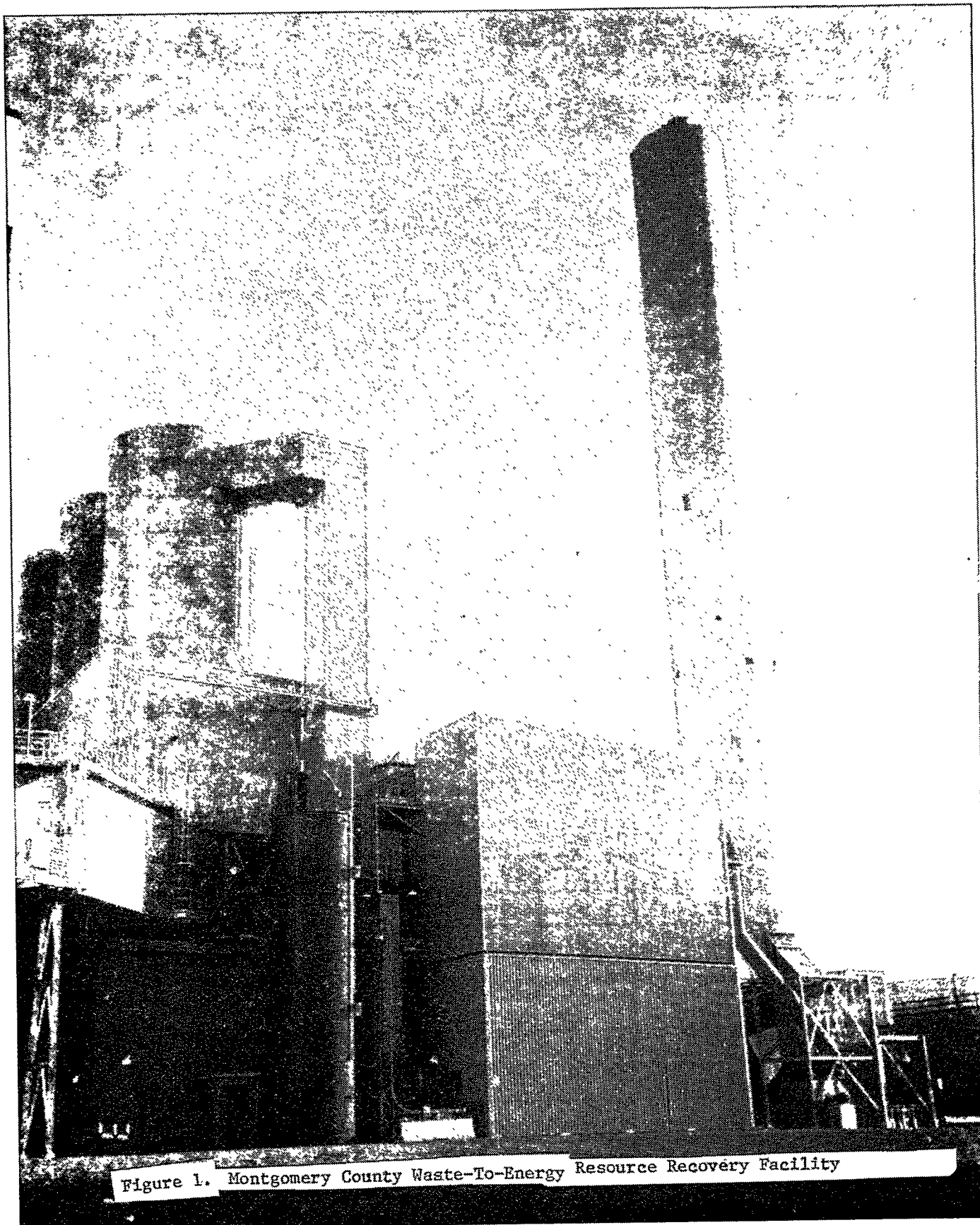


Figure 1. Montgomery County Waste-To-Energy Resource Recovery Facility

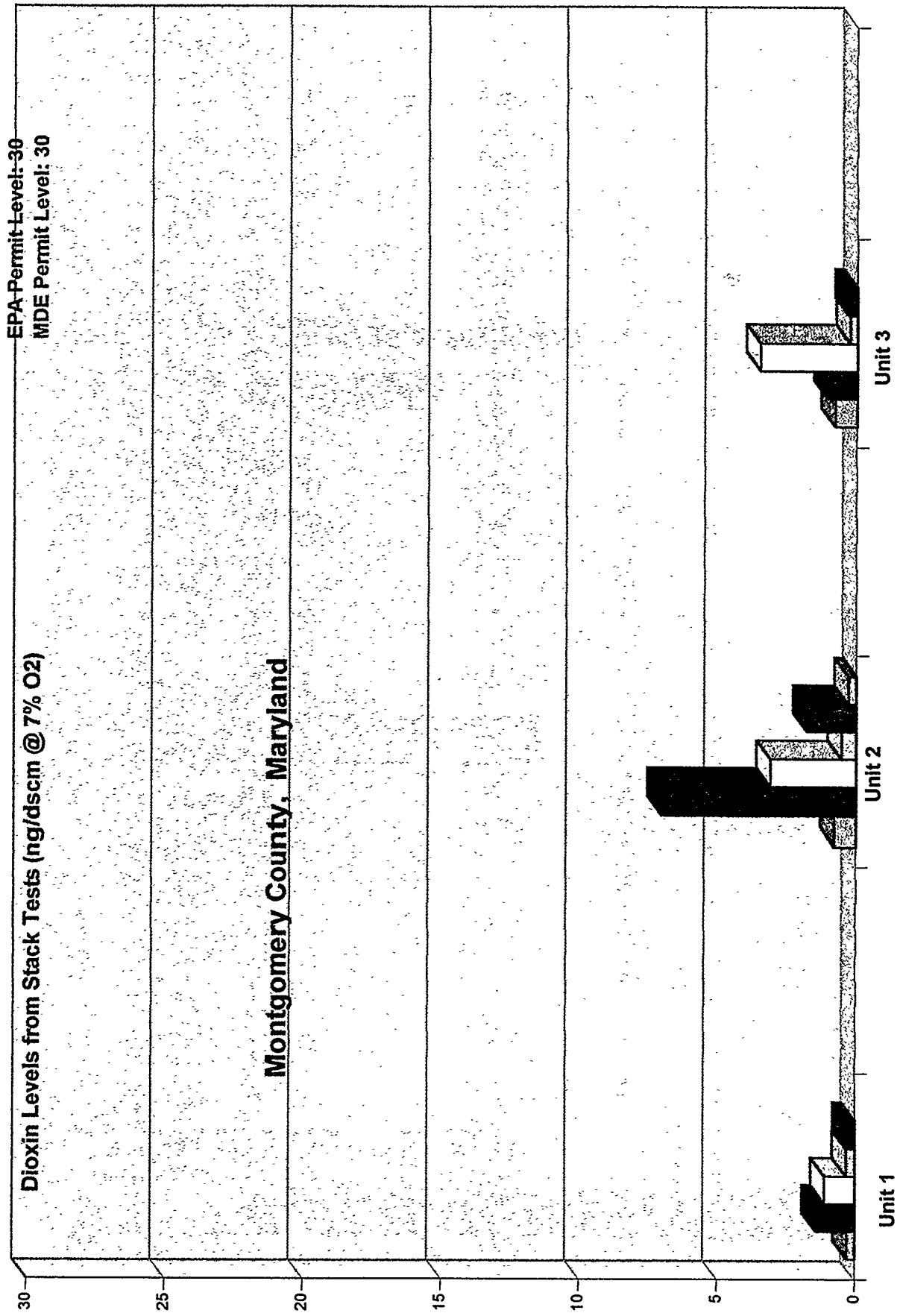


Figure 2. Average Dioxin Concentrations for each test series.

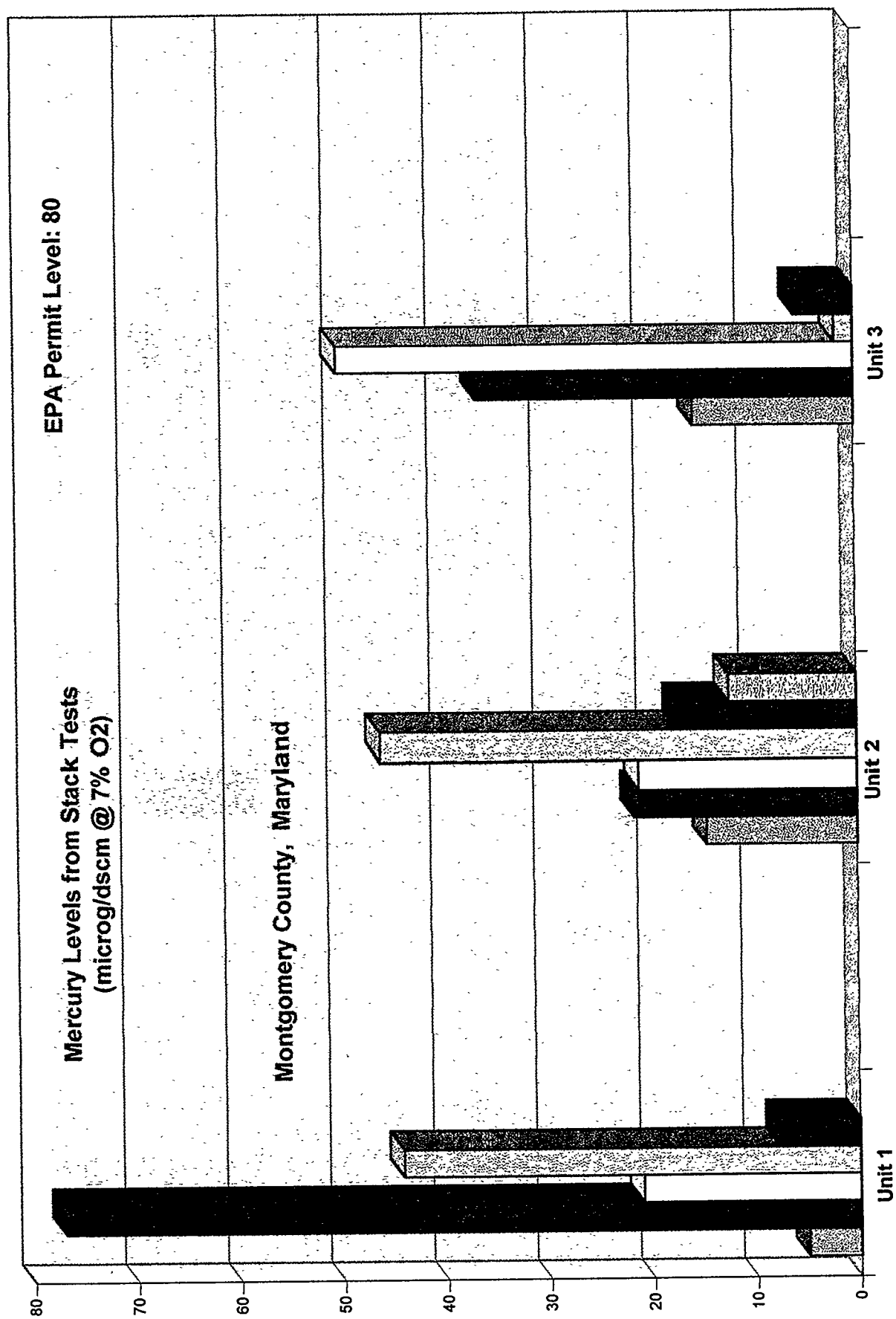


Figure 3. Average Mercury Concentrations for each test series.

Developing Laboratory Test Facilities to Evaluate Carbon Based
Materials to Control Mercury Emissions

Anthony Licata, Technical Advisor
Dravo Lime Company
345 Concord Road
Yonkers, N.Y. 10710

Lutz-Peter Nethe
Märker Umwelttechnik GmbH
Oskar Märker Strasse 24
Harburg/Schwaben D-86655, Germany

Louis Terracciano
Licata Energy & Environmental Associates
345 Concord Road
Yonkers, N.Y. 10710

ABSTRACT

Changes in carbon technology and new applications for the technology have led to the development of a research and testing facility which can be used to evaluate new carbons and formulations quickly, and at a relatively low cost. Märker Umwelttechnik GmbH has developed a testing facility that simulates the thin layer of adsorbent on a fabric filter through which a simulated flue gas can be passed. A novel development in this flue gas simulation system is the use of mercuric chloride (HgCl_2) instead of elemental mercury (Hg°). Most research into mercury adsorption has been conducted using elemental mercury while in most municipal waste combustors (MWCs), HgCl_2 makes up about 85% of the total mercury emissions.

This paper discusses the development of the test facility and describes how it is used to develop new adsorption products. A comparison of laboratory test results to actual field testing will be presented to illustrate the value of this system.

INTRODUCTION

Regulatory requirements for the control of mercury emissions are becoming ever more stringent and their implementation more speedy. In light of this fact and in response to its need to provide both timely and cost effective service its clients needs, Märker Umwelttechnik GmbH (Märker) set out to develop a testing facility to simulate the thin layer of carbon or Sorbalit® on a fabric filter. This test facility has enhanced Märker's ability to promptly and economically evaluate product formulations by replicating the actual operating conditions in the field. Typical conditions simulated include flue gas concentrations of moisture and HCl, gas temperature and fabric filter materials and layer thickness.

Because of mercury's great volatility and the variety of its binding forms, the process of controlling mercury and its compounds is a difficult one. Due to their high vapor pressures even at low temperatures, mercury and its compounds are present in the flue gas mainly as gas phase materials. Also, depending upon the quantity of chloride in the stack gas, the flue gas components, the combustion process and the operating conditions of the plant, mercury may be present in a variety of forms in the flue gas. In passage through the gas path of a plant, conversion reactions between individual species can and do take place. In addition to its elementary form, mercury is emitted mostly as HgCl_2 and other mercury compounds such as mercury sulfide or mercury oxide may also be present albeit to a much smaller degree. Further, mercury bound as HgCl_2 predominates in the flue gas of most waste combustion processes such as MWCs, MWIs and HWIs where the HgCl_2 component of the mercury emissions can be as much as 85% to 95% of the total. Typically for fossil fuel fired boilers, mercury bound as HgCl_2 is 50% or less in the flue gas.

Historically, most researchers have evaluated carbon adsorption on the basis of elemental mercury removal which Märker scientists did not believe would provide representative results of actual field conditions. Since elemental mercury by virtue of its smaller molecular size ($\sim 3.6\text{\AA}$) is not as easily adsorbed as HgCl_2 ($\sim 5.4\text{\AA}$) or HgSO_4 ($\sim 5.3\text{\AA}$), projections of mercury removal requirements for waste incineration processes based on the assumption that elemental mercury needed to be removed would overestimate the carbon requirement. Since open hearth coke (HOK) which is a residual coke material with a reduced surface area than activated carbon costs about DM 590/tonne (\$360/ton) and activated carbon depending on activation

method and impregnation method, costs from DM 1700 - DM 14,000 /tonne (\$1,000 - \$8,500/ton) such an assumption was both expensive and wasteful.

Therefore, Märker concluded that to determine representative total mercury emissions and removal efficiencies both in the field and in the laboratory, it is generally both sufficient and representative to detect only the HgCl_2 component. Further, the increase in regulatory activity with regard to acid gases and heavy metals in general and to mercury emissions specifically, increased client urgency for Märker to develop product formulations which were both effective in controlling emissions and yet economically attractive. In response to this urgent client need for optimized product formulations, and in light of the high costs and time frames associated with field testing, Märker designed a test facility specifically geared to generating mercury laden test gases and simulating field conditions so that various product formulations could be easily, effectively, and inexpensively evaluated.

TEST FACILITY DESCRIPTION

Reference test gases are essential for determining the adsorbitivity of a product formulation. The mercury test gases now available in pressure cylinders are characterized by good stability, but in some cases the indicated concentrations differ considerably from actual values. To ensure high test gas quality, a test gas generator system has been developed for accurately generating mercury in the form of HgCl_2 . The principle of gas diffusion, in which a carrier gas (N_2 & O_2 mixture) controlled by a mass-flow regulator is conducted through a temperature-controlled gas cell, is used for this purpose. A test gas with a reference mercury content can be generated in the Märker laboratory test facility at constant conditions (temperature, volumetric flow).

The laboratory test setup allows a known quantity of mercury, as HgCl_2 to be passed through the substance to be tested (typically activated carbon or Sorbalit®) within a given time and the residual content of mercury exiting the test material can then analytically determined. This procedure allows conclusions concerning the adsorbitivity of individual substances to be drawn.

The laboratory test setup is designed with the following components:

- ◆ Test Gas Station: This consists of a 40 liter test gas cylinder filled with a mixture of nitrogen and 10% oxygen.
- ◆ Gas metering: The metering is performed using a Tylan instrument which operates on the basis of the thermal conductivity of gases.
- ◆ Hg metering: The metering is performed by using a hose pump to aspirate a solution of HgCl_2 from a glass container into a U-tube evaporator thru a Teflon tube immersed in the solution. The glass container is set onto a laboratory scale. The hose pump is set at about 0.2 g/min. The quantity of HgCl_2 is determined with precision by means of the difference in the laboratory scale readings at the beginning and end of a test.

- ◆ U-Tube Evaporator: This serves to evaporate the HgCl_2 solution, mix it with the test gas, and introduce the gas mixture into the reactor. The evaporator consists of a glass U-tube in an electrically heated oven which operates at a temperature of 640°C . Test gas from the test gas station is heated in the first part of the U-tube and mixed with the HgCl_2 solution in the second part using glass wool or glass beads to facilitate evaporation of the HgCl_2 solution and mixing of the gases. All connections are made with standard laboratory connections.
- ◆ Adaptor: This is a glass tube wrapped in heating tape and connects the evaporator outlet to the inlet of the reaction tube via ground glass tapered joints.
- ◆ Reactor: It consists of heated enclosure which contains a reaction tube containing the substance being tested (e.g. activated carbon or Sorbalit®). The reactor chamber is heated and maintained at the desired temperature. The test substance is contained within the reactor tube as a one (1) cm thick layer imbedded between layers of densely packed quartz wool. Figure 1 is a sketch of the reactor tube which illustrates the main components. Figure 2 is a photo of the reactor tube set into the heated enclosure.
- ◆ End piece: It is attached to the reactor via a ground glass tapered joint and provides an interconnection to the adsorption bottle and is equipped with a thermowell for the insertion of a thermocouple positioned as closely as possible to the test substance layer.
- ◆ Adsorption bottle: This contains 40 ml of 10% HNO_3 . The gases from the reactor are passed through the HNO_3 solution to precipitate Hg from the test gas stream.
- ◆ Gas meter: The precise test gas volume through the system is determined using a calibrated gas meter. Test gas flow is readily determined using a stop watch in conjunction with the meter readings.

Figure 3 is a photo of the test system. The HgCl_2 solution is aspirated by means of a gas pump and fed into the evaporator through a Teflon nozzle and mixed in a layer of glass wool or glass beads. In the evaporator, the HgCl_2 solution is evaporated, introduced and thoroughly mixed into the hot test gas upstream of the reactor. In the reactor, the mercury-laden test gas flows through the layer of the substance by which the mercury is adsorbed. The test gas stream containing the unadsorbed mercury is then directed into the HNO_3 solution in the adsorption bottle to precipitate mercury from the gas stream. The mercury content of this solution is determined and compared with the initial value. The degree of mercury removal by the test substance can then be calculated.

TEST PROCEDURE

Prior to testing, the reaction tube is loaded with a densely packed layer of quartz wool about three (3) cm long. Then 250 mg of the test substance together with two (2) grams of quartz sand are weighed into the reaction tube and are mixed and compressed into a dense structure using quartz wool in the tube.

The system is then prepared for the test as follows:

- ▶ The evaporator is turned on and temperature set and maintained at 640°C.
- ▶ The end piece is attached to the reaction tube which contains the previously charged test substance and a thermocouple is inserted via a thermowell fitted into the end piece.
- ▶ The adsorption bottle containing 40 ml of 10% HNO₃ is attached to the end piece.
- ▶ Prior to starting up the reactor, the cooling water supply to the reactor infrared oven must be turned on.
- ▶ The reactor infrared oven is turned on and the reactor is heated to the desired temperature (typically, 180 - 300°C). In addition for heating, the test gas feed to the gas cylinder at the main valve must be opened and set to a pressure of 1 bar.
- ▶ The test gas flow is set at 1.8 l/m using the Tylan instrument.
- ▶ When the reactor has reached the desired temperature, the test gas flow is turned off again
- ▶ The fixed setting for the HgCl₂ solution is about 0.2 g/m. The actual quantity pumped is precisely determined by scale reading which is set to “zero”, the HgCl₂ solution container is set up on the scale, and the Teflon tube is connected to the hose pump.
- ▶ At the end of these preparations, the gas meter and the scale readings are noted and the values recorded.
- ▶ The Teflon nozzle is then introduced into the evaporator and the test is begun. To start a test, the test gas feed must be opened and the pump turned on.
- ▶ The duration of a test is ten (10) minutes.
- ▶ During the test, the temperature of the adaptor must be kept at 100°C and the reaction temperature constant.
- ▶ Values are logged every two (2) minutes.
- ▶ If condensation appears in the evaporator or in the adaptor, it should be removed with a hot air blower.

When the test is over;

- ▶ The pump and test gas are turned off and the Teflon nozzle is removed from the evaporator.
- ▶ The scale and the gas meter readings are noted and recorded in the test log.

- ▶ The adsorption bottle with the hose is pulled off and the frit and the hose are rinsed. The rinsing are transferred to a 100-ml measuring cylinder and the quantities noted and recorded. The rinsing are then places in a 250-ml sample bottle and labeled.
- ▶ Lastly, the reaction tube is removed from the reactor and cleaned.

As stated previously, the amount of HgCl_2 into the reactor is determined by weight difference of the HgCl_2 solution container. However, this value is confirmed for all tests by running a blank sample (i.e. with an empty reactor tube) and measuring the HgCl_2 concentration as though the reactor tube had been charged with reagent.

NEW PRODUCT DEVELOPMENT

The Märker test facility has greatly improved the evaluation and development process for new Sorbalit® /Sorbalime™ products by reducing both testing time and cost factors while markedly improving the reliability of the test results. Previous to Märker's development of the test facility, the most reliable source of data was gathered from the full-scale testing of a new application. Typically (and obviously), the full-scale testing method was not only very expensive by any economic measure in terms of labor and time but in that the information gathered could not be considered either typical or reproducible. The result was that the final product material was ultimately developed by the "fine tuning" of intermediate product formulations.

The development of product formulations involves variations in product carbon content, sulfur content, and product type as well as the use of a whole range of carbon sources (e.g. coconut shell, wood, coal etc.) and suppliers (e.g. Calgon and Norit). In addition, new applications requiring mercury removal continually surface which require an expeditious response by Märker from both marketing and regulatory reasons.

As a result of these pressing needs, the Märker analytical department set out to define and refine a laboratory scale analytical methodology in the new product developmental cycle rather than being required to continually "fine tune" each new product formulation on a full scale until it was optimized.

COMPARISON OF LABORATORY AND FIELD TESTING RESULTS

Table 1 is illustrative of the test results gathered using the test facility. As shown in the table, an initial test is run using a blank tube (containing no substance) to confirm that the system has been properly set up and that the reference values are as indicated.

Test 1 was performed on a test substance consisting of a 250 gram sample of Sorbalit® containing 5% open-hearth carbon. An average (over three test runs) of 6.8 micrograms (μg) of mercury (as HgCl_2) were passed through the test substance using the 90% nitrogen/10% oxygen carrier test gas. The average mercury (as

HgCl₂) exiting the test substance over the three test runs was 0.27 micrograms (μg) yielding a collection efficiency of 96.0% for the test.

Test 2 was performed on a test substance consisting of a 250 gram sample of ground up pellets of hydrated lime mixed with 5% activated carbon, 0.5% sulfur and 5% Bentonite. An average (over three test runs) of 6.8 micrograms (μg) of mercury (as HgCl₂) were passed through the test substance using the 90% nitrogen / 10% oxygen carrier test gas. The average mercury (as HgCl₂) exiting the test substance over the three test runs was 0.20 micrograms (μg) yielding an apparent collection efficiency of 97.1% for the test.

Test 3 was performed on a test substance consisting of a 125 gram sample of Sorbalit® containing 7.5% open-hearth carbon and 10% Portland cement. An average (over four test runs) of 4.02 micrograms (μg) of mercury (as HgCl₂) were passed through the test substance using the 90% nitrogen / 10% oxygen carrier test gas. The average mercury (as HgCl₂) exiting the test substance over the four test runs was 1.48 micrograms (μg) yielding an apparent collection efficiency of 63.3% for the test.

The table illustrates the variations in the test substance type and quantity as well as the mercury quantity and concentration which can be inexpensively, expeditiously simulated, and reproduced in the test facility thus enhancing Märker's ability to economically and reliably optimize its products to its clients' needs.

Since the test facility is a recent addition to Märker's technical services department, laboratory testing comparisons to field tests are limited. However, Märker has performed both laboratory and field tests for a MWC in WI Geiselbullach. The results are as follows:

Location	Operating Temperature, °C	Hg Total Quantity In μg/m ³	Hg Total Quantity Out μg/m ³	% Hg Removal
Test Facility	180	300	45	85.0%
WI Geiselbullach	200	260	13	95.0%

CONCLUSIONS

In response to regulatory requirements for the control of mercury emissions which created urgency on the part of Märker's client industries, Märker designed a testing facility to simulate the thin layer of sorbent on a fabric filter has enhanced its ability to promptly and economically evaluate product formulations in response to both its internal needs and to clients demands. Testing to date using this facility confirms that mercury laden test gases can be synthesized to simulate almost any client application. As a result, we can now quickly and economically evaluate various product formulations geared to the simultaneous control of mercury and other pollutant emissions such as HCl.

Major savings in terms of both cost and time, together with test results which are more reliable and representative are the hallmark for the use of the Märker test facility. The typical cost for performing a test

in the Märker test facility is in the range of \$600 - \$1,000 per sample while the cost of performing mercury tests in the field is in excess of \$10,000.

Test results of various formulations have provided valuable information concerning the effectiveness of using open-hearth carbon, activated carbon, Portland cement, Bentonite and various sulfur compounds. The test facility's ability to test these product formulations and vary the amounts as well as the types of additives has enhanced client confidence in Märker's products to provide them with effective emissions control coupled with quantifiable cost savings.

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Table 1. Sorbalit® Research Test Data

Test No.	Reaction Conditions (Adsorbent Weight, mg)	Adsorbent	Reactor Temp °C	HgCl ₂ Solution					% Hg Removal
				Hg Content μg/g	HCl Content mg/g	Solution Metered g	Hg Total Quantity In μg	Hg Total Quantity Out μg	
B1	Empty Tube	None	180	1.7	125	4	6.8	6.7	
B2	Empty Tube	None	180	1.7	125	4	6.8	6.8	
1A	250		180	1.7	125	4	6.8	0.49	92.8%
1B	250	Sorbalit® with 5% HOK	180	1.7	125	4	6.8	0.19	97.2%
1C	250	95% Ca(OH) ₂	180	1.7	125	4	6.8	0.13	98.1%
Average Test 1			180	1.7	125	4	6.8	0.27	96.0%
2A	250	Dravo pellets:	180	1.7	125	4	6.8	0.32	95.3%
2B	250	5% Carbon	180	1.7	125	4	6.8	0.14	97.9%
2C	250	0.5% Sulfur	180	1.7	125	4	6.8	0.13	98.1%
Average Test 2			180	1.7	125	4	6.8	0.20	97.1%
3A	125		180	2.1	125	2.002	4.20	1.70	59.6%
3B	128	Sorbalit® pellets:	180	2.1	125	1.656	3.48	1.30	62.6%
3C	124	7.5% HOK	180	2.1	125	2.001	4.20	1.50	64.3%
3D	125	10% Portland	180	2.1	125	2.001	4.20	1.40	66.7%
Average Test 3			180	2.1	125	1.915	4.02	1.48	63.3%

Table 1. Sorbalit® Research Test Data

Test No.	Reaction Conditions (Adsorbent Weight, mg)	Adsorbent	Reactor Temp °C	HgCl ₂ Solution				Hg Total Quantity In µg	Hg Total Quantity Out µg	% Hg Removal
				Hg Content µg/g	HCl Content mg/g	Solution Metered g				
B1	Empty Tube	None	180	1.7	125	4		6.8	6.7	
B2	Empty Tube	None	180	1.7	125	4		6.8	6.8	
1A	250		180	1.7	125	4		6.8	0.49	92.8%
1B	250	Sorbalit® with 5% HOK	180	1.7	125	4		6.8	0.19	97.2%
1C	250	95% Ca(OH) ₂	180	1.7	125	4		6.8	0.13	98.1%
Average Test 1			180	1.7	125	4		6.8	0.27	96.0%
2A	250	Dravo pellets:	180	1.7	125	4		6.8	0.32	95.3%
2B	250	5% Carbon	180	1.7	125	4		6.8	0.14	97.9%
2C	250	0.5% Sulfur	180	1.7	125	4		6.8	0.13	98.1%
Average Test 2		5% Bentonite	180	1.7	125	4		6.8	0.20	97.1%
3A	125	89.5% Ca(OH) ₂	180	2.1	125	2.002		4.20	1.70	59.6%
3B	128		180	2.1	125	1.656		3.48	1.30	62.6%
3C	124	Sorbalit® pellets: 7.5% HOK	180	2.1	125	2.001		4.20	1.50	64.3%
3D	125	10% Portland	180	2.1	125	2.001		4.20	1.40	66.7%
Average Test 3		82.5% Ca(OH) ₂	180	2.1	125	1.915		4.02	1.48	63.3%

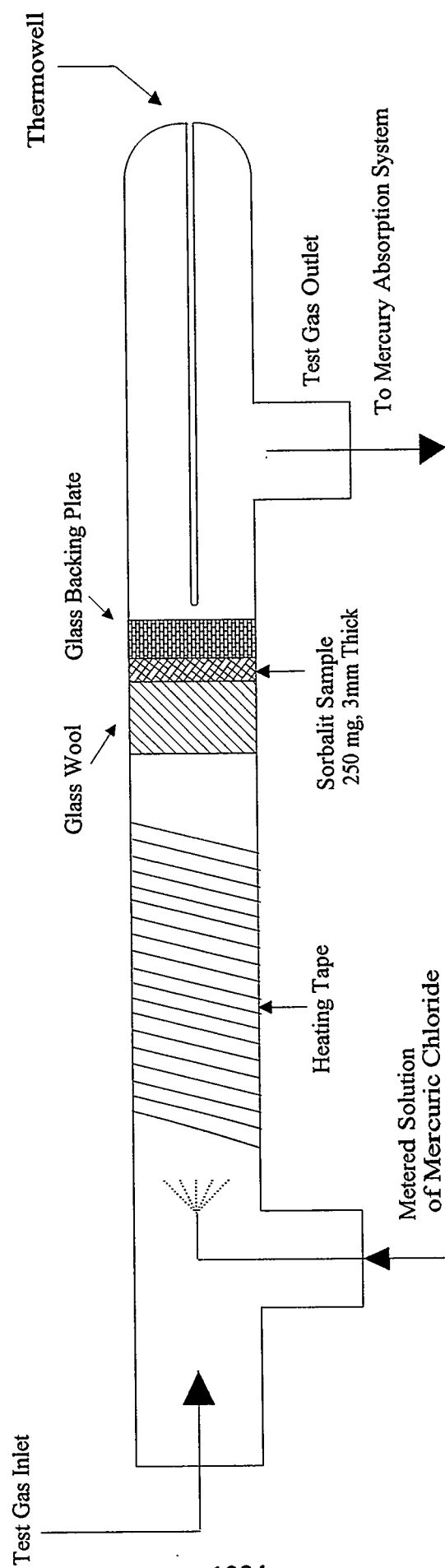


Figure 1. Sketch of Märker's reaction tube assembly.

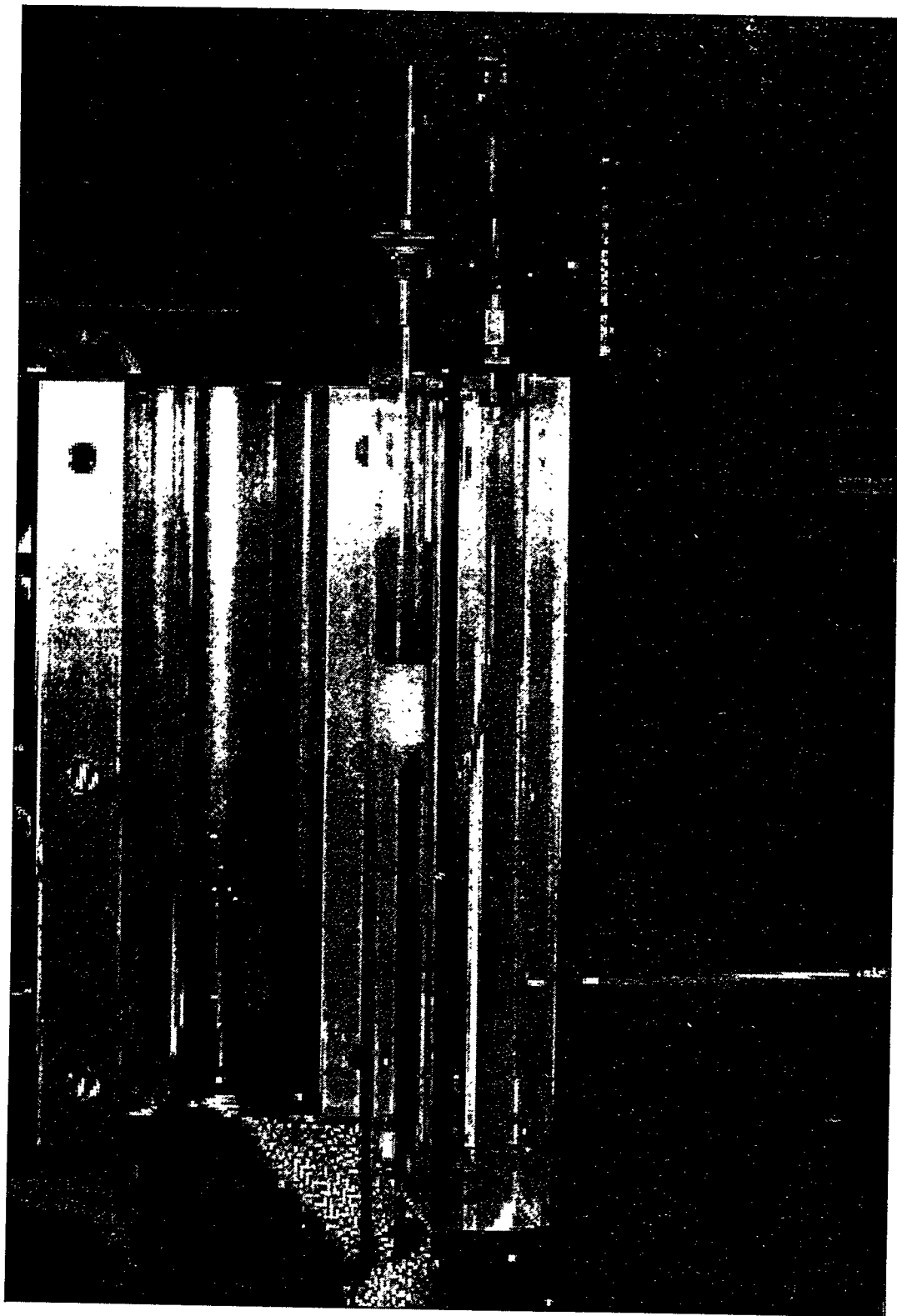


Figure 2. Reactor tube and oven

PEER-REVIEW

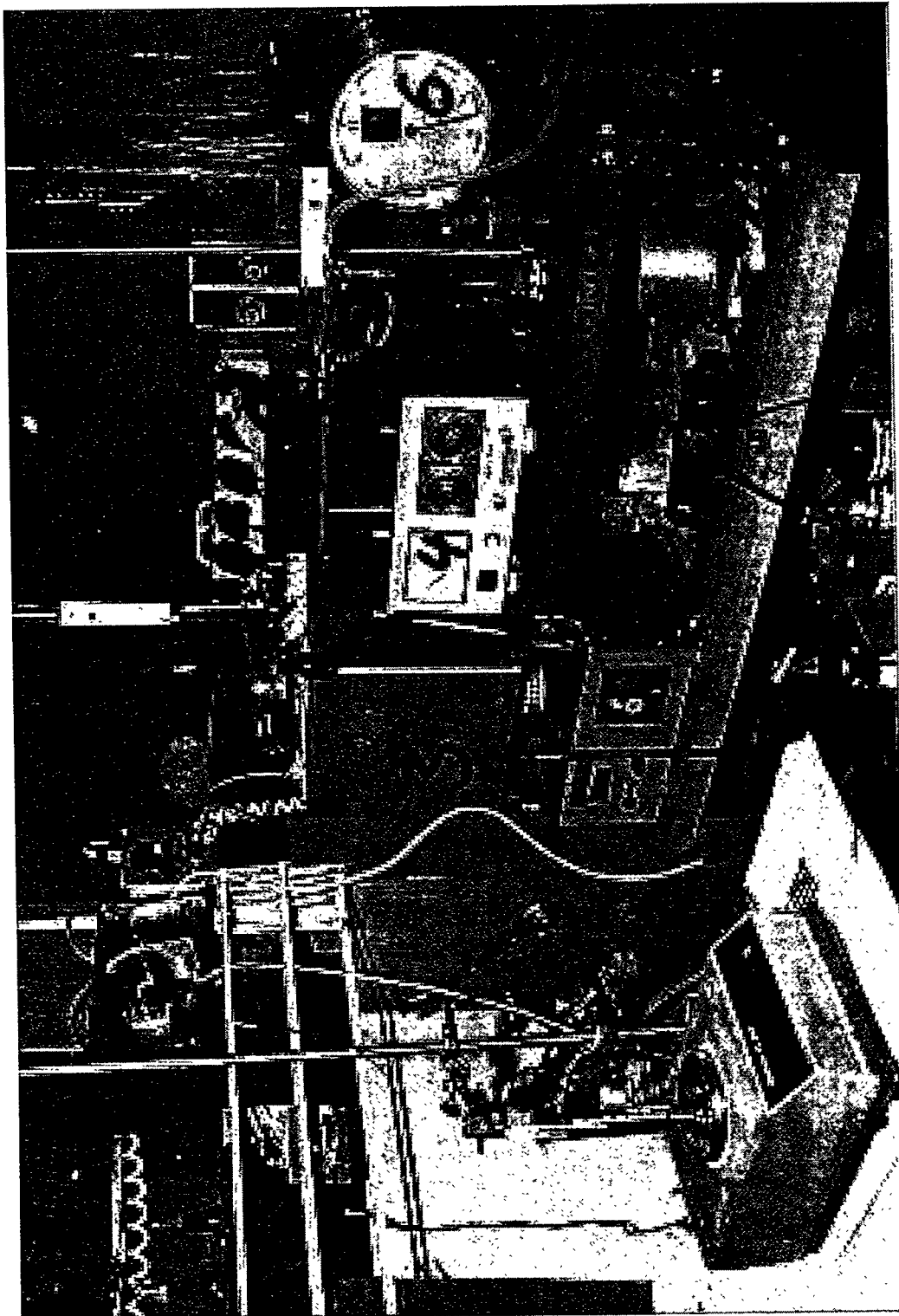


Figure 3. Märker's mercury testing system

PEER-REVIEW

SPEAKER CONTACT LISTING

FIFTH ANNUAL NORTH AMERICAN WASTE-TO-ENERGY CONFERENCE

SPEAKER CONTACT LISTING

Jan Barnes
Duos Engineering (USA), Inc.
6622 Southpoint Drive S., # 31
Jacksonville, FL 32216
PH: (904) 296-2807
FX: (904) 296-4103

Robert Barton
Midwest Research Institute
425 Volker
Kansas City, MO 66110-2299
PH: (816) 753-7000
FX: (816) 531-0315

Catharina Baverman
Royal Institute of Technology
KTH/KAT
Stochholm SE-10044
SWEDEN
PH: +46 8790-6404
FX: +46 8810-5228

Jacques Besnainon
Ecobalance, Inc.
15204 Omega Drive, Suite 220
Rockville, MD 20850
PH: (301) 548-1750
FX: (301) 548-1760

Linda S. Birnbaum
US EPA
Research Triangle Park, NC 27711
PH: (919) 541-2854
FX: (919) 541-0554

Eric Bock Esq.
Baise & Miller
815 Connecticut Ave., NW
Suite 620
Washington, DC 20006
PH: (202) 331-9100
FX: (202) 331-9060

Don Castro
HDR Engineering, Inc.
128 S. Tryon St.
Charlotte, NC 28202
PH: (704) 338-1800
FX: (704) 338-6760

A. John Chandler
AJ Chandler & Associates, Ltd.
12 Urbandale Ave.
Willowdale ON M2M 2H1 CANADA
PH: (416) 250-6570
FX: (416) 733-2588

Ni-Bin Chang
National Cheng-Kung
University
Dept. of Environmental Eng.
Tainan TAIWAN

Matthew Clark
HDR Engineering, Inc.
128 S. Tryon, Suite 1400
Charlotte, NC 28202-5001
PH: (704) 338-1800
FX: (704) 338-6760

David H. Cleverly
US EPA
Research Triangle Park, NC 27711
PH: (919) 541-2854
FX: (919) 541-0554

Timothy J. Coco
Coco & Co.
20 Park Plaza # 431
Boston, MA 02116
PH: (617) 423-1011
FX: (617) 423-4045

Michael J. Cooper
Foster Wheeler Environmental
Corporation
Perryville Corp. Park
Clinton, NJ 08809
PH: (708) 713-3161
FX: (708) 713-3165

Katie Cullen
Intergrated Waste Services Association
1401 H Street NW
Washington, DC 20005
PH: (202) 467-6240
FX: (202) 467-6225

Steve Daley
Porter Novelli Communications
International Group.
1120 Conn. Ave., NW
Washington, DC 20036

Kentaro Doi
Ministry of Health and Welfare
1-2-2 Kasumigaseki
Tokyo 100 JAPAN
PH: +81 3350-3171
FX: +81 3350-2004

Nathiel Egosi
RRT Design & Connstruction Corp.
125 Baylis Rd.
Melville, NY 11747
PH: (516) 756-1060
FX: (516) 756-1064

Taylor Eighmy
Environmental Research Group
University of New Hampshire
A115 Kingsbury Hall
Durham, NH 03824
PH: (603) 862-2206
FX: (603) 862-2364

Karsten Felsvang
Nior A/S
Gladsaxe VEJ 305
Soeborg 2860 DENMARK
PH: +45 3954-5454
FX: +45 3954-5815

Frank Ferraro
Wheelabrator Technologies, Inc.
4 Liberty Lane West
Hampton, NH 03842
PH: (603) 929-3305
FX: (603) 929-3365

Peter J. Finis
Procedair Industries
Corporation
12700 Shelbyville Rd.
Louisville, KY 40243

Keith Forrester
Forrester Environmental
Services, Inc.
P.O. Box 2008
Hampton, NH 03843

Stephen Fotis
Van Ness Feldman
1050 Thomas Jefferson Street
Washington, DC 20007

Behrooz Ghorishi
Acurex Environmental
Corporation
4915 Prospectus Drive
Durham, NC 27713
PH: (919) 541-5419
FX: (919) 544-5690

Stephen Goff
American Ref-Fuel
6127 Vista Terrace
Orefield, PA 18069
PH: (610) 530-0551
FX: (610) 530-8874

Jeffrey L. Hahn
Ogden Energy Group
876 Mt. View Dr.
Lafayette, CA 94549
PH: (510) 284-2006
FX: (510) 284-2284

Lyle Hanna
American Ref-Fuel Company
P.O. Box 3151
Houston, TX 77253
PH: (713) 584-4534
FX: (713) 584-4696

Kenneth W. Harrison
North Carolina State University
Dept. Civil Engineering
Box 7908
Raleigh, NC 27695
PH: (919) 515-4342
FX: (919) 515-7908

Hans-Ulrich Harteusteu
L.X.C. Steiunweller Guibh
Fabriksmasse 1
Guwwesbach 51647
DENMARK
PH: +22 6185-2451
FX: +22 6185-4020

Larry S. Jenkins
Wood Quinn & Crapo, L.C.
60 E. South Temple #500
Salt Lake City, UT 84111
PH: (801) 366-6060
FX: (801) 366-6061

Bruce Jordan
US EPA/OAQPS
Emission Standards Division
(MD 13)
Research Triangle Park, NC
27711
PH: (919) 541-5572
FX: (919) 541-0072

Martha Keating
US EPA
Research Triangle Park, NC 27711

Ruud Keegel
Feniks Recycling
Uranusstraat 4
Oudorp N-H 1829 XD
NETHERLANDS

James D. Kilgroe
US EPA
Air Pollution Prevention &
Control Air Pollution Technology
Branch
Research Triangle Park, NC
27711
PH: (919) 541-2854
FX: (919) 541-0554

Maureen Koetz
Senate Energy & Natural Res. Comm.
304 Dirksen Senate Office Bldg
Washington, DC 20510
PH: (202) 224-4971
FX: (202) 224-6163

Sum Yong Lee
Acurex Environmental
Corporation
P.O. Box 13109
Research Triangle Park, NC
27709
PH: (919) 541-0336
FX: (919) 541-1887

Anthony Licata
Licata Energy and Environmental
Consultants
345 Concord Rd.
Yonkers, NY 10710-1848
PH: (914) 779-3451
FX: (914) 779-4234

Brian Magee
Ogden Environmental & Energy Services
239 Littleton Rd., Suite 75
Westford, MA 01886
PH: (508) 692-9090
FX: (508) 692-6633

Patrick E. Mahoney
Energy Answers Corporation
79 North Pearl Street
Albany, NY 12207
PH: (518) 434-1227
FX: (518) 436-6343

Frank E. Mark
Dow Europe/APME
Horgen 8810 CH
PH: +41 1728-2726
FX: +41 1728-2965

Paul Mauriello
Dade County
Dept. of Solid Waste Management 8675
N.W. 53rd Street, Ste. 201
Miami, FL 33166
PH: (305) 594-1621
FX: (305) 594-1591

John A. Merritt
Merritt Environmental Solutions
152 North Main Street
Natick, MA 01760
PH: (508) 655-4951
FX: (508) 651-3340

Angus M. Miller
Montenay Power Corporation
4001 Veterans Memorial
Highway
Ronkonkoma, NY 11779
PH: (516) 471-7800
FX: (516) 471-7807

Craig Musselman
CMA Engineers, Inc.
35 Bow Street
Portsmouth, NH 03801-3819
PH: (603) 431-6196
FX: (603) 431-5376

Alfredo Napoli
Ecole Des Mines D'Albi -
Carmaux
Campus Jarlard Route de Teillat
81013
FRANCE
PH: +33 5634-9306

Sid Nelson
Sorbent Technologies Corporation
1664 E. Highland Road
Twinsburg, OH 44087

Chuck Nettle Ship
Steel Recycling Institute
1667 K. St., N.W.
Washington, DC 20006
PH: (202) 496-9686
FX: (202) 496-9702

Walter R. Niessen
Camp, Dresser & McKee
Ten Cambridge Center
Cambridge, MA 02142
PH: (617) 252-8357
FX: (617) 621-2565

Kjell Nilsson
Akervagen 20
S-24562 Hjarup SWEDEN
PH: +46 4046-4743
FX: +46 4046-4743

Fred L. Porter
US EPA
Combustion Group
Emission Standards Division (MD 13)
Research Triangle Park, NC 27711
PH: (919) 541-5264

Ramana Rao
Montgomery County
DOT/DSWS
101 Monroe St., 6th Floor
Rockville, MD 20850
PH: (301) 217-6708
FX: (301) 217-2681

James Reynolds
Montgomery County Division of
Solid Waste
101 Montroe Street 6th Floor
Rockville, MD 20850
PH: (301) 217-2418
FX: (301) 217-2681

H. Gregor Rigo, PhD.
Rigo & Rigo Associates, Inc.
1 Berea Commons, Suite 211
Berea, OH 44017-2534
PH: (216) 243-5544
FX: (216) 243-2759

Leo Pierre Roy
Energy Answer Corporation
79 North Pearl St.
Albany, NY 12207
PH: (518) 434-1227
FX: (518) 436-6343

Hakan Rylander
SYSAV
Ostergatan 30
S-211 22 Malmo SWEDEN
PH: +46 4010-1920
FX: +46 4023-7909

Mark R. Sankey
Research-Cottrell
P.O. Box 1500
Somerville, NJ 08876
PH: (908) 685-4272
FX: (908) 685-4310

John R. Serumgard
Scrap Tire Management Council
1400 K. Street, N.W.
Washington, DC 20005
PH: (202) 682-4842
FX: (202) 682-4854

Lars Soerum
Sintef Energy, Department
7034 Trondhem NO
PH: +47 7359-2965
FX: +47 7359-2889

K.C. Strange
World Resources Foundation
Bridge House High St.
Tonbridge TN9 1DP Great Britain
PH: +44 1732-3683
FX: +44 1732-3683

Bruce G. Studley
Foster Wheeler Power Systems,
Inc.
Perryville Corporate Park
Clinton, NJ 08809
PH: (908) 713-2782
FX: (908) 713-2055

Marty Suchan
American Ref-Fuel
183 Raymond Blvd.
Newark, NJ 07105
PH: (201) 817-7376
FX: (201) 344-4999

Masaru Tanaka
The National Inst. of Public Health
B113 Somechi 2-8-3
Chofu City, Tokyo 182 JAPAN
PH: +81 3344-1711
FX: +81 3344-6483

Edith G. Tanenbaum
Long Island Regional Planning
Board
220 Rabro Drive
P. O. Box 6100
Hauppauge, NY 11788-0099
PH: (516) 853-5195
FX: (516) 853-4044

Susan A. Thorneloe
U.S. EPA
Global Emissions & Control Div.
Global Warming Control Branch
Research Triangle Pk, NC 27711
PH: (919) 541-2709
FX: (919) 541-7885

Jurgen Vehlow
ITC-BTA
P.O. Box 3640
D-76021 Karlsruhe
DENMARK

Edwin Weaver
Belco Technologies Corporation
7 Entin Road
Parsippany, NJ 07054
PH: (201) 515-8909
FX: (201) 884-4775

Carlton Wiles
National Renewable Energy Lab
1617 Cole Blvd.
Golden, CO 80401
PH: (303) 275-2915
FX: (303) 275-2905

Stephen C. Yohay
McDermott, Will & Emery
1850 K Street, NW
Washington, DC 20006

Maria Zannes
IWSA
1401 H Street NW, Suite 220
Washington DC 20005
PH: (202) 467-6240
FX: (202) 467-6225