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A Technology Assessment of Solar Energy Systems

Characterization of Solid Waste Conversion and Cogeneration Systems

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A Technology
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Prepared by:
Lawrence Berkeley Laboratory

U.S. Department of Energy
Assistant Secretary for Environment
Office of Environmental Assessments
Washington, D.C. 20545

FORWARD

The U. S. Department of Energy, Office of Environment, Office of Environmental Assessments, is conducting a project entitled Technology Assessment of Solar Energy (TASE) Systems, to evaluate the range of potential environmental, health, and socioeconomic consequences of rapid, large-scale commercialization of solar technologies. The goal of this project is to identify and analyze both the positive and negative effects of solar technology deployment. The project will provide a basis for avoiding potential problems and for grasping opportunities during the transition to solar energy in the U. S.

Massive solar development will force major increases in the use of those raw materials needed to make solar system components. Along with this increased resource consumption and production will come associated pollution. In addition, rapid solar energy development may mean significant secondary or unplanned changes in institutions and lifestyles as the nation moves toward greater use of solar energy systems. The TASE project is designed to provide a quantitative analysis of the direct and indirect effects of solar energy use. In so doing, it will help define an environmentally acceptable solar future.

This report is an element of the TASE Solar Technology Characterization Series. We would like to express our appreciation to Ron Ritschard and Ken Haven of the Lawrence Berkeley Laboratory for their efforts in preparing this document.

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INTRODUCTION

The Technology Assessment of Solar Energy Systems (TASE) is being conducted by the Division of Technology Overview (Office of Technology Impacts) of the Office of the Assistant Secretary for Environment (ASEV/OTI/DTO) of the Department of Energy (DOE). Analytical efforts have been undertaken by several of the DOE national laboratories for Phase I of the TASE program. This report presents the Phase I assessment of assigned technologies by the Lawrence Berkeley Laboratory (LBL). Two renewable resource technologies have been allocated to LBL for analysis in the TASE program: Municipal Solid Waste (MSW) energy conversion and cogeneraton.

The primary objective of the TASE program is to determine the probable consequences to the environment and to public health and safety resulting from widespread implementation of major solar and renewable resource technologies. The specific principal Phase I objective is to determine the levels of residuals most likely to result throughout the complete energy cycle from the utilization of each of the solar and renewable resource technologies.

At a time of rising energy prices and diminishing domestic supplies of crude oil and natural gas, many municipalities are also faced with a solid waste management crisis. The cost of direct landfill disposal is rising and available landfilled sites are becoming scarce in many areas. Recovery of energy resources from MSW presents a partial solution to both areas. MSW energy recovery can reduce the mass of landfilled wastes by as much as 95 percent and can tap a vast new energy resource. The yearly collection of MSW is estimated to be 125 million tons nationwide (Lowe, 1974). The typical energy content of raw MSW is 4500 Btu/lb. Thus, the maximum potential energy resource base is enormous (1.25×10^{15} Btu/yr).

Three basic technologies for recovering energy from MSW are considered in this study. These are: (1) direct combustion using a waterwall incinerator in which the heat from burning refuse is converted to steam by circulating water in steel tubes jacketing the interior of the incinerator; (2) manufacture of a relatively uniform shredded, pulverized or pelleted refuse-derived fuel (RDF) for supplemental firing in a utility boiler; and

(3) pyrolysis or destructive distillation of MSW to extract a low-Btu fuel gas. While resource recovery and energy recovery systems can be installed independently, the processes described here include both energy and resource recovery systems as well as necessary pollution control equipment for gaseous emissions. While it is realized that other MSW resource recovery technologies are being developed (e.g. anaerobic digestion or methane recovery from landfills), only the three technologies mentioned above have been selected for inclusion in this study.

Initial MSW energy recovery in the United States involved the retrofit of waste heat boilers onto existing incineration units. Additionally various incinerators have been retrofit with direct waterwall heat recovery systems. Beyond the direct combustion techniques, MSW energy recovery technology has not reached a level of development associated with on-line commercial application. Rather, existing RDF and pyrolysis plants are supported as either test plants or as demonstration plants. The principal problems associated with commercialization of these technologies have been technical performance problems with existing system designs and failure to successfully market facility energy products (Schnelle and Yamamoto, 1974).

Current "on-line" and planned MSW energy and/or resource recovery plants are listed in Appendix C (Table C-1). Additionally, Appendix C contains a list of private companies involved in MSW research and development (Table C-2), and an inventory of current research activities (Table C-3). Table 1 summarizes the current and projected on-line capacity and approximate electrical energy generating plant equivalent. The resulting total 1985 MSW energy capacity of 3135 MWe is conservative since required lead time for most MSW energy recovery plant types is less than four years (plants could be on-line in 1985 and not announced until late 1980).

At the other (optimistic) end of the possible forecasting spectrum, St. Clair (1975) reported on the results of a survey of U.S. cities in which 33 percent of all responding cities with populations over 100,000 and 45 percent of all cities responding with populations over 250,000 plan to adopt capital-intensive MSW resource and/or energy

Table 1

Summary of Current and Projected MSW Energy Recovery Operational Plants

Type of System	On-Line Plants[1] TPD Capacity	On-Line Plants[1] MWe Equivalent	Planned Plants[2] TPD Capacity	Planned Plants[2] MWe Equivalent	Total TPD Capacity	Total Mwe Equivalent
Direct Combustion	9180	530	10,400	600	19,620	1130
RDF	6163[4]	355	26,900	1550	33,063[3]	1905
Pyrolysis	1698[5]	100	0	0	1698	100
Total	17,041	985	37,340	2150	54,381	3135 MWe

[1] Includes operational, demonstration and test plants.

[2] All Planned Plants are scheduled to be on-line by 1985.

[3] Plant Capacity (MWe) at 60 percent capacity load factor required to generate the amount of electrical energy which could be produced from MSW using mean conversion efficiencies listed in Table C-4 of this report.

[4] Includes 325-TPD St. Louis plant no longer on-line.

[5] Includes 75-TPD Erie County, N.Y. plant and 1000-TPD Baltimore plant, neither of which is currently on-line.

recovery facilities by 1980. Extrapolated across the country, this would indicate a near-term MSW energy capacity of as much as 40,000 MWe. Actual 1985 on-line MSW energy recovery may be expected to fall somewhere between these two extreme values.

The principal forecasting implication of Appendix C is that near-term MSW energy recovery activity will be dominated by direct combustion and RDF systems with pyrolysis gaining real importance in the long term (1990 or later) based upon the results of ongoing pyrolysis testing and research.

Cogeneration has recently received increased attention from utilities, industries, and those involved in the public policy of energy supply and demand. Interest is based on the very high energy efficiency and the possibility of reduced emissions from power generation. Cogeneration systems are modified power plants which provide both electricity and process heat or steam, such as required by many industries and some large commercial and residential buildings. The systems may use steam boilers, steam turbines, electric generators, gas turbines, diesel engines, and waste heat boilers. Traditionally, cogeneration has been a system where high pressure steam is used in a turbine to generate electric power and low-pressure steam, which is used for its heating value in an industrial process. There are other equally valid processes using the same principle.

Three end use applications of cogeneration systems are characterized in this report. The end uses analyzed include: (1) fluidized bed cogeneration systems for use in the pulp and paper industry; (2) diesel system using the digested sewage gas of a sewage treatment plant for electricity generation as well as heating and pumping; and (3) an enhanced oil recovery system.

No new technology is needed for cogeneration systems and, in fact, a few cogeneration systems have been operating for many years. Though common in Europe, cogeneration has steadily declined in the United States, largely because of institutional barriers and transition costs. Nevertheless, functionally cogeneration is quite attractive because of its very high efficiency of fuel use, corresponding decrease in pollution and negligible consumption of water. For these reasons, people are advocating public policies to remove institutional barriers and encourage cogeneration. Estimates of the cogeneration capacity of the United States in 1985 range from 20 to 250 GW.

To meet the Phase I objective, LBL staff have characterized the individual application associated with each general technology; calculated operational residuals generated by each application; determined the input capital requirements and, when possible, annual operating input requirements; and have identified the technical and institutional constraints for the widespread implementation of each application.

A description is presented of the energy and material development cycle required for the implementation of each technology. In addition, the capital requirements are compiled and presented in a SEAS system format. These capital costs will be used at a later time to compute the material demands and capital residuals.

Based on the technology characterization, estimates of the operating residuals per 10^{12} Btu of energy produced are made for each stage in the energy cycle. The results of this analysis, which represented the expected level of pollutants discharged to the environment, will be used in Phase II to determine the environmental impact of these selected technologies as a function of the number of quads of energy produced and are summarized in SEAS input format in Appendix A.

TECHNOLOGY APPLICATIONS

Direct Combustion of MSW

Introduction

Of the three MSW energy recovery technologies considered for this study only direct combustion systems depend entirely upon existing equipment and processes. Direct combustion systems generally involve no front end systems but rather load MSW directly into incinerators. They may be differentiated from RDF systems by this absence of pre-processing of received refuse which is a necessity in the RDF process. In general, MSW is delivered directly into an incinerator and burned with the resulting heat being partially recaptured through boilers or, much less often, through gas turbines. The char is removed to either a resource recovery process or is land filled, and the waste gas stream is treated and released after energy recovery. Several direct incineration systems, however, do employ coarse shredders before incineration. Further pre-processing would shift this process to an RDF process. Only two basic energy products may be obtained from direct combustion systems: steam and electricity.

There are two general types of direct combustion systems currently being used in the U.S.: refractory wall incinerators and waterwall incinerators. Steam is a basic energy product of both systems which can be converted to electricity in a steam turbine. Refractory wall incinerators have been used for many years as MSW volumetric reduction incinerators. In volume reduction incineration no energy is recovered and all heat escapes up the plant stacks. The conversion of such a plant to a steam-producing plant conceptually requires only the insertion of a boiler between the incinerator and the stack.

Waterwall incineration technology has existed in the U.S. for 25 years and was designed specifically for energy recovery operations. In a waterwall incinerator steam boiler tubes are located along an upper wall of the incinerator, and steam is generated directly in the incinerator. A more detailed review of these two systems and of their operating characteristics is contained in Appendix F to this report.

Technology Description

Because of its smaller waste gas flow and lower waste gas water vapor content, a waterwall incinerator system was selected as the model application for direct combustion technology. Figure 1 shows a detailed process flow diagram for a typical waterwall incinerator system. MSW is received directly from local collection trucks into a large holding pit from which material is transferred by crane into the waterwall furnaces. Bulky items are separated and shredded prior to incineration. Furnace temperature is maintained at 1700° F to 1800° F to avoid slagging. Solid residue is quenched and undergoes a resource recovery process as described in Appendix B. This type of system, exemplified by the Wheelabrator-Frye design, can operate with as little as 70% excess air instead of the 250% to 300% typical of refractory wall incinerators. Output steam is usually in the range of 400-600 psi and 500-700° C. Electrostatic precipitators are used to clean the gas stream prior to discharge. Major technological characteristics of this system are summarized in the Technology Summary Sheet - I.

The major inputs and outputs from this system are summarized in Table 2. As shown, energy recovery efficiency is 69.9% and total system efficiency (including ancillary energy requirements) is 68%. The system, as shown in Table 2, produces 1 x 10^{12} Btu of steam per year and this represents approximately 1.25 x 10^{12} Btu of fossil fuel equivalent energy. This equivalent represents an annual savings of approximately 50,000 tons of coal. Further detail on this equivalency calculation is provided in Appendix F. Residual concentrations are included in the Environmental Data section.

Refuse-Derived Fuel

Introduction

Municipal solid wastes (MSW) contain substantial quantities of combustible material such as paper, plastics, wood and other organic fiber. Since MSW varies in composition from area to area, the resulting refuse

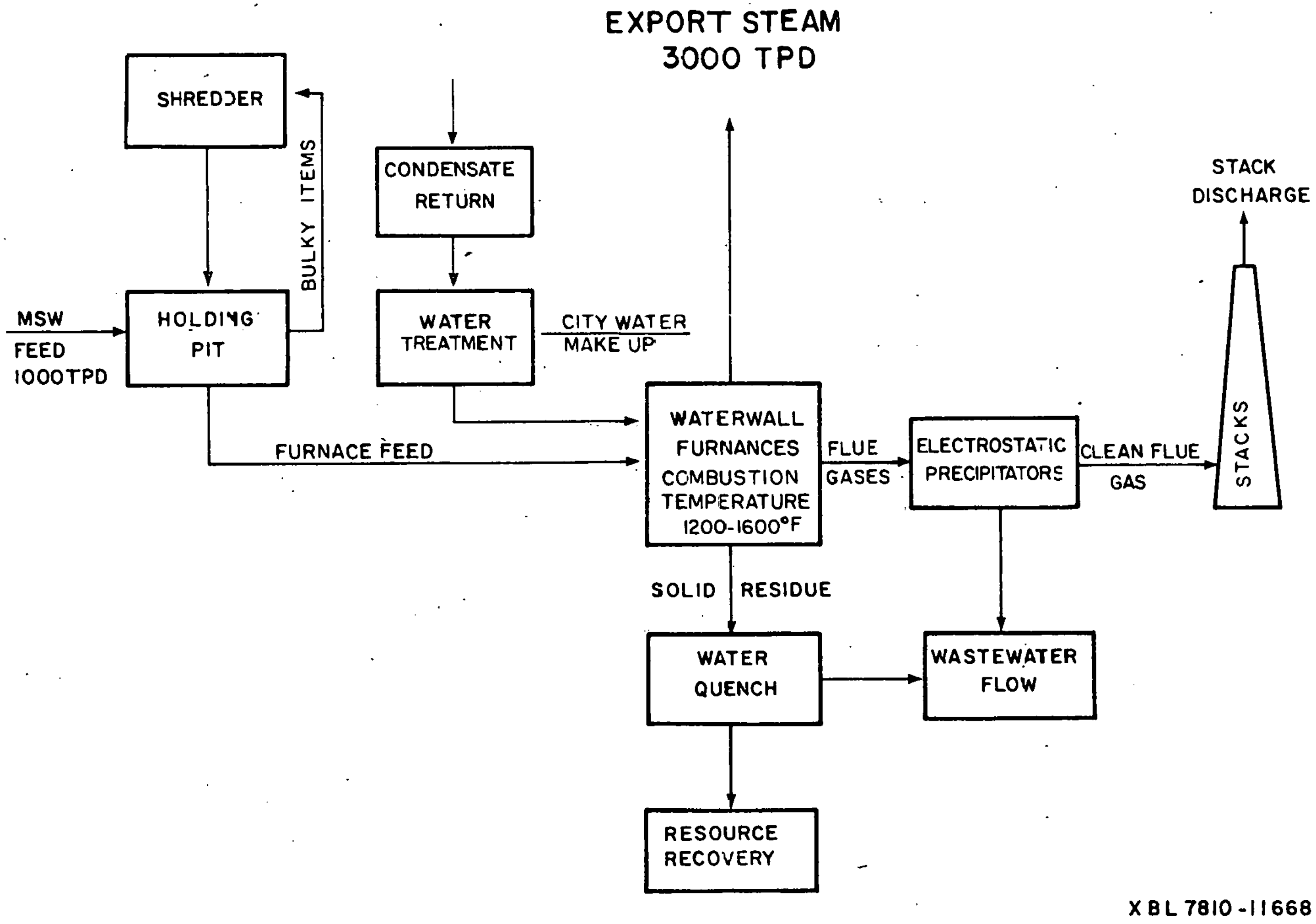

Fig. 1. Waterwall Process Flow Diagram

TECHNOLOGY SUMMARY SHEET - I

TECHNOLOGY: Direct Combustion of MSW

DESCRIPTION: Direct combustion systems involve the aerobic combustion of MSW without any preprocessing of the received MSW prior to incineration. Waste heat is captured by either steam boiler tubes inserted directly into the furnace (waterwall system) or through a separate boiler (refractory wall). Produced steam may be used directly or converted to electrical energy. Solid char residual may be directly landfilled or subjected to iron, aluminum and glass recovery processes. Waterwall systems require less excess air (100%-150%) than refractory wall systems (250%-350%), and burn at slightly higher temperatures (1100-2000°F) than refactory wall systems (900°-1500°F). Plant capacities for both waterwall and refractory wall systems vary from several hundred to several thousand TPD with greater economies of scale possible at the higher plant capacities. Product steam quality can vary up to the range of 750°F and 600 psi.

DESIGN SELECTION CRITERIA: Direct combustion has been selected for characterization for several major reasons. First, the system uses only existing, "off-the-shelf" technology. Second, it is a low-cost alternative. Third, it is compatible with many existing municipal incinerators used to reduce the volume of landfill material. Fourth, it is currently being used in over 50 cities within the United States.

The waterwall system was selected for characterization because its lower off-gas flow rate increases the efficiency of emissions control equipment and decreased residual flow rates, because the system has a higher efficiency, and because average costs are slightly lower than refractory wall systems.

END USE: Steam - either for district heating or for industrial process heat.

TECHNOLOGY SUMMARY SHEET - 1 (continued)

RESIDUALS: The basic system design includes both electrostatic precipitators and scrubbers. However, significant flows of both air and waterborne residuals are generated which result in the highest residual generation rate of all MSW energy recovery systems. Stack gas includes NO_x, CO, HCl, NH_3, particulates and SO_2. While the scrubber waste flow is acidic, high in dissolved solids and hardness, the quench waste has a pH of 9.9, is high in suspended solids and is 90°C at the outlet.

Table 2

Summary of Direct Combustion Inputs and Outputs

Parameter	Amount per 10^{12} Btu output/year
INPUTS	
Capital Inputs	
Land	10.8 acres
Labor	~1.4×10^6 Hrs.
Dollars	~$\$48 \times 10^6$
Operational Inputs	
MSW	1.57×10^5 Tons (1.43×10^{12} Btu)
Process Water	1.008×10^5 Tons
Electricity	2.94×10^{10} Btu
Other Material Costs	~$\$2.5 \times 10^6$
Labor	~25,000 Hrs.
OUTPUTS	
Steam	4.72×10^5 Tons (1×10^{12} Btu)
Iron	1.18×10^4 Tons
Glass Aggregate	8.65×10^3 Tons
Char	1.73×10^4 Tons
Stack Emissions	1.63×10^6 Tons
Waste Water Flows	1.008×10^5 Tons

fuel may also have a different content. Appendix G contains a brief discussion of the chemical characterization of RDF. If properly processed, MSW can serve as an energy source offering the advantage of "tapping" an otherwise wasted material. Its use can decrease demand for more conventional fossil fuels such as natural gas, oil or coal. Utilization of MSW also greatly reduces the volume of refuse for disposal, thus relieving pressure on landfill operations.

Several of the methods proposed for the mechanical processing of MSW for resource recovery produce a low bulk density fraction suitable for use as a fuel. The list of conversion processes includes:

1) wet processing (hydropulping) followed by component separation and dewatering of the fuel fraction. This process is demonstrated by Black Clawson at Franklin, Ohio.

2) dry processing (shredding) followed by chemical processing to produce what is called ECO-Fuel II. This process is demonstrated by the Combustion Associates plant at East Bridgewater, Massachusetts; and

3) dry processing (shredding) followed by air classification. This process is demonstrated by several projects including Union Electric in St. Louis and the cities of Ames and Milwaukee.

The technology description will focus on the finely shredded air-classified fuel, since the major part of the experience relates to this technology. The product is combustible with a reasonably high heat of combustion and is being utilized as a supplementary fuel in the utility boilers at several locations (see Appendix C). In Technology-Summary Sheet - II is a description of the RDF technology selected as the model system for the analysis.

Technology Description

The co-combustion of RDF with a fossil fuel in a modern power plant is a very cost-effective form of incineration (Klumb, 1976). The major advantage is its low investment cost, if existing furnaces and boilers are used, when compared with other alternatives. Use of RDF as a fuel

TECHNOLOGY SUMMARY SHEET - II

TECHNOLOGY: Refuse Derived Fuel

DESCRIPTION: Municipal solid waste contains many valuable constituents which can be extracted by the RDF process and used for fuel. Because the composition of the input waste changes with time and location, there is no standard figure of merit which defines the precise heat value of this fuel. Despite this non-uniformity, the co-combustion of RDF with coal or oil can significantly reduce our dependence on more conventional fuels.

In this process solid waste is collected, shredded, air classified, transported and burned. Alternative processes use hydropulping instead of shredding. Costs are related to the degree of MSW preparation and the value of the derived fuel.

DESIGN SELECTION CRITERIA: The design is based on the Horner and Shifrin RDF system used in the city of St. Louis. The process assumed the outputs, including residues, related to an input of 1000 tons per day. The system produces an approximated 725 tons per day of refuse-derived fuel which has an average heat value of 11.4 x 10^6 Btu/Ton. The Horner and Shifrin system was selected because it has been employed successfully to process MSW into a fuel that can be co-fired with coal in a utility boiler. Furthermore, there is extensive literature available which describes the technical and environmental concerns of the process.

END USE: RDF combustion results in process steam production which has a typical value of 7.19 x 10^6 Btu per ton of MSW input at 63 percent efficiency.

RESIDUALS: Process residuals include heavy metals, ash, water emissions and air emissions such as NO_x, Cl, SO_2, and particulates. Shredders produce noise emissions, odors, and airborne particulates.

source requires more processing than does direct burning. Such processing results in the expenditure of capital monies as well as the annual cost of operation and maintenance. Table 3 summarizes cost estimates for three different sized RDF systems. The cost of processing is a complex function of several variables, including:

1) Size of RDF processing facility
2) Location of RDF processing facility and points of RDF use
3) Operating schedule
4) Cost of MSW received
5) Cost of energy
6) Cost of alternative means of municipal refuse disposal
7) Marketability of reclaimed materials such as ferrous metals, aluminum and glass.
8) Costs of obtaining raw garbage.

In the shredded RDF system (see Figure 2), the refuse is delivered to a preparation area where bulky items (e.g., mattresses) are separated or sheared to a size the shredders can handle. The refuse is fed into a hammermill that shreds the refuse to 8-13 cm. (3-5 in.) particles. The shredded material is air classified to separate the light fraction (about 80 percent of the input refuse) which are primarily the combustible materials and the heavy non-combustible fraction (20 percent of input MSW).

The heavy fraction from the air classifier goes to a magnetic separator which removes the ferrous metals that are cleaned and sold as scrap. The rest of this fraction is compacted and sent to a landfill. It is possible to process this inert fraction through a series of steps to recover usable materials such as glass, aluminum and other metals.

The light fraction from the air classifier is sent to a secondary shredder (fine shredder) where it is reduced in size to 2.5 cm. (1-2 in.) particles. This low density RDF can be piped over short distances or temporarily stored and then hauled by truck over long distances to the utility. Pollutant sources at the processing plant include dust from the shredders and air classification systems, sound from equipment operation, odors, water-borne contaminants from wash of storage areas, and residue destined for landfill.

Table 3

Annual Production of RDF as a Function of Facility Size

Processing Capacity	Units	Plant Size 1,200 ton/day	 500 ton/day	 250 ton/day
Annual Average Refuse Input	tons/day	1,200	500	250
Actual Refuse Per Working Day[1]	tons/day	1,680	700	350
Required Process Rate[2]	tons/hr	120	50	25
Nominal Output[3]	tons/hr	150	65	35
RDF Produced	tons/yr	343,200	143,000	71,500
Ferrous Metal Salvage	tons/yr	29,130	12,135	6,070
Reject Materials	tons/yr	65,700	27,380	13,690
Heat Value of RDF	Btu x 10^{12}	3.84	1.60	0.80

[1] Based on 5-day work week, 260 days/yr.

[2] Based on a 14-hr. day processing operation.

[3] Based on an 80% production factor to account for unscheduled down-time.

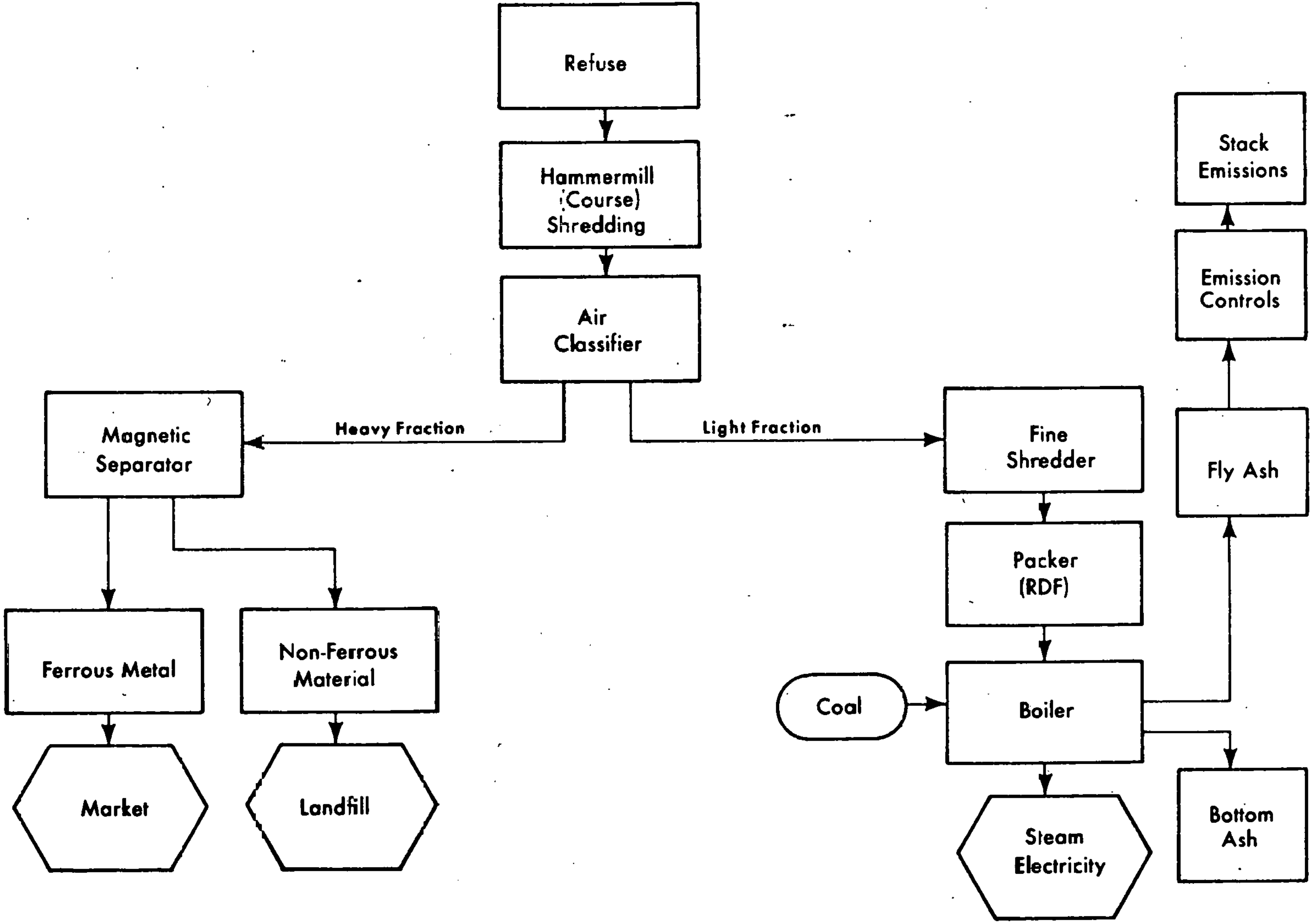

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Fig. 2. Shredded Air-Classified RDF System

At the power plant RDF is unloaded into a receiving bin and is transferred pneumatically into storage bunkers. From the storage bunker the RDF is conveyed by pipelines into the boilers and fired in suspension. Sufficient velocity is imparted to the particles to carry them into the high temperature zones where along with coal, the particles ignite and burn. The refuse firing system is designed to provide from 10-20 percent of the boiler input heat. Light particles are carried out with the flue gas. Ash and heavy unburned particles fall into the boiler ash pit and become part of the bottom ash.

Principal pollutant sources at the power plant are the boiler stack particulate emissions, stack gaseous emissions, bottom ash residue, and sluice water used to hydraulically convey boiler residue to the ash disposal impountment. Various equipment is employed to control particulate and gaseous emission, including electrostatic precipitators, Venturi scrubbers, cyclones, and baghouses.

The technology description given above represents the Horner and Shifrin fuel recovery process, which was operated by the city of St. Louis from 1972 to 1977. Table 4 contains a summary of the input and output of the described RDF system. The values used represent the best estimates from the St. Louis project (Kigore, et al., 1976; Klumb, 1976; and Sheng and Alter, 1975). A material and energy balance for the Horner and Shifin RDF system are illustrated in Appendix G (Figures G-1 and G-2).

With the St. Louis approach as a pattern several applications of the basic process have been employed in other locations. For example, the city of Milwaukee has its total volume of MSW (1200 tons/day) handled by a resources recovery system. Like the St. Louis system, refuse is shredded through two shredders and air classified into light and heavy fractions. About 7 percent of the refuse (e.g., newspaper and corrugated material) is removed before the initial shredding process. After magnetic separation, ferrous metals, glass, and aluminum are segregated and marketed. Another example is the 200 ton/day recovery system which began operation in September 1975 in Ames, Iowa. Both of these operations have proven capable of consistently processing both commercial and residential

Table 4

RDF System Input/Output Summary

INPUTS	Amount per 10^{12} Btu Steam Output per Year
Land	9 Acres
Capital Costs[a]	\$3.76 x 10^5
MSW[b]	1.39x10^5 tons (1.58x10^{12}Btu)
Water	169 gal/min. (272 Acre-ft.)
Electricity	7.94x10^3 Mwhr (2.71x10^{10}Btu)
OUTPUTS	
Steam	3.34x10^5 tons (1 x 10^{12} Btu)
Ferrous Metals	9.73 x 10^3 tons
Glass	1.11 x 10^4 tons
Nonferrous Metals	1.39 x 10^3 tons
Residue	4.73 x 10^4 tons
Stack Exhaust	4.17 x 10^4 tons
Water Effluent	2.78 x 10^4 tons

[a] Assumes no capital investment for boilers or additional air pollution equipment.

[b] Assumes average heat value of 11.4 x 10^6 Btu/ton.

waste (Holloway, 1978).

There are numerous other processes that transform MSW into a usable fuel. The Black Clawson fuel recovery process basically involves the separation of fuel from other constituents of municipal refuse by wet pulping and separation techniques used in the paper industry (General Electric Co., 1975). The resulting pulped fuel is of a very fine consistency with about a 50 percent moisture content. No experience with extensive use of the fuel in utility boilers exists, however, all elements of the fuel preparation process have been in operation at the material recovery demonstration plant in Franklin, Ohio.

ECO-Fuel II, a cellulosic powder obtained by the hydrolytic chemical treatment of the organic fraction of refuse can be pelleted (General Electric Co., 1975). This fuel is a denser and more stable type of material which can be more easily stored and transported. Since ECO-Fuel II is a homogeneous fuel similar to powdered coal, it can probably be used as a larger fraction of the total fuel in co-combustion. The extent to which this type of RDF can be employed in existing or new utility boilers has not been demonstrated.

The Combustion Power Corporation (PU-400 process (Menlo Park)) is a package plant designed to consume 400 tons of waste per day (Schnelle and Yamamoto, 1975). Steel, glass and aluminum are separated out, and most of the balance is burned in a fluidizing bed combustor with head recovery accomplished by using a gas turbine generator. The process is modular in nature and can be expanded to larger sites.

It is recommended that any one or all of these alternative methods for processing MSW for use as RDF be analyzed in any future characterization of solid waste conversion systems.

Pyrolysis

Introduction

Pyrolysis is a process in which organic material is decomposed at elevated temperatures in either a low oxygen or an oxygen-free environment. Unlike incineration with air, which is a highly exothermic reaction, pyrolysis is endothermic and requires the application of heat, either through the addition of fuels or through partial oxidation of the pryolysis reaction. Again, unlike incineration, which produces primarily carbon dioxide and water, pyrolysis produces a complex mixture of primarily combustible gases, liquids and solid char residues (Weinstein and Toro, 1976).

Pyrolysis offers several significant advantages over MSW energy recovery systems. First, either gas or liquid fuels may be directly produced by controlling the design of the reaction vessel and the reaction temperature. Second, pyrolysis requires the addition of only small volumes of air and thus has a much smaller gaseous waste stream to deal with for emissions control. In the case of gas producing systems atmospheric emissions are almost entirely eliminated.

The major drawbacks of pyrolysis are that the technology is still in a developmental stage and has not been demonstrated in a large plant, and that both the capital and operating costs of a pyrolysis tend to be higher than RDF systems.

The chemistry of a pyrolytic reaction is described in Appendix H. The product mix of this reaction is highly sensitive to the reaction temperature. Thus, the temperature of reaction is used to distinguish two general types of pyrolytic reactions: those designed to produce gaseous energy products and those designed to produce oils. The reaction temperature is adjusted to maximize the production of the desired produce (gas or oil) and, since both gas and oil are always produced in a pyrolytic reaction, the other product is consumed as an auxiliary fuel within various elements of the overall process.

Figure 3 shows the schematic flow for all pyrolysis processes. The front end systems generally include shredding and classifying and may include drying and screening prior to the pyrolysis reaction. For oil producing systems such as the Garrett Research plant at San Diego (see Appendix H), gas products are drawn off following the pyrolysis reaction and used primarily as a heat source for MSW drying. These systems then depend on either partial oxidation or the use of supplemental

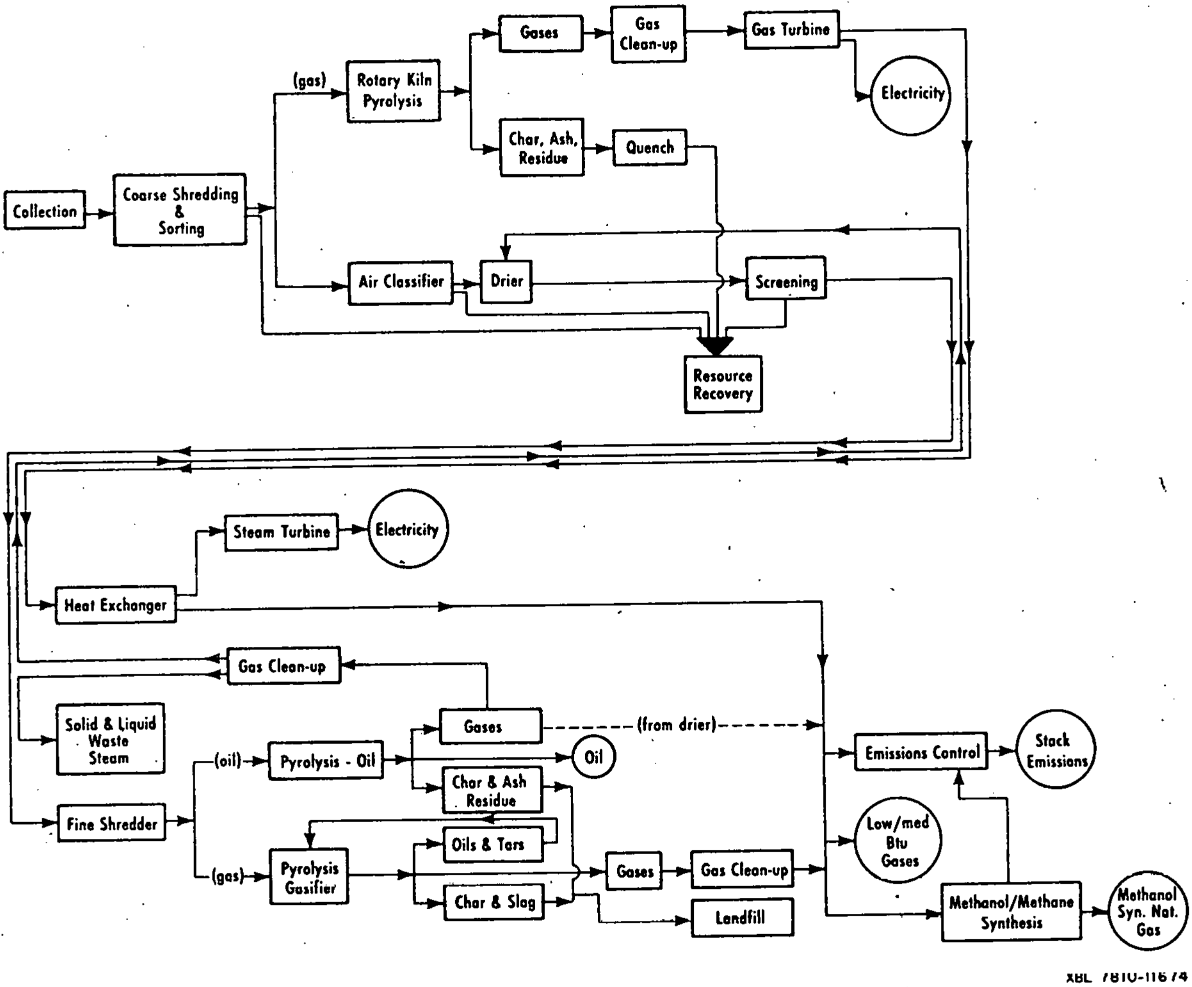

Fig. 3. MSW Pyrolysis Schematic Diagram

fuels to drive the pyrolysis process. Gas producing systems such as Union Carbide's PUROX plant, on the other hand, generally use the oil produced by pyrolysis as the fuel to drive the pyrolytic reaction and thus need no auxiliary fuel.

While the general system described above is most representative of the current generation, systems are being tested which bypass most of the front end processes. This type of system (see Monsanto's Landguard plant in Appendix H) uses only a coarse shredder before feeding the unclassified and unsorted MSW into a rotary kiln. The char from such a system contains recyclable glass and metal and is fed into the resource recovery process. The low grade off-gasses are fed into an afterburner/heat exchanger to generate steam for use in district heating. In pyrolytic oil or gas systems the basic energy product is the gas or oil itself. Conversion processes may then be used to convert this product to steam or to electricity for an end use product as required.

Actual pyrolysis systems (Purox, Torrax, Landguard and the Garrett plants) were reviewed for selection as the model application. Criteria included minimization of waste flows, proven technological feasibility, and proven economic viability. For all three categories the PUROX system appeared to be the system of choice. This system has therefore been selected as the model application for the pyrolysis technology. The Landguard and Garrett process plants are described in Appendix H, however capital and environmental data in Appendix A are based exclusively on the PUROX system.

Technology Description

Union Carbide's PUROX system is a high temperature (3000°F) slagging pyrolysis process which produces a low to medium Btu gas rated as 300 to 320 Btu/scf. A small test plant was completed in Mt. Vernon, New York, in 1969 and was operated over a five year test period before dismantling (Marple, 1974). Based on the success of this plant a 200 TPD prototype plant was completed in Charleston, W. Virginia in 1974 at a cost of $16 million. Since then the plant has operated continuously except for planned upgrade and modification periods.

As shown on the block diagram in Figure 4, the PUROX process front end system includes a coarse shredder (shredding to a maximum size of four inches) a magnetic separator for ferrous metal recovery, and an aluminum recovery process. Shredded waste is fed into the top of a vertical shaft pyrolysis furnace. As the MSW descends it is first dried by the rising hot gases and then undergoes pyrolysis at a temperature of 3000°F in the central portion of the furnace. The driving force in the pyrolytic reaction is pure oxygen which is injected at the bottom of the furnace to burn the char descending below the pyrolysis zone. The inert slag passing from the bottom of the furnace is quenched and sold as a glass aggregate for construction. Composition of this slag aggregate is shown in Appendix H.

The gases rising from the furnace pass through an electrostatic precipitator, an acid neutralizer and a condenser prior to collection of the fuel gas. Ash and oil collected during this gas purification process are recycled into the pyrolysis furnace. Typical composition of the final fuel gas is shown in Appendix H and the application is summarized on Technology Summary Sheet III.

The PUROX system has several important advantages over the pyrolysis systems. These include:

1. There is no air emission stream. All gases are either aqueously collected or are part of the product fuel gas.
2. The solid slag forms a fused grit which can be sold as construction or road bed aggregate.
3. Oxygen is used rather than air to drive the pyrolysis reaction. While a certain energy cost is paid to produce the oxygen, its use produces a higher heating value gas with NO_x content.
4. All oils and sludges are recycled into the furnace so that only one waste water flow exists.

In a comparison of 10 MSW energy recovery systems conducted in 1974-1975, H. W. Schulz (1975) concluded that, from an efficiency, engineering and environmental standpoint, PUROX was the best available system.

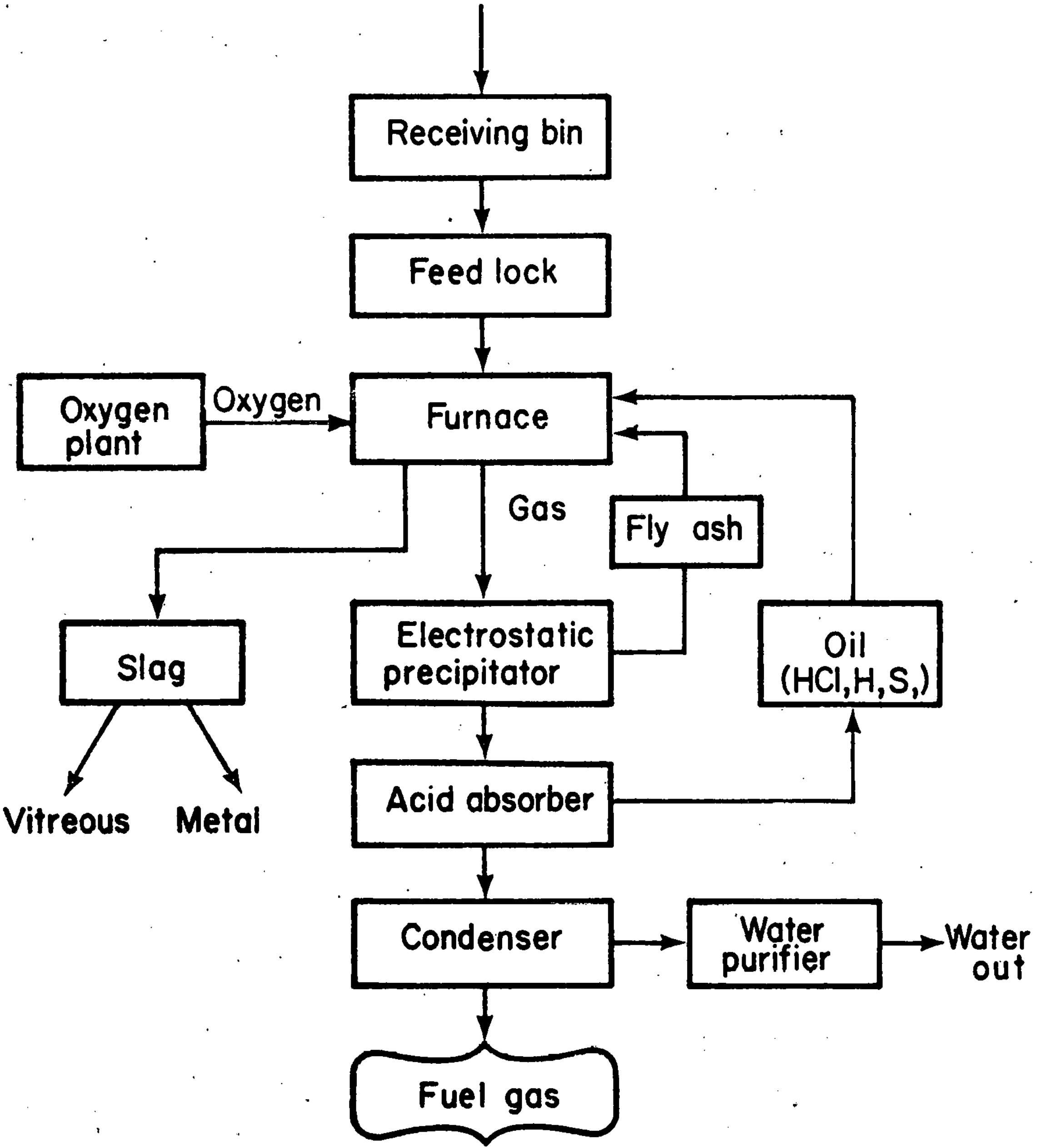

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Fig. 4. Flow Diagram of Union Carbide System

TECHNOLOGY SUMMARY SHEET - III

TECHNOLOGY: Pyrolysis of MSW

DESCRIPTION: The Union Carbide PUROX system is a high temperature (~3000°F) oxygen enriched pyrolysis process which produces oil and low Btu gas simultaneously. By controlling the temperature of reaction at approximately 3000°F gas production is optimized with respect to pyrolytic oil. Oil is fed back into the furnace to drive the pyrolytic reaction. The low Btu product gas (~300 Btu/Scf) is cleaned in a two-step process prior to collection. Front end systems include shredding, magnetic separation of metalic or recoverable ferric matter, and MSW drying, which occurs as MSW enters the furnace. Several 200 TPD or smaller plants have been successfully built and operated and it is estimated that a 2000 TPD plant can be economically operated.

DESIGN SELECTION CRITERIA: Pyrolysis was selected as a technology for characterization because the process offers several significant advantages over the other MSW energy recovery systems. First, it is a flexible system and can produce either pyrolytic oil or gas. Second, air emissions are greatly reduced over other technologies. Third, the process reduces landfill requirements below those of other systems.

The PUROX system was selected as the specific application because of the following factor: higher heating value and reduced NO_x content of its process gas, the slag byproduct has value as construction or road bed aggregate, the system has no air emissions except for the releases from the front end shredder, the residual concentrations in the waste water flow are lower than those for several other pyrolysis systems, and the system has been successfully demonstrated.

END USE: Pyrolytic gas may either be collected and sold as a system end use product, or, as with this application, converted to electricity.

TECHNOLOGY SUMMARY SHEET - III (continued)

RESIDUALS: While there are no air emissions other than the minor flows from the MSW shredder, waterborne residuals include Hg, Zn, Pb, Ni, Cd, waste heat, solubles and sludge. Ammonia or Methanol conversion results in additional CO_2, sulfur, NO_x, Co, CH_3OH. Also included are iron and fused slag.

Due to the success of the West Virginia plant and the practicality of the process, plans are being made to expand to large scale plants. Union Carbide now projects that these plants will be made up of combinations of modular units of between 200 TPD and 300 TPD (Donegan, 1975). It is anticipated that such systems can be economically built at the 1000 TPD to 2000 TPD level. Additional front end resource recovery steps for glass and aluminum recovery may be included in these future modules.

The basic inputs to the PUROX process per ton of MSW are 120 Kwhr of electricity and 400 lb O_2. Major outputs include a 0.265 ton waste water flow, 0.635 tons of dry fuel gas, and 0.2 tons of slag aggregate. Total output for a 200 TPD plant is approximately 4.34 x 10^{11} Btu/year. Material and energy balances for the PUROX process are shown in Appendix H (Figures H-2 and H-3).

A summary of PUROX inputs and outputs is shown in Table 5. As can be seen, the PUROX system is significantly simpler both in major funcitonal blocks and in inputs and outputs than is either the Landguard system or Garrett process; however, it is also significantly more capital intensive.

PUROX residual flows are shown in the Environmental Data section.

Cogeneration Systems

Introduction

The cogeneration systems considered in this report attempt to match the temperature of a heat supply to the demand by using high temperature energy which rejects heat at the temperature needed for process use. Thus cogeneration is a means of increasing our use of the thermodynamic potential of the fuels we burn. This is important for both fossil fuels and waste fuels such as the wood waste and digester gas used in the systems described here. Burning such fuels to do work necessitates the use of a heat engine. Heat engine efficiency in turn is intrinsically tied to the input and output temperatures of the engine. Thus temperature determines the amount of work

Table 5

PUROX Inputs and Outputs per 10^{12} Btu Output

Inputs	Quantity per 10^{12} Btu Output per year
Land	20.71 acres
Capital	\$36.82 x 10^6
MSW	1.45 x 10^5 Tons (1.28 x 10^{12} Btu)
Electricity	1.59 x 10^{10} Btu
Oxygen	2.9 x 10^4 Tons (2.83 x 10^{10} Btu)
Outputs	
Iron	8.5 x 10^3 Tons
Slag Aggregate	2.96 x 10^4 Tons
Water Condensate	4.3 x 10^4 Tons
Dry Fuel gas	9.29 x 10^4 Tons (1 x 10^{12} Btu)

available from a Btu of heat energy. It is wasteful to lower the temperature of heat energy significantly without extracting the available work. Current status of cogeneration projects is described in Appendix D.

There are three engines of primary importance in cogeneration systems and they are all used in the applications considered in this report. They are diesel engines, combustion turbines and backpressure steam urbines. These engines, in turn, exhaust hot gas or steam at usable temperatures. The important features which were considered in the choice of systems and application were size, fuel capability, steam pressure requirements, and the ratio of power to heat produced. Details of these characteristics are presented in Appendix E.

The benefits of cogeneration are increased efficiency and decreased costs in most applications. Also cogenerated electricity at the least will reduce industrial electricity demand on utilities and in many cases will supply baseload or peaking power to the utility grid on a regular basis. This, of course, raises institutional problems with respect to the local electric utility attempting to protect its interests in the electric power business.

Finally, there are environmental issues with respect to air emissions and their location. The greater efficiency of cogeneration allows for a decrease in fuel combustion for electricity and heat taken together. Normally, however, there will be an increase in emissions at the cogeneration site which is more likely to be in an urban area than a utility power plant and for that reason the health impact may be greater even with lower emissions.

Fluidized Bed Steam Cogeneration for the Pulp and Paper Industry

Introduction

Fluidized bed boilers for use in steam turbine cogeneration systems can be used to good advantage in pulp and paper mills because of their size scale and fuel flexibility including coal and wood wastes. The pulp and paper industry has already shown its interest and willingness for in plant generation as indicated by existing facilities. These are primarily fueled by residual oil and natural gas with only 18% of the energy from coal. (Therm Electron, 1966, p. 4). This proposal would eliminate the consumption of oil and gas by replacement with coal and waste fuels for all electric and steam generation. It is expected that roughly half of the fuel input would be coal and half waste products such as bark, wood chips and spent liquor. Recently, such an example with the Simpson Paper Company has been researched (Davis, 1978). This particular example would have a boiler capacity of 300,000 lb/hr steam at 850 psi and 900°F. The turbine generates 19 MW and includes a condenser. The process steam will be extracted at 75 psi and 175°F. The plant has a very high load factor with a year-round average electric demand of 17 MW and a steam demand average of 225,000 lb/hr. This high load factor is well matched to the operational abilities of a steam boiler system which should not be turned on and off frequently. A particular advantage of using a fluidized bed is the ease of burning waste hog fuel which is plentiful in the area. The hog fuel costs only $\$.50/10^6$ Btu compared to $\$1.50/10^6$ Btu for coal.

The primary problem that will be encountered in the implementation of this system is slowness with which fluidized bed boilers are being developed. The present American demonstration projects appear to be several years behind the level of technology and experience being used in Europe. This problem may be related to the small size of fluidized bed boilers which make them appropriate for cogeneration but not utility central stations. At present it appears that 5 to 10 years will be necessary before such boilers will be offered commercially.

A second institutional problem relates to the problems of selling excess electric power to the local utility. At present utility payments for such power are very low and will barely cover the fuel costs of a cogenerator.

The cogeneration system as described here is easily applicable to any industry needing team and having an interest in burning coal or coal and waste fuels. Further work is needed only in the development and deployment of fluidized bed boilers ensuring proper credit for excess power sold to the utility.

Technology description

Fluidized bed combustion is characterized by the rapid flow of combustion air upward from a gridplate through the bed material including the coal. This air flow causes great turbulence and mixing of the bed materials as if they were suspended in a turbulent liquid. In fact, it is material fluidized by air. A fortunate side effect of fluidization is the excellent mixing which promotes complete combustion even of waste materials or coal even when it constitutes only 2% of the bed material. The large amount of bed material can be limestone which in turn allows for efficient removal of SO_2 as a dry solid waste. Further, the heat exchange boiler pipes can be submerged directly in fluidized bed. This allows for very good conductive heat transfer at moderate temperatures such as 1500° F rather than depending on radiant heat transfer from flames at 3500° F. This is very important in reducing the amount of nitrogen oxides created from nitrogen in the combustion air. Technology Summary Sheet - IV describes the salient features of this process.

Figure 5 illustrates the major components of the fluidized bed boiler cogeneration proposal for a pulp and paper plant. Table 6 summarizes the inputs and outputs for the fluidized bed cogeneration system.

Secondary Water Treatment Plant Cogeneration Using Diesel Systems

Introduction

One application of diesel cogeneration systems using biomass involves the use by sewage treatment plants of digested sewage gas for electricity generation as well as heating and pumping. An interesting example of this is contained in the plans of the Sanitation District of Los Angeles County for a waste gas cogeneration system.

Currently the District maintains a system of 24 digestion tanks operating continuously. Each tank has a capacity of several hundred gallons and each is fed and drained alternately in increments over a 24 hour period. These tanks digest anerobically the primary sewage sludge of the plant, producing about 5.3×10^6 cubic feet of sewage gas

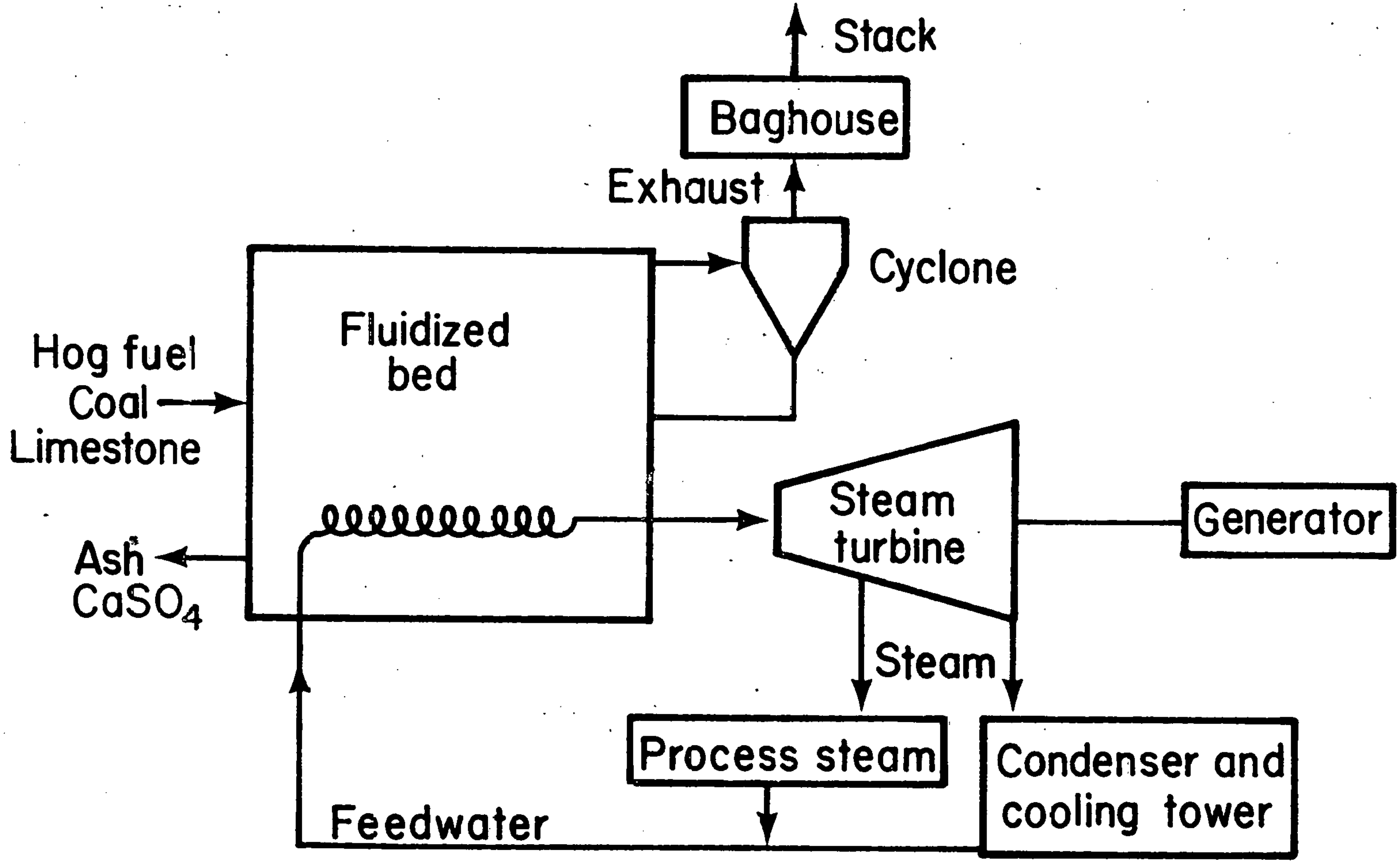

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Fig. 5. Fluidized Bed Cogeneration for Pulp and Paper Plant

TECHNOLOGY SUMMARY SHEET - IV

TECHNOLOGY: Fluidized Bed Boiler

DESCRIPTION: This cogeneration system is simply comprised of a fluidized bed boiler powering a backpressure steam burbine-generator. The exhaust steam is directly usable for processes in the pulp and paper industry.

DESIGN SELECTION CRITERIA: The fluidized bed technology was used in the pulp and paper industry application because of its ability to burn both wood wastes and coal. Also the size scale and steam pressures available were well matched.

END USE: This application was to provide the pulp and paper industry with electricity and steam. It could, however, be applied to any industry needing low and or medium pressure steam and which can burn coal and/or waste material.

RESIDUALS: Fluidized bed boilers have low NO_x emissions because of low temperature combustion. Sulfur dioxide is effectively controlled by limestone in the bed and particulates are very effectively controlled with the use of fabric filters.

Table 6

Summary of Fluidized Bed Cogeneration Inputs and Outputs

Parameter	Amount per 10^{12} Btu output/year
INPUTS	
Capital Cost	\$11.054 x 10^6
Land	4.2 Acres
Coal	42,000 Tons
Water	210,000 Tons
Labor - Construction	353,000 Hrs.
Operation	~2 x 10^4 Hrs.
OUTPUTS	
Ash	4750 Tons
Electricity	0.45 x 10^{12} Btu
Steam Heat	0.55 x 10^{12} Btu
Steam Flow	210,000 Tons

per day. A third of this is used by the District for heating the digestion tanks and to run the plant's pumping engines. The remainder is sold to the Fletcher Oil Company in Carson, California. The Btu content of the gas has been estimated for selling purposes and has been found to be between 500-580 Btu per cubic foot.

Technology Description

The District of Los Angeles County has developed several proposals to expand its treatment system and to implement electrical cogeneration. The plan considered here uses a diesel reciprocating engine waste heat boiler topping cycle generating 12.6 MW and steam at a rate of 27.4×10^6 Btu/hr. At this stage of the plant's operations the total electrical demand would be about 15 MW; the remaining demand would be purchased under an agreement for parallel generation with Southern California Edison Company (SCE). The District would install eight additional anerobic tanks for digesting of aerated secondary wastewater activated sludge. Total sewage gas available from both primary and secondary sludge digestion would be approximately 6.7 million standard cubic feet per day. Of this, about 35 percent would be allocated directly to meet the plant's increased heating and pumping needs. The remaining 4.4 million cubic feet, together with about 2,000 gallons per day of #2 diesel pilot oil (see Figure 8) would be entirely available for cogeneration. Technology Summary Sheet V presents an overview of the system.

A diesel engine system has the advantages of being able to burn low Btu fuel efficiently; some 37 percent of the waste gas's energy could be converted to electricity. The disadvantages of a diesel system is the high level of its NO_x emissions. This could cause a siting problem in the South Coast Air Basin, an area in which EPA requires that new generation facilities have pollutant offsets. Table 7 lists a summary of the system inputs and outputs.

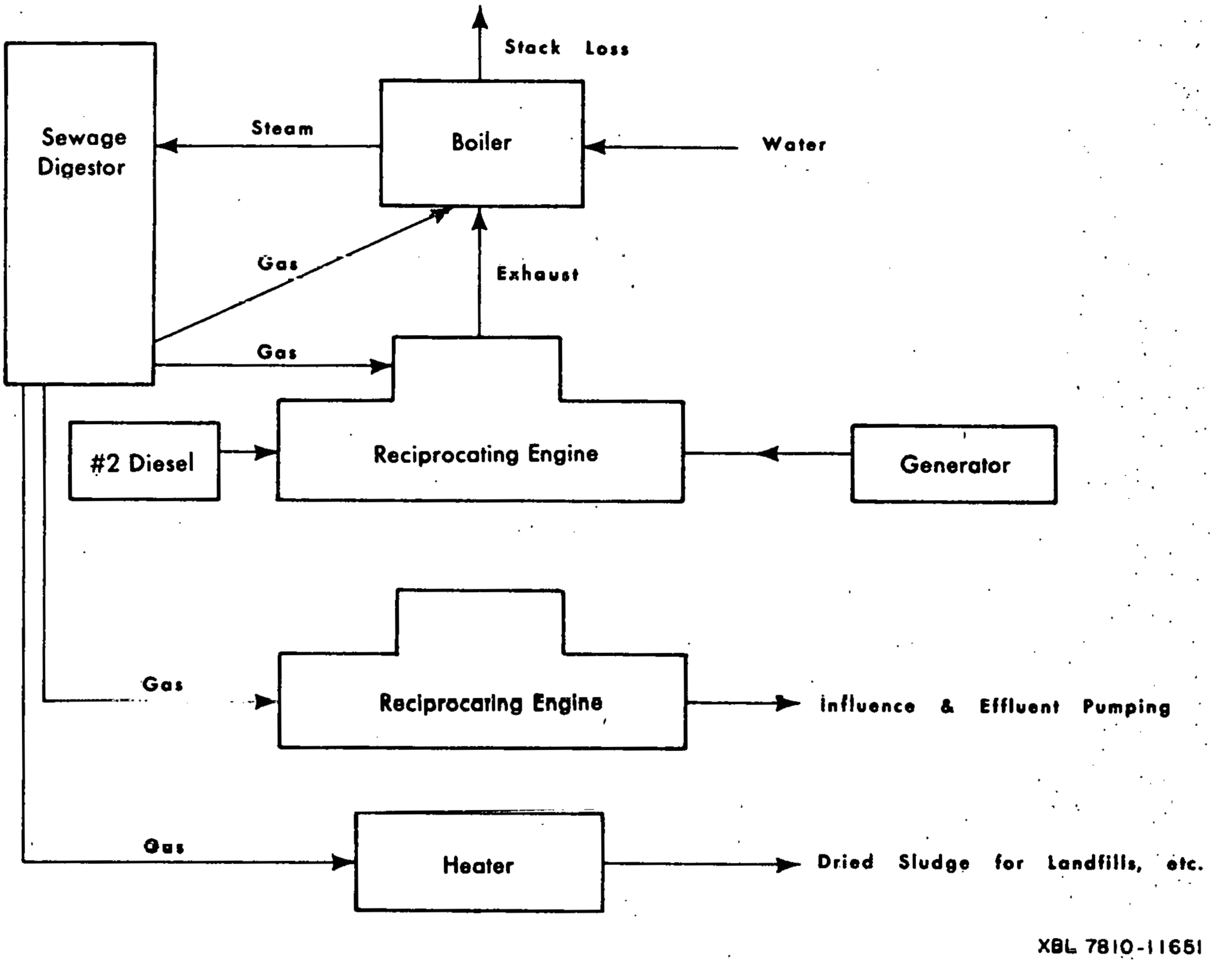

Fig. 6. Energy Flows for Sewage Treatment Plant Cogeneration System

TECHNOLOGY SUMMARY SHEET - V

TECHNOLOGY: Gas Diesel Engine

DESCRIPTION: In this cogeneration system byproduct methane gas from a sewage treatment plant is used in a reciprocating engine to generate electric power. The engine exhaust is then used to generate steam to heat the sewage digesters.

DESIGN SELECTION CRITERIA: The diesel engine was selected for this system because of its very high efficiency in burning gas to generate a large amount of electricity.

END USE: The sewage treatment plant was chosen as an end use for this cogeneration system because of its supply of waste gas and need for low grade heat.

RESIDUALS: The primary problem with diesel emissions is NO_x because of high combustion temperature. Sulfur dioxide and particulate emissions are low when burning gas.

Table 7

Diesel Cogeneration System Input/Output Summary

Inputs	Amount per 10^{12} Btu Energy Output per Year
Land	0.1 Acres
Capital	\$11.54 x 10^6
#2 Diesel Pilot Oil	1,192,609 Gallons
Sewage Gas	3963.5 x 10^6 Cu. Ft. (581 Btu/cu.ft.)
Water	300 x 10^6 Lbs.
Labor - Construction	1.26 x 10^5 Hrs.
Operation	6000 Hrs.
Outputs	
Electricity	178,891 MWh
Pumping	20,586 MWh
Heated Sludge	502.8 x 10^{12} Cu. Ft.
Steam	300 x 10^6 Lbs.
Boiler Stack Losses	198,768.2 x 10^6 Btu

Enhanced Oil Recovery

Introduction

An important petroleum industry which is becoming much more energy-intensive is oil production. Oil well recovery factors are typically about one third of oil in place or less when it is tightly bound in the rocks or the oil viscosity is very high. The latter is particularly true in California where the heavy oil recovery can be tripled to about 50-60 percent by heating. This is presently being done on a large scale with high pressure steam from boilers burning high sulfur, cheap, first-tier oil to recover second-tier oil which is twice as valuable. This political economic situation discourages any switch to coal as a fuel in the near future. However, during the period 1980 to 2000, it is possible that both local crude oil and Western coal will be used efficiently in cogeneration systems to provide electricity to utilities and steam to oil fields. This would include fuel gasification for use in combustion turbines.

Technology Description

A preliminary schematic of a possible cogeneration system is given in Figure 7. The main components are an oil gasifier which fuels a combustion turbine generating electricity and hot exhaust which in turn generates steam in the heat recovery steam generator. The net electric power available to the utility grid will be 260 MW at a very high load factor. Technology Summary Sheet - VI characterizes the system.

There are several reasons for this proposed setup. First, the fact that very high pressure steam is required meant that a combustion turbine would have to be the prime mover because backpressure steam turbines and diesel engines cannot produce high enough pressure steam. Combustion turbines, in turn, require gas or oil fuel which for practical purposes meant oil. Then the economic factor of price controls lead to the decision to gasify low value first tier oil rather than bring in refined oil at a much higher price. This decision obviously is artificial and may not be the best in the long run. The inputs and outputs of the system are summarized in Table 8. Operational residuals for the described enhanced oil recovery system are shown in Appendix 1. Capital requirements for the system are listed in the capital residuals section of this report.

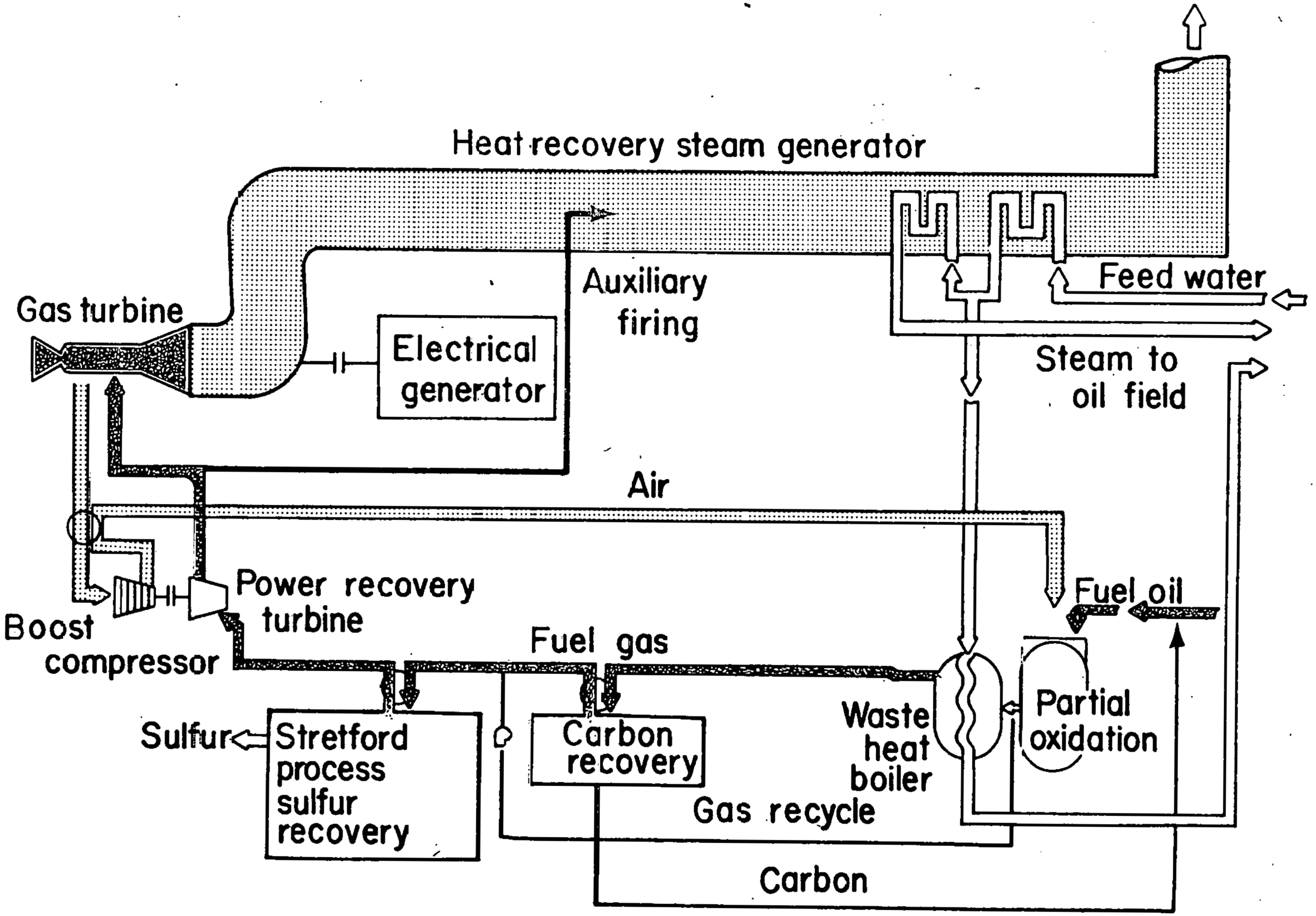

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Fig. 7. Thermally Enhanced Oil Recovery Cogeneration System Diagram

TECHNOLOGY SUMMARY SHEET - VI

TECHNOLOGY: Combustion Turbine for Enhanced Oil Recovery

DESCRIPTION: The system in this application will consist of a Texaco crude oil gasification process which fuels three large combustion turbine-generators. The turbine exhaust is then used to raise high pressure, low quality steam in the heat recovery boiler. This steam is driven into the oil reservoir to heat and drive the heavy crude oil out.

DESIGN SELECTION CRITERIA: Combustion turbines were the only possible choice because of the requirement for high pressure steam. The oil gasifier was chosen because of the opportunity to use artificially cheap first tier oil before it enters a refinery and requires entitlement to be paid.

END USE: Enhanced oil recovery was the chosen end use because of its requirement for high pressure steam as produced by a combustion turbine cogeneration system.

RESIDUALS: The primary residual will be NO_x from the turbine. Sulfur is removed from the gas stream and particulate emissions are low.

Table 8

Summary of Enhanced Oil Recovery Inputs and Outputs

Parameter	Amount per 10^{12} Btu output/year
INPUTS	
Land	negligible
Crude oil	210,000 bbl.
Capital	\$16.37 x 10^6
Labor Construction	8.38 x 10^6 Hrs.
Operation	2.7 x 10^3 Hrs.
OUTPUTS	
Electricity	.25 x 10^{12}Btu
Steam Heat	.75 x 10^{12}Btu
Steam Flow	288,000 Tons

ENVIRONMENTAL DATA

Direct Combustion

System Residuals

Direct combustion systems produce significant gaseous and waterborne wastes. Table 9 gives mean values for stack emissions from municipal incinerators. These figures assume the presence of scrubber systems and thus are lower than would be the case if data were taken in front of the scrubbers. Efficiency for scrubbers is reported to be as high as 95 percent (Walker, 1967; Ongerth and Tucker, 1970). However. lower values of 85 percent to 90 percent may be encountered in refractory wall systems due to high flue gas flow rates.

Table 10 lists waterborne residuals for major direct combustion waste water flows. It should be noted that several systems studied have essentially no flow from the quench water settling tank since a sufficient mass of water is entrained with the solid char flow out of the quench tank to avoid the necessity for direct quench water discharge. In all cases the quench water flow is small and less significant than the scrubber flow.

Land, water, labor and other capital residuals associated with a direct combustion system are listed in Appendix A as are residual data in the format compatible with SEAS model input.

Refuse-Derived Fuel

Since there is little published data concerning the environmental aspects of RDF systems, this report will rely on information reported on the City of St. Louis/Union Electric demonstration plant. An evaluation of emissions from the refuse processing plant and the Union Electric refuse firing boiler was reviewed earlier (Kilgroe et al., 1976; Holloway, 1976). For discussion purposes, the RDF system has been divided into three parts: collection and transport, processing (e.g. shredding and air classifying), and energy conversion. The latter components are emphasized below.

The residuals associated with the collection and transport of municipal refuse have been described previously (Aerospace Corporation, 1976). In that report, solid waste disposal was characterized as one

Table 9
Direct Combustion Average Stack Effluent Characteristics[1]

Component	ppm	lb/Ton	Ton/10^{12}Btu output
particulates	.06 grains/scf	30	2.3×10^3
N_2	---	14,557[2]	1.1×10^6
H_2O vapor	---	1445[2]	1.1×10^5
SO_2	28	1.8	136
NO_x	95	3	227
O_2	---	2980[2]	2.26×10^5
CO	---	10[2]	758
CO_2	---	1738[2]	1.32×10^5
HCl	55	1.0	75.8
total acids	85	1.4	106.1
NH_3	18	0.3	22.7

---

[1] From: Kaiser, 1967; Macadam, 1976; Carotti and Smith, 1974; Walker, 1967; and Moore, 1967.

[2] Assume 9.6 tons excess air for combustion.

Table 10

Direct Combustion Waterborne Residuals

Residual	Mean Concentration	Tons/10^{12} Btu output
1. <u>Scrubber Waste Flow</u>		
pH	3.9	---
suspended solids	1350 mg/l	22.8
dissolved solids	6200 mg/l	104.6
alkalinity	1.0 mg/l	1.69×10^{-2}
chlorides	2540 mg/l	42.8
hardness	3430 mg/l	57.8
sulfates	1250 mg/l	---
phosphates	80 mg/l	---
2. <u>Quench Waste Flow</u>		
pH	9.9	---
suspended solids	1860 mg/l	31.4
dissolved solids	2330 mg/l	39.3
alkalinity	300 mg/l	5.06
chlorides	820 mg/l	13.8
hardness	510 mg/l	8.6
sulfates	505 mg/l	8.5
phosphates	30 mg/l	0.51
temperature	90°C	---

From: Ongerth and Tucker, 1970; Hann, 1970.

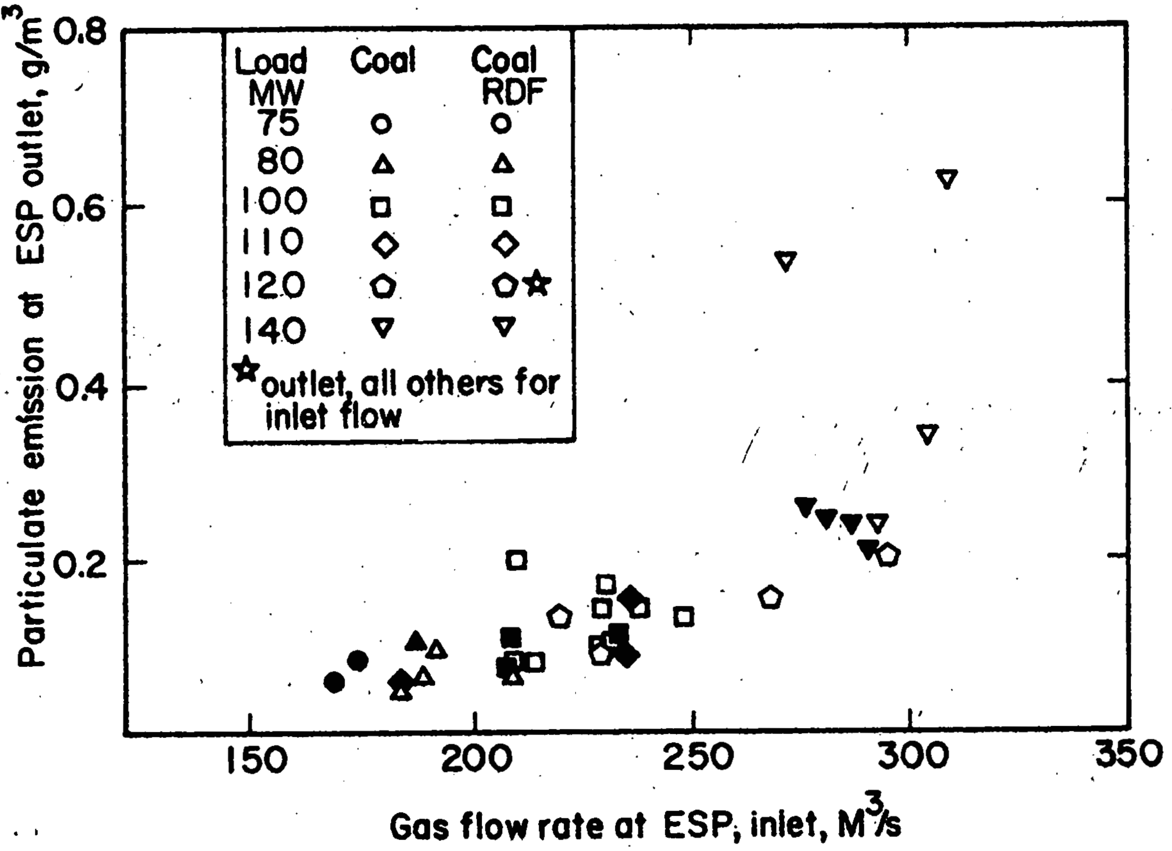
of the most hazardous occupations in the country. Statistical results show a higher than normal incidence of coronary heart disease for sanitation workers, compared to other male population groups. Carbon monoxide exposure was suggested as a possible cause. In this report we have not calculated the residuals generated during refuse collection and delivery.

Municipal waste is received, sorted, shredded and air classified in an effort to separate recoverable materials as the organic fraction is upgraded to a usable fuel. All conversion processes essentially have the same front end operations. The major residuals during front end operations are: particulates from the hammermill (shredder) and air classification systems, noise from the processing equipment, waterborne contaminants from washdown of the waste handling area, residue for landfill and odors. In addition, bacterial and virus activities have been found in the processing plant dust (Kilgroe, 1976).

The typical particle emissions from the hammermill and air classifier were reported to be .032 kg/ton and .346 kg/ton, respectively (Kilgroe, 1976). The majority of these particles (more than 90 percent) were greater than 7 μm in diameter, which is larger than those normally respired by humans. The particulates can be controlled by dust collectors.

During the energy conversion process at the power plant there are expected to be pollution problems related to the content of ash, nitrogen, sulfur and chlorine in the refuse fuel. The chemical composition of RDF determines its emission characteristics.

The boiler stack particulate emissions have been studied by various groups including the Midwest Research Institute. The particulates can be effectively collected by electrostatic precipitators (ESP). It has been reported, however, that ESP collection efficiency is reduced when RDF is co-fired with coal, which is dependent on the fuel mix (Holloway, 1976). This reduction primarily occurs at loads above 100 MWe because of the higher gas flow volumes (see Figure 8). The level of particulate emission after ESP collection (assuming 99 percent efficiency) was estimated to be 160 tons/10^{12} Btu (Teknekron, 1975).



Source: Kilgroe, J.D. et al., 1975
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Fig. 8. Effect of Volumetric Gas Flow Rate on Particulate Emissions

The gaseous stack emissions have been analyzed at the St. Louis/ Union Electric Demonstration plant (Kilgroe, 1976; Klumb, 1976). Table 11 compares the data for coal only and coal/RDF firing. There is no discernible effect on SO_2, SO_3 or NO_x, since the higher SO_2 values in the coal/RDF system were the result of an increased sulfur content of the coal. The chlorine emissions in the stack gasses, however, are about 20 percent higher in the coal/RDF tests. The increase in chloride emissions is due to a mixture of polyvinyl chloride and cellulose products found in the processed refuse. There appears to be no data available on the release of heavy metals from the stack gas.* The flue gas residuals resulting from a typical RDF system are presented in Table 13.

The level of residual bottom ash was found to be significantly greater in the co-fired system than in one burning only coal at comparable boiler loads. An average boiler residue of 4350 kg/hr was reported for the RDF system compared to 790 kg/hr for the coal-fired system (Kilgroe, 1976). This increased level of bottom ash, which subsequently must be landfilled, consists of inert solid particles (glass, metals, etc.) and unburned solid particles (wood, plastic, leather, etc.), in addition to coal ash. The bottom ash represents about 20 percent of the boiler residue.

Since the residue from a co-fired boiler is 4-7 times higher, a potential exists for water pollution from the boiler ash ponds that receive ash removed by water from the bottom of the furnace (Aerospace, 1976). Tests by Union Electric Company indicate that three parameters in the coal-RDF ash pond effluent do not meet state guidelines. Table 12 compares these three parameters in a coal pond and a coal-RDF pond. Other water quality parameters are higher in the coal-RDF ash pond effluent than the coal ash effluent (Kilgroe et al., 1976). These include ammonia, boron, calcium, chemical oxygen demand, iron, manganese, oil and grease, and total organic solids. Sulfates, however, were significantly lower in coal-RDF ash effluent. Table 13 presents the concentration of several ash pond effluents in tons per 10^{12} Btu.

The residual emission rates for the RDF system in the format required for input to the SEAS model are found in Appendix A.

---

*Mercury will probably appear in the stack emissions (Holloway, 1976).

Table 11

Stack Gas Emissions[a]

Components	Coal	Coal/RDF
SO_2 (ppm)	943	1067[b]
SO_3 (ppm)	9	8
NO_x (ppm)	298	285
Cl (mg/m^3)	335	402

[a] Source: Kilgroe, J.D., et al., 1976.

[b] 13 percent increase in SO_2 emissions during coal-RDF tests resulted from a 24 percent increase in coal sulfur content.

Table 12

Comparison of Ash Pond Effluents[a]

	Biochemical Oxygen Demand (ppm)	Dissolved Oxygen (mg/l)	Suspended Solids (ppm)
Coal-RDF Pond	50 - 100	3 - 10	10 - 150
Coal Pond	10	10 - 14	10 - 50

[a] Source: Kilgroe, J.D., et al., 1976.

Table 13
Residuals from Typical RDF System

PROCESSING	POLLUTANT	RESIDUALS PER 10^{12} Btu SYSTEM OUTPUT
Hammermill	Particulates	1.15 tons
Air Classifier	Particulates	53 tons
Energy Conversion		
Stack Emissions.		
	Particulates[a]	160 tons
	SO_2	192 tons
	NO_x	150 tons
	Chloride (Cl^-)	50 tons
Ash Pond Effluents		
	(BOD) Biochemical Oxygen Demand	.039 tons
	(DO) Dissolved Oxygen	.0078 tons
	(TSS) Total Suspended Solids	8.08 tons
	Acid	1.34 tons
	Phosphates	.678 tons
	Chromates	.039 tons
	Boron	5.38 tons
	Organics	1.08 tons
	Chloride (Cl_2)	.428 tons
Bottom Ash		
	Residue	40 tons

[a] After ESP, assuming 99 percent efficiency

Pyrolysis

Waste flows from the PUROX process are limited to a combined scrubber and quench waste water flow and to the exhaust from the front end shredders. Oils and captured solids in the off-gas flow are recycled into the pyrolysis reaction. Solid lag residues are sold as a secondary product along with recyclable aluminum and ferrous metals. Major residuals associated with each of the two waste flows from the PUROX are listed in Table 14. Land, water and labor requirements for the system as well as capital residuals are listed elsewhere in this report. The operational residuals listed in Table 14 are also presented in Appendix A on SEAS data input sheets.

Cogeneration Systems

The generation of steam and electric power is a significant use of fossil fuels and causes a large fraction of present day air pollution emissions. Cogeneration in nearly all cases is based upon the combustion of fossil fuels and so air pollution problems must be addressed. With respect to water bodies, cogeneration can significantly reduce the impact of the electrical generator because normally there will be negligible water consumption and thermal discharge beyond that normally associated with the process heat. The emission values for these pollutants are given in Table 15 and Appendix A.

Table 14

Residual Concentration for PUROX System

Air Residuals	Concentration	Mass per 10^{12} Btu output
particulate (from shredders)	7.5×10^{-3} Kg/Ton some bacteria and viruses	1.17 Tons
combined waterborne residuals		
HCL	5.8 lb/Ton MSW	408.9 Tons
Hg	.01 ppm	4.2×10^{-3} Tons
Zn	3.1 ppm	1.33 Tons
Pb	2.2 ppm	9.46×10^{-1} Tons
Ni	1.0 ppm	4.3×10^{-1} Tons
Cd	0.01 ppm	3.8×10^{-1} Tons
Other solubles	18.6 lb/Ton MSW	1310 Tons
Heat	---	1.06×10^{11} Btu
Waste water flow	66 gpm	4.3×10^{4} Tons
Other Residuals		
Sludge	---	1.06×10^{3} Tons

Table 15

Summary of Cogeneration Residual Generation

Residual	Production per 10^{12} Btu Output (tons)
Fluidized Bed	
SO_2	94
NO_x	68
Particulates	250
Ash to Landfill	3500
Dolomite	5800
Solid Waste to Landfill	4.2 acre-ft
Diesel	
Particulates	50
Ash to Landfill	950
SO_2	0.014
NO_x	1600
Hydrocarbons	545
Sludges to Landfill	0.663
Enhanced Oil Recovery	
NO_x	70
Hydrocarbons	7.1
CO	19
Particulates	0.12
SO_2	4.8
Ash to Landfill	2.28

Fluidized Bed Boiler

The primary pollutants from the fluidized bed boiler for the paper plant will be NO_x, SO_2, particulates, and solid waste.

NO_x emissions are effectively controlled in the fluidized bed by limiting the combustion temperature to 1600°F. This is possible because the heat transfer surface is immersed in the bed.

SO_2 emissions are able to be controlled with 90 percent effectiveness by absorption in the limestone bed. The spend limestone and ash mixture is then withdrawn as a dry solid waste. This in itself can be a problem because of the volumes involved. It can be mitigated by using lower sulfur fuel or regeneration.

Particulate emissions from fluidized bed boilers would be high if they were not controlled. Fortunately the controls such as a cyclone and fabric filter baghouse in series are technically simple, very reliable and flexible.

Diesel Engine

The primary pollutant from the combustion turbine burning gas is NO_x. Emissions of SO_2 are avoided by removing the sulfur from the fuel gas stream which is relatively easy compared to removing sulfur from liquid fuels or flue gasses. Particulate emissions are very low for any engine burning gas as a fuel. The NO_x problem can be reduced by injecting steam or water into the combustion chamber of the engine, although at some efficiency cost. Note that in any case an engine burning low-Btu gas will produce less NO_x than when burning oil.

From an environmental standpoint it is unfortunate that cogeneration tends to be site-specific to industrial areas which are likely to have existing air pollution problems. Finding solutions to this problem may become more difficult than overcoming the economic and institutional barriers.

A major policy question raised by cogeneration and environmental control is the priority for clean, high quality fuel. Industries can be expected to desire high quality fuel for cogeneration systems to decrease their capital investment in fuel handling, engine cost and pollution controls. Policies which can make clean light distillate oil or natural gas available on a reliable basis will go far towards improving the economics and thus implementation of cogeneration. Because of its high energy efficiency, cogeneration can afford higher prices for fuel and economic efficiency is served by its use. Furthermore, environmental efficiency may be served by using better fuels in cogeneration systems. Particularly with gas turbines and diesel engines an industrial site may create less pollution with a clean fuel cogeneration system producing electricity and steam than would have been produced by a normal industrial boiler burning lower quality fuel. Thus environmental efficiency suggests using the best fuels in the most environmentally efficient processes such as cogeneration.

This fuel issue is very important for two of the systems considered in this report which require oil and gas. The enhanced oil recovery cogeneration system must use oil or gas in the combustion turbine which is required for the high pressure steam needs. The sewage treatment plant burns methane in a diesel engine which directly removes that fuel from natural gas users because the gas is presently sold to the local gas utility for residential use.

Another environmental issue concerns pollutant mismatches which may prevent offset. A large cogeneration potential exists with gas turbines, which may require a NO_x offset. However, the old boilers replaced may have emitted large amounts of SO_2 and particulates but little NO_x. It may be difficult to control a large amount of NO_x emissions because of economic and transaction costs plus constraints on allowable offsets. A policy allowing offset credit at some ratio for other pollutants exceeding air quality standards would encourage cogeneration and lead to a greater reduction in total emissions. At present EPA policy does not allow inter-pollutant tradeoffs although there are situations where such tradeoffs would aid achievement of a healthy air environment. The California Air Resources (CARB) but not the EPA, recognizes this and is willing to consider inter-pollutant tradeoffs if the net result is a decrease in health threatening pollution. This strategy has already been accepted by CARB and Congress with respect to automotive diesel engines which are allowed to exceed the new car emission standards for NO_x because their other pollutant emissions are so low and meeting the original NO_x standard would be very difficult if not impossible to attain. Diesel engines used for cogeneration are not faced with an absolute standard but the need for offset for NO_x effectively makes sitting this engine a problem or other pollution sources for offset. Thus cogeneration opportunities requiring diesel engines may be blocked.

FACTORS INFLUENCING UTILIZATION OF SOLID WASTE CONVERSION AND COGENERATION

Several factors influence the application of any solid waste conversion project or cogeneration process. In addition to technical feasibility, reliability and economic success, there are questions of environmental quality. Will a conversion to these untested technologies merely be a trade of one type of pollution for another? In order to analyze the feasibility for solid waste conversion and cogeneration systems, it is necessary to identify their characteristics and evaluate the constraints they will place on using the fuel products. This section of the report will briefly outline a few of the major factors influencing implementation.

Solid Waste Conversion

The implementation of solid waste conversion systems depends on several factors including the supply and quantity of wastes, technical and economic feasibility and potential environmental impacts.

The residential and commercial waste stream can be subject to considerable modification in composition over a period of time. This can be an impediment to the practicality of using these resources. The central problem of MSW conversion plants is that they require a guaranteed supply of garbage for the 20-year life of the plant, in order to produce revenues to meet their high fixed capital costs.

Technologies for recovering energy from waste are developing rapidly. However, under any current technology, the major barrier to wider adoption of MSW energy recovery is greater than the value of the energy in the marketplace. The MSW energy projects operating under construction or in various stages of planning are feasible only where revenues from the recovery of secondary materials (e.g. ferrous metals, glass and aluminum) and high waste disposal fees ($7-$15/ton) are added to the energy sales, thus enabling the projects to break even or show a profit (Gordian Associates, 1977).

The value of MSW energy products in the marketplace is closely related to the price of fossil fuels they displace and the cost of substituting the particular MSW product. To a large utility, buying MSW electricity is analogous to buying power from municipal power companies. Its production is viewed as inefficient, unreliable and a small part of the total capacity.

Solid waste has a composition that can readily be upgraded to a valuable fuel. On its "as received" form, it has some undesirable characteristics if used as a fuel, but preparation and separation overcome most of these. The heating value of the processed product must be high enough to minimize the effect of the fuel on the boiler or furnace efficiency. Costs of transporting, storing and handling increase as the heat value decreases, since a greater amount of fuel has to be processed in order to obtain the same amount of energy. Enough of the final product must be available to justify any expenses that the user will incur in modifying the facility to accept this new fuel source.

Solid refuse can be used as a substitute for conventional fossil fuels in existing or newly designed combustion units. The major markets are utility steam electric boilers, industrial steam and steam electric boilers, and downtown steam and chilled water distribution utilities. Since resource recovery systems are capital-intensive, there will continue to be a lack of confidence in their economic feasibility until the systems are fully demonstrated and developed. Technologies that work on a small scale (35 tons/day) may develop unexpected problems when applied on a large scale (1000 tons/day).

Another potential economic constraint on the use of a solid waste conversion system relates to its acceptance at the local level. Many local governmental units when faced with the problem of disposing of solid wastes tend to use the traditional methods of landfilling rather than investigating the new possibilities of resource recovery. For example, Union Electric Company of St. Louis, which was one of the first utilities to burn processed refuse fuel in a demonstration project, abandoned its operation in April 1977. The problems were economic and political. The voters of Missouri had adopted a proposition that prevented the utility companies from including the carrying costs for construction funds in their electric rates. That restriction, plus rising costs, made the economics of the project questionable (EPRI, 1977).

A critical aspect of the feasibility of any resource recovery system is the quality of the products. This is true for both the secondary materials (ferrous metals, aluminum, glass) and the processed fuel. Claims to recovery materials from mixed waste have not been borne out. Only ferrous metals separation, which is a long-established technology, has proven itself in practice. The high degree of purity required by markets for use of secondary materials has been difficult to achieve once materials are contaminated with mixed garbage.

Varying composition and moisture content of the processed fuel results in emissions of great inconsistency and erratic functioning of the emission control devices (electrostatic precipitators). Even though the sulfur content of MSW is relatively low in comparison to coal, there are potential problems with particulates and heavy metals. Fuel derived from refuse, for example, contains higher levels of cadmium, lead, copper, chlorine and zinc than coal (Wentworth, 1970).

Ash residues from plants, which burn solid wastes or raw garbage, may be hazardous wastes which must be trucked to special landfills that control leachates. Water pollution problems are of concern in some pyrolysis methods as well because of the high organic content of the effluent.

Critics of solid waste conversion systems argue that solid pollution problems are being traced for air and water pollution problems. The topic of concern is the actual cost needed to meet the applicable Federal and state pollution control standards. These Federal and state emissions limitations will determine the technological and economic feasibility of compliance. Furthermore, state and local review of actions regarding new projects will determine whether a new source of emission, in fact, will be permitted to locate in a given area.

The principal reason for the lack of activity in resource recovery is that the activity is risky. For most communities, the key to adoption of recovery is costs that are competitive with landfill. For the nation as a whole, this generally means that the public sector must be the main risk taker. Furthermore, the unique financial and revenue structure of the heavily regulated utility industry contributes to why the financial and operating risks of MSW energy recovery are unattractive (Gordian Associates, 1977).

Contributing causes include inflation, high interest rates, lack of sufficient investment capital, and the likelihood that MSW investment costs will not be allowed in a utility rate base (e.g. St. Louis experience).

In order to overcome some of the barriers to the utilization of municipal refuse, there are certain emerging patterns. The future development calls for not involving the utilities directly in waste disposal problems. An intermediary is suggested instead to operate the recovery facility, collect a disposal fee, convert MSW to energy, and sell the secondary materials recovered (Gordian Associates, 1977).

Cogeneration

In reality cogeneration implementation depends on technical and institutional feasibility plus economic feasibility which reflects energy efficiency. All of these variables are indirectly affected by another figure which is the ratio of power output to heat output. This determines how much, if any, electricity will be sold to the grid. For example, a steam boiler/turbine system may produce 50 kWh/10^6 Btu of steam heat. A gas turbine/waste heat boiler, however, produces 200 kWh/10^6 Btu of steam heat. This is a ratio rather than an efficiency so that while a gas turbine produces more electricity, it also produces less steam heat. The important use for this power/heat ratio is matching energy maximizing electrical generation if institutional arrangements allow an economic advantage from selling power. The problem at present is that utilities offer very low prices for excess power generation. All of the variables affecting cogeneration interact in a complex way to determine the best system choice as illustrated in Figure 9.

The generation of steam and electric power is a significant use of fossil fuels and causes a large fraction of present day air pollution emissions. Cogeneration in nearly all cases is based upon the combustion of fossil fuels and so air pollution problems must be addressed. With respect to water bodies, cogeneration can significantly reduce the impact of electrical generation because normally there will be negligible water consumption and thermal discharge beyond that normally associated with the process heat.

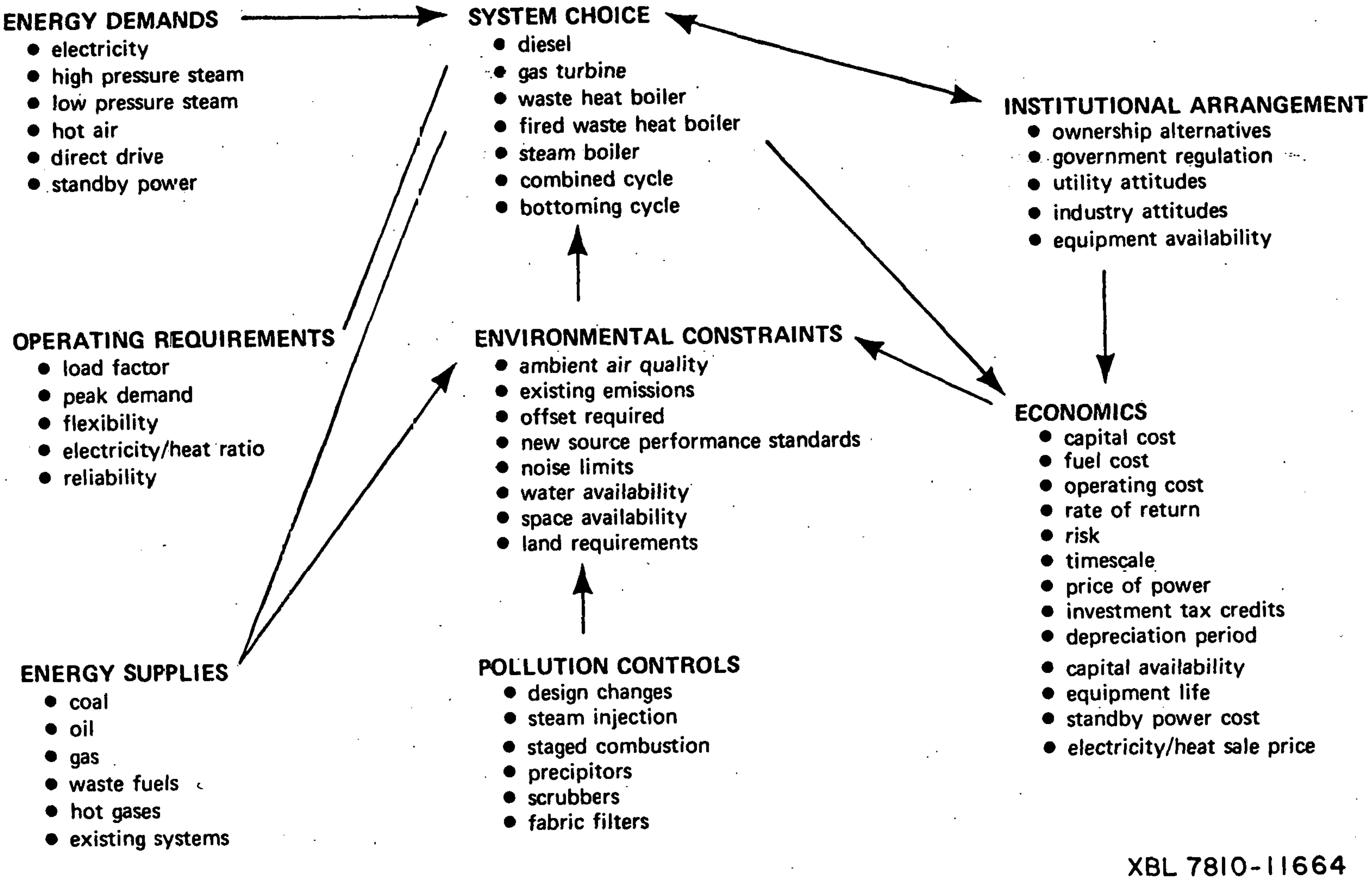

Fig. 9. Cogeneration System Alternative Analysis

With respect to air pollution, guidelines are given in the standards and regulations established under the Clean Air Act. Of first concern are the Ambient Air Quality Standards set by EPA for SO_2, NO_x and particulates. The primary standards for these pollutants are set to protect human health. Unfortunately a large fraction of industrialized Air Quality Control Regions do not meet the standard for one or more pollutants. In these non-attainment areas new pollution sources are not allowed to interfere with meeting the standard. One compromise to prevent economic stagnation is pollution offset whereby a new stationary source can be built if a greater amount of the same pollutants are removed from the same locality. The importance of offset to cogeneration systems is that it puts a premium on low emissions including controls stricter than New Source Performance Standards which normally apply to electrical generation. Under offset regulations each pollutant must be more than offset be decreasing or ceasing emissions elsewhere. Thus the type of emissions available for offset may be important in deciding system choice.

From an environmental standpoint it is unfortunate that cogeneration tends to be site-specific to industrial areas which are likely to have existing air pollution problems. Finding solutions to this problem may become more difficult than overcoming the economic and institutional barriers.

A major policy question raised by cogeneration and environmental control is the priority for clean, high quality fuel. Industries can be expected to desire high quality fuel for cogeneration systems to decrease their capital investment in fuel handling, engine cost and pollution controls. Policies which can make clean light distillate oil or natural gas available on a reliable basis or natural gas will go far towards improving the economics and thus implementation of cogeneration. Because of its high energy efficiency, cogeneration can afford higher prices for fuel and economic efficiency is served by its use. Furthermore, environmental efficiency may be served by using better fuels in cogeneration systems. Particularly with gas turbines and diesel engines an industrial site may create less pollution with a clean fuel cogeneration system producing electricity and steam than would have been produced by a normal industrial boiler burning lower quality fuel. Thus environmental efficiency suggest using the best fuels in the most environmentally efficient process such as cogeneration.

CONCLUSIONS

The primary environmental problems of converting municipal refuse to energy or utilizing cogeneration systems vary with the type of process employed. Several specific applications associated with MSW conversion and cogeneration have been characterized in the previous sections of this report. This section will briefly compare the various technologies according to several key parameters including system inputs, outputs, stack effluents and waterborne residuals.

Table 16 contains a comparison of system inputs per 10^{12} Btu steam output. Land requirements are minimal for all systems. The RDF system is by far the cheapest to build and is also the most efficient in terms of energy recovery per ton of MSW. The fluidized bed system has the highest overall system efficiency. However, the PUROX system uses the least ancillary energy and is the only system not requiring an input water flow. Thus the RDF is the most favorable for capital inputs and the PUROX is the most favorable for operational inputs.

In Table 17 is found a similar comparison of system outputs. System energy products have been left as the primary system product rather than converting each fuel to a common end use product such as electricity.

The available data on stack emissions are compared in Table 18. The major air pollutants of concern are: SO_2, NO_x, HCl, hydrocarbons, and particulates. The RDF system which was characterized in this study involved co-combustion with coal and therefore it is not surprising that the resultant SO_2 levels are relatively high. The sulfur emissions, however, would be expected to be lower than those from a 100 percent coal-fired boiler. Nitrogen oxides seem to be only a problem in the direct combustion system and the cogeneration applications. The diesel system associated with primary and secondary sewage treatment plants has the highest level of NO_x emissions of the processes under study. Chlorides, in the form of HCl, are characteristic of solid waste conversion processes because of the presence of polyvinyl chlorides in the waste stream. Chlorides released to the air would be an effluent of some concern, since there are no emission standards as yet. Particulates are a major component of all the systems studied. Direct Combustion

Table 16

Systems Inputs Comparison
(amount/10^{12} Btu steam per year)

No.	Parameter	Systems							
		LG	GP	PX	DC	RDF	FP	DI	EO
1	Land (acres)	5.9	35	20.7	10.8	9	4.2	0.1	0.1
2	Capital (dollars)	11.2×10^6	7.42×10^8	36.82×10^6	48×10^6	3.76×10^5	11.05×10^6	11.54×10^7	16.4×10^7
3	MSW (tons)	1.8×10^5	2.38×10^5	1.45×10^5	1.57×10^5	1.39×10^5	4.2×10^4	**	--
4	Air (tons)	1.78×10^5	--	0	--	--	--	--	--
5	O_2 (tons)	0	0	2.82×10^4	0	0	--	--	--
6	Fuel Oil	1.28×10^6	567	--	--	--	--	1.19×10^6	2.1×10^5
7	Electricity (Btu's)	4.05×10^{10}	1.14×10^{11}	1.6×10^{10}	2.94×10^{10}	2.71×10^{10}	--	--	--
8	H_2O (tons)	1.15×10^8	9.2×10^4	0	1.008×10^5	1×10^3	2.1×10^5	1.5×10^5	--

LG = Landguard pyrolysis
GP = Garrett flash pyrolysis
PX = Union Carbide Purox process
DC = Direct combustion
RDF = Refuse-derived fuel
FB = Fluidized-bed cogeneration
DI = Diesel cogeneration
EO = Enhanced oil recovery (cogeneration)

*Coal replaces MSW

**Sewage replaces MSW (3.96 x 10^6 cf)

Table 17

Systems Output Comparison
(tons/day/10^{12} Btu steam per year)[a]

No.	Parameter	Systems							
		LG	GP	PX	DC	RDF	FB	DI	EO
1	Steam (tons)	4.32×10^5	5.97×10^5	0	4.72×10^5	3.34×10^5	2.1×10^5	2.1×10^5	144
2	Electricity (kW-hr)						1.51×10^8	1.76×10^8	2.20×10^8
3	Fuel Oil	0	4.03×10^4	0	0	0	--	--	--
4	Fuel Gas	0	1.97×10^4	0.65×10^4	0	0	--	--	--
5	Ferrous Metal	1.26×10^3	1.61×10^3	3.45×10^3	1.18×10^4	9.73×10^3	--	--	--
6	Non-Ferrous Metal	--	1.53×10^4	1.05×10^3	--	1.39×10^3	--	--	--
7	Glass	3.06×10^4	1.06×10^5	2.96×10^4	8.65×10^3	1.11×10^4	--	--	--
8	Waste H_2O	4.68×10^4	1.32×10^4	4.3×10^4	1.08×10^5	--	--	--	--
9	Char	1.44×10^3	35.05	0	1.73×10^4	4.75×10^4	3.5×10^3	950	2.28
10	Stack Effluent	585	1.06×10^5	1.17	1.63×10^6	4.17×10^4	412	3.15×10^3	101
11	Water Effluent	4.68×10^9		5.6×10^4	335.17	2.78×10^4	--	--	--

LG = Languard pyrolysis
GP = Garrett flash pyrolysis
PX = Union Carbide Purox process
DC = Direct combustion
RDF = Refuse-derived fuels

FB = Fluidized-bed cogeneration
DI = Diesel cogeneration
EO = Enhanced oil recovery (cogeneration)

[a] blank indicates no available data

Table 18

Stack Effluents Comparison
(tons/10^{12} Btu steam per year)

No.	Parameter	Systems							
		LG	GP	PX	DC	RDF	FB	DI	EO
1	N_2	--	--	0	1.1×10^6	--	--	--	--
2	H_2O Vapor	--	--	0	1.1×10^5	--	--	--	--
3	SO_2	127	22.9	0	136	192	94	0.014	4.8
4	NO_x	72.2	8.2	0	227	150	68	1.6×10^3	70
5	O_2	--	--	0	2.26×10^5	--	--	--	--
6	CO	--	--	0	758	--	--	--	19
7	CO_2	--	--	0	1.32×10^5	--	--	--	--
8	HCl	306	3.3	0	75.8	--	--	--	--
9	Hydrocarbons	12	0.65	0	--	--	--	545	7.1
10	Chlorides	55.2	--	0	--	50	--	--	--
11	Particulates	7.6	112.4	1.17	2.3×10^3	160	250	50	0.12
12	Char/Ash to Landfill	1.44×10^3	1.33×10^4	2.34×10^4	1.73×10^4	4.17×10^4	3.5×10^3	950	2.28

LG = Landguard pyrolysis

GP = Garrett flash pyrolysis

PX = Union Carbide Purox process

DC = Direct combustion

RDF = Refuse-derived fuel

FB = Fluidized-bed cogeneration

DI = Diesel cogeneration

EO = Enhanced oil recovery (cogeneration) systems contribute the highest level per 10^{12} Btu output, which may limit the use of this technology in areas with strict particulate standards. There are, however, available control technologies to control this environmental concern. From the point of view of stack effluents, the PUROX pyrolysis system seems to contribute the lowest quantities of air pollutants, while direct combustion operations produce the highest. There are more available data in the case of direct combustion units which may contribute to this situation.

Table 19 summarizes the data on waterborne residuals. The major pollutants are: suspended solids, ash quench water, trace metals, organics and acids. Because of the paucity of information in the literature on water effluents from waste conversion and cogeneration processes, it is difficult to compare the various technologies. It is reported elsewhere that both the oxygen pyrolysis (gas utility) and flash pyrolysis (oil utility) systems produce large quantities of waste water that must be cleaned and disposed (Aerospace, 1976). The major environmental concern is the effectiveness of water pollution controls on the spread of hazardous materials.

Table 20 presents a summary of the major environmental problems for each of the systems selected for analysis. Future effort within the project will be directed toward expanding and refining the intersystem comparison as data on the various effluents become available.

Table 19

Waterborne Residuals Comparison
(tons/10^{12} Btu steam per year)[a]

No.	Parameter	LG	GP	PX	DC	RDF
1	HCl	--	--	408.9	--	--
2	Hg	--	--	4.2×10^{-3}	--	--
3	Zn	--	--	1.33	--	--
4	Pb	--	--	9.46×10^{-1}	--	--
5	Ni	--	--	4.3×10^{-1}	--	--
6	Cd	--	--	3.8×10^{-1}	--	--
7	Other Solubles	--	--	--	--	--
8	Suspended Solids	--	--	--	--	8.08
9	Sulfates	--	--	--	8.5	--
10	Chorides	--	--	--	56.6	.428
11	Phosphates	--	--	--	0.51	.6785
12	Hardness	--	--	--	66.4	--
13	Waste Heat	--	--	--	1.06×10^{11}	--
14	Waste H_2O	4.68×10^{4}	1.06×10^{5}	4.3×10^{4}	1.008×10^{5}	2.78×10^{4}
15	BOD	--	--	--	--	.039
16	COD	--	1.44×10^{3}	--	--	--
17	Sludge	--	--	--	--	40

LG = Landguard pyrolysis
GP = Garrett flash pyrolysis
PX = Union Carbide Purox process
DC = Direct combustion
RDF = Refuse-derived fuel

[a] No available data on cogeneration Systems

Table 20

Summary of Major Environmental Problems

System	Emissions to Air	Discharges to Water	Problems
Direct Combustion	Significant amounts of SO_2, NO_x, HCl and especially particulates	Emissions from scrubber water	Potential difficulty meeting local air quality standards
RDF	SO_2 (depending on S content of coal), particulates, HCl	Greater BOD and COD levels than coal combustion	Significant levels of bottom ash for disposal
Purox	Particulates (from shredder)	Significant amounts of HCl and trace metals	
Fluidized Bed (cogeneration)	Significant amounts of SO_2, NO_x and particulates	Data not available	*
Diesel (cogeneration)	Significant amounts of NO_x and hydrocarbons	Data not available	*
Enhanced Oil Recovery	Significant amounts of NO_x	Data not available	*

* Cogeneration tends to be site-specific to industrial areas which are likely to have existing pollution problems.

APPENDIX A

CAPITAL AND OPERATIONAL RESIDUAL INPUT SHEETS FOR SEAS MODEL APPLICATION

This appendix contains the formatted input sheets for capital and operational system residuals. For each Technology Application, sheets are included in the following order: Capital Expenditures and Material Requirements Summary Reporting Form, Technology Capital Costs: Works Sheets, Technology Capital Costs: Work Sheets—Annual Operating Costs, and Residual Data Sheets.

SO_2 scrubbers and either baghouses or electrostatic precipitators are included as a basic element of each system and are reflected in capital costs and in the residual generation rates. An extra column has been added onto all Capital Material Requirements Sheets. This column is used to indicate whether or not the corresponding material is recycled upon either replacement or decommissioning or is described as a land residual. It should be noted that all waste water flows described in this appendix can be discharged directly into municipal sewer systems without pretreatment.

Side Equations

The three MSW energy recovery processes described in this report also produce secondary products which are not sold in proportion with or to the same customers as the basic energy products. The sale of these secondary products is handled in the SEAS model system through the use of "side equations." The side equations for the MSW technologies are shown in Table A-1. Included in this table are both production rates for secondary equations and identification of general sectors to which these products are sold.

Table A-1

MSW Technology Side Equations

System	Product	Production Rate (tons/10^{12} Btu of output)	Sectors Sold To
Direct Combustion	Iron	$1.8\text{x}10^4$	Recycled to metal fabrication industries
	Glass	$8.65\text{x}10^3$	Recycled to stone, glass, clay industries
RDF	Iron	$9.73\text{x}10^3$	Recycled to metal fabrication industries
	Aluminum	$1.39\text{x}10^3$	Recycled to Non-Ferrous Metal Industries
	Glass	$1.11\text{x}10^4$	Recycled to stone, glass, clay industries
Pyrolysis	Iron	$8.45\text{x}10^3$	Recycled to metal fabrication industries
	Aluminum	$1.41\text{x}10^3$	Recycled to non-ferrous metal industries
	Glass Aggregate	$2.34\text{x}10^4$	Sold for construction and road bed aggregate

CAPITAL EXPENDITURES AND MATERIALS REQUIREMENTS
SUMMARY REPORTING FORM

TECHNOLOGY	Municipal Solid Waste	REGIONAL APPLICABILITY OF DATA:	
APPLICATION	RDF	NATIONAL:	X
DATE SUBMITTED	8 August 1978	FEDERAL REGION NOS.	all
SUBMITTED BY	LBL	STATES:	all

A. CAPITAL COSTS	$1977	DEFLATOR	$1972
1. MATERIALS	$ 71,952,800	1.43	50,316,600
2. TRANSPORTATION	6,150,000	1.43	4,300,700
3. CONSTRUCTION LABOR	39,629,600	1.43	27,713,000
4. PROFIT & OVERHEAD	29,136,900	1.43	20,375,460
A.1 TOTAL	$146,869,300	1.43	102,705,800

B. ANNUAL SYSTEM 10^{12} BTU OUTPUT	6.45 (10^{12}BTU)
C. ANNUAL SYSTEM FOSSIL FUEL EQUIVALENT/10^{12} BTU OUTPUT	19.35 (10^{12}BTU)
D. TOTAL CAPITAL COST/10^{12} ANNUAL BTU $\left[\frac{A.1}{B}\right]$	$ 15,923,400
E. NUMBER OF YEARS TO CONSTRUCT FACILITY	5

F. PHASING OF CONSTRUCTION COSTS ($ EACH YEAR):

YEAR	1	2	3	4	5	6	7	8	9	10
%	20	20	20	20	20					

G. EXPECTED LIFE OF FACILITY (YEARS)	30
H. MAN YEARS TO CONSTRUCT FACILITY	1455
I. MAN YEARS/10^{12} BTU ANNUAL OUTPUT $\left[\frac{H}{B}\right]$	225.4
J. ESTIMATED LAND USE	9.5 acres

TECHNOLOGY CAPITAL COSTS: WORK SHEET

TECHNOLOGY: Municipal Solid Waste APPLICATION: Refuse Derived Fuel DATE: 8 August 1978 1 out of 3

Expenditures			(4) Total Cost 1977$x	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			411	2432	Veneer & Plywood	45	.28	based on		0
			814	2431, 2433	Mill work & wood	46	.55	current		0
			275.4	281	Industrial Chem	64	.19	designs and		0
			1,056.9	299	Petroleum Refin.	76	0.72	research		0
			1,364.	3272	Cement, Concrete gypsum	89	.93	a scale		0
			83.6	321	Glass	86	.057	factor of		0
			336.5	3293	Other Stone, Clay, Glass	90	0.23	one is assumed		0
			815.7	331, 332	Steel	91	0.56	for all years		1
			589.4	3331	Copper	92	.40	through		1
			167.2	3334	Aluminum	95	.11			1
			402.2	3339	Other Primary non-ferrous	96	.27			1
			22,372.1	3441, 3442, 3443	Fabricated Structure Material	104	15.2			1
			3,250.2	3494	Pipes, Valves, fittings	109	2.21			1
			6,7220	3499	Fabricated Metal Nec	110	458			1

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

TECHNOLOGY CAPITAL COSTS: WORK SHEET

2 out of 3

TECHNOLOGY: Municipal Solid Waste APPLICATION: efuse Derived Fuel DATE: 8 August 1978

Expenditures			(4) Total Cost 197 $	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			2346.7	-	Misc Material	-	1.60			0
			14931.7	3511	Engine & Turbine	111	10.17			1
			322.6	3623	Welding Apparatu	133	0.22			0
			3458.8	3434, 3435	Material Handlin	114	2.34			1
			872.1	3820	Mech. Measuring	157	0.59			0
			2270.8	3569	Gen. Ind. Machine	122	1.55			1
			5962.5	3561	Pumps, Generator	119	4.08			1
			2980.4	3621	Motors & Gen.	131	2.03			0
			12.5	3572, 3576	Other Office Mach	124	0.0085			0
			134.5	3999	Misc. Manufactur	166	0.092			0
Material and Equipment		Total	71,952.8							
Transportation			6150.		Trucking	169	4.19			0

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

TECHNOLOGY CAPITAL COSTS: WORK SHEET

3 out of 3

TECHNOLOGY: Municipal Solid Waste APPLICATION: Refuse Derived Fuel DATE: 8 August 1978

Expenditures			(4) Total Cost 197 $	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
Service & Management			10.76	-	-	-	0.73			0
Labor	2.9657X10^{6} hr	$13./hr	38,553.6	-	-	-	26.25			0
OH Labor			11,566.1	-	New Construction	19	7.88			0
OH Other			3,855.4	-	New Construction	19	2.63			0
Profit			13,715.4	-	-	19	9.34			0
	Total		146,869.3				99.97			
Land	10 acres		1,420.5							

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

TECHNOLOGY CAPITAL COSTS: WORK SHEET

1 of 2

TECHNOLOGY: Municipal Solid Waste APPLICATION: RDF - Annual Operation DATE: 8 August 1978

Expenditures			(4) Total Cost 197 $	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			80	281	Industrial Chem	64	1.95			0
			7	3272	Cement, Concert Gypsum	89	0.17			0
			2	321	Glass	86	0.049			0
			6	3293	Other Stone, Glass, Clay	90	0.14			0
			4	3331	Copper	92	0.097			1
			2	3334	Aluminum	95	0.049			1
			9	3339	Other, non-Ferrous	96	0.022			1
			675	3441 3443	Fab. Struct.	104	16.40			1
			375	3494 3498	Pipes, Valves, Fittings	109	9.13			1
			30	-	Other Misc Mat.	-	0.73			0
			280	3561	pumps, compress	119	6.82			1
			165	353	Materials, handling equipment	114	4.02			1
			59	3622	Industrial Cont	157	1.45			0
			1.5	3572	Other off. Eqpt	124	0.037			0
			80	3511	Engines & Turbines	111	1.95			1

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

TECHNOLOGY CAPITAL COSTS: WORK SHEET

2 of 2

TECHNOLOGY: Municipal Solid Waste APPLICATION: RDF - Annual Operation DATE: 8 August, 1978

Expenditures			(4) Total Cost 1977$	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			80	3621	Motor & Gen	131	1.96			1
			20	371	Motor Vehicles	157	0.48			0
Total Material & Equipment			1934.5							
			203	494	Electricity	180	4.99			0
			550	494	Water & Sewer	179	13.44			0
			30	494	Heating Fuel	178	0.76			0
Transportation			150.9	-	Trucking	169	3.65			0
Labor			928	-	Labor	20	22.63			0
OH Wage			278.4	-	New Construction	20	6.80			0
OH Other			92.8	-	New Construction	20	2.25			0
			4108.6		Total		99.99			

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

Attachment (B)

1 of 2

Residuals Data Sheet

Technology Municipal Solid Waste
Application RDF
Date Submitted 8 August 1978
Submitted By LBL

Level of Regionalization:
National Yes
Federal -
State -

Code #
Code #
(Use Regional Code Taxonomy)

Residual Category/ Component	Taxonomy 4 digit #	Medium of Transport	Hardness	Gross Residuals per 10^{12} BTU end-use Energy	Gross Residuals 10^{12} BTU Input	Abatement Removal Efficiency	$ Abatement/10^{12} BTU		Secondary Residuals		Secondary Residual Coefficient	Footnotes
							Capital	Operating	Residual Category/ Component	4 digit Taxonomy		
Processing (Front End)												
23	07	land	3	51.44	16.33							
01	00	air	3	2.71	0.86							
19	00	air	3	?	?							
Energy Conversion												
23	07	land	2	152.0	48.25							
01	00	air	2	8.0	2.54							
02	00	air	2	192.0	60.95							
03	00	air	3	150.0	47.62							
07	20	air	3	50.0	15.87							
Ash Pond												
09	00	water	2	0.039	0.0124							
12	00	water	2	8.08	2.57							
15	00	water	2	1.34	0.43							
20	00	water	2	0.678	0.215							
20	21	water	2	0.039	0.0124							
20	12	water	2	5.38	1.71							

Attachment (I)

2 of 2

Residuals Data Sheet

Technology Municipal Solid Waste
Application RDF
Date Submitted 8 August 1978
Submitted By LEI

Level of Regionalization:
National X
Federal all
State
Code # [For Regional
Code # Code Taxonomy]

Residual Category/ Component	Taxonomy 4 digit #	Medium of Transport	Hardness	Gross Residuals per 10^{12} BTU end-use Energy	Gross Residuals 10^{12} BTU Input	Abatement Removal Efficiency	$ Abatement/10^{12} BTU		Secondary Residuals		Secondary Residual Conditions	Footnotes
							Capital	Operating	Residual Category/ Component	4 digit Taxonomy		
Ash Pond (Cont'd)												
11	00	water	2	1.03	0.34							
20	20	water	2	0.428	0.136							
Bottom Ash												
23	07	Solid	1	40.0	12.70							
Capital Residuals												
38	99	Land		9 acres	2.85 acres							
Operational Residual												
43	00	Labor	1	6.12×10^4 hrs	1.94×10^4 hr							
20	78	water	1	2.78×10^4 Tons	8.825×10^3 Tons							

Attachment (E)

1 of 2

Residuals Data Sheet

Technology Municipal Solid Waste
Application Direct Combustion
Date Submitted 8 August 1978
Submitted by Lawrence Berkeley Lab

Level of Regionalization:
National Yes
Federal -
State -

Code #
Code #
[Use Regional Code Taxonomy]

(1) Residual Category/ Component	(2) Taxonomy 4 digit #	(3) Medium of Transport	(4) Hardness	(5) Gross Residuals per 10^{12} BTU end-use Energy (tons)	(6) Gross Residuals 10^{12} BTU Input	(7) Abatement Removal Efficiency	(8) $ Abatement/10^{12} BTU		(9) Secondary Residuals		(10) Secondary Residual Coordinates	Footnotes
							Capital	Operating	Residual Category/ Component	4 digit Taxonomy		
43	00	labor	1	$2.62x10^4$hr	$8.73x10^3$hr							
20	78	water	1	$1.008x10^5$	$3.36x10^4$							
23	69	solid	1	$1.73x10^4$	$5.77x10^3$							
Stack Emission												
01	07	air	2	115	38.35							
02	00	air	2	13.6	4.5							
03	00	air	2	227	75.67							
05	00	air	2	758	252.67							
15	00	air	2	106.1	35.37							
07	93	air	2	22.7	7.57							
07	78	air	2	$1.1x10^5$	$3.67x10^4$							
19	00	air	2									
23	07	land	3	$2.28x10^3$	$7.29x10^2$							
27	00	land	3	122.4	40.8							

Attachment [illegible]

2 of 2

Residuals Data Sheet

Technology Municipal Solid Waste

Application Direct Combustion

Date Submitted 8 Aug 78

Submitted by Lawrence Berkeley Lab

Level of Regionalization:

National yes

Federal all

State all

Code # ______ [Use Regional

Code # ______ Code Taxonomy]

Residual Category/ Component (1)	Taxonomy 4 digit # (2)	Medium of Transport (3)	Hardness	Gross Residuals per 10^{12} BTU end-use Energy (5)	Gross Residuals 10^{12} BTU Input (6)	Abatement Removal Efficiency (7)	\$ Abatement/10^{12} BTU (8) Capital	Operating	Secondary Residuals (9) Residual Category/ Component	4 digit Taxonomy	Secondary Residual Criteria (10)	Footnotes
Scrubber Waste Flow												
12	00	water	2	22.8	7.6							
13	00	water	2	104.8	34.87							
16	20	water	2	42.8								
20	86	water	2	21.1	14.27							
14	60	water	2	1.62	0.54							
Slag Quench Waste Water Flow												
12	00	water	2	31.4	10.46							
13	00	water	2	39.3	13.1							
16	20	water	2	13.8	4.6							
20	86	water	2	8.5	2.83							
14	00	water	2	0.51	0.17							
21	78	water	2	1.7×10^{5} BTU	5.67×10^{4} BTU							

CAPITAL EXPENDITURES AND MATERIALS REQUIREMENTS
SUMMARY REPORTING FORM

TECHNOLOGY Municipal Solid Waste
APPLICATION Pyrolysis
DATE SUBMITTED 8 August 1978
SUBMITTED BY LBL

REGIONAL APPLICABILITY OF DATA:
NATIONAL: X
FEDERAL REGION NOS.
STATES:

		$1974	DEFLATOR	$1972
A.	CAPITAL COSTS			
	1. MATERIALS	116,458,000	1.18	98,693,300
	2. TRANSPORTATION	9,458,000	1.18	7,994,100
	3. CONSTRUCTION LABOR	50,708,000	1.18	42,972,900
	4. PROFIT & OVERHEAD	39,971,000	1.18	33,873,700
A.1	TOTAL	217,920,000	1.18	184,678,000

B.	ANNUAL SYSTEM 10^{12} BTU OUTPUT	15.3 (10^{12} BTU)
C.	ANNUAL SYSTEM FOSSIL FUEL EQUIVALENT/10^{12} BTU OUTPUT	19.13 (10^{12} BTU)
D.	TOTAL CAPITAL COST/10^{12} ANNUAL BTU $\left[\frac{A.1}{B}\right]$	12,070,500
E.	NUMBER OF YEARS TO CONSTRUCT FACILITY	4

F. PHASING OF CONSTRUCTION COSTS ($ EACH YEAR):

YEAR	1	2	3	4	5	6	7	8	9	10
%	25	25	25	25						

G.	EXPECTED LIFE OF FACILITY (YEARS)	30
H.	MAN YEARS TO CONSTRUCT FACILITY	2100
I.	MAN YEARS/10^{12} BTU ANNUAL OUTPUT $\left[\frac{H}{B}\right]$	137
J.	ESTIMATED LAND USE	10 acres

TECHNOLOGY CAPITAL COSTS: WORK SHEET 1 of 3 : 1

TECHNOLOGY: Municipal Solid Waste APPLICATION: Pyrolysis DATE: 2 August 1978

Expenditures (1) Category[a]	Expenditures (2) Quantity & Units	Expenditures (3) Price[b]	(4) Total Cost 197 $	Inforum Sector Designation (5) SIC#[c]	Inforum Sector Designation (6) SEAS SECTOR	Inforum Sector Designation (7) SEAS #	(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
			410	2432	Veneer & Plywood	45	0.19			0
			820	2431 2433	Millwork & Wood	46	0.38	based on		0
			10	281	Industrial Chem	64	0.0046	current		0
			110	299	Petroleum Ref.	76	0.0505	designs,		0
			6741	3272	Cement, Concrete, Gypsum	89	3.09	assumed		0
			40	321	Glass	86	0.018	to be one		0
			1560	3293	Other stone, Glass	90	0.72	for all		0
			330	331 332	Steel	91	0.15	years		1
			259	3331	Copper	92	0.12	through		1
			69	3334	Aluminum	95	0.032	2000		1
			82	3339	Other Primary non Ferrous	96	0.038			1
			19850	3441 3444 3443	Fabricated Struct	104	9.11			1
			10600	3494 3498	Pipes, Valves, Fittings	109	4.86			1
			340	-	other misc. met.	-	0.615			0

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

TECHNOLOGY CAPITAL COSTS: WORK SHEET

TECHNOLOGY: Municipal Solid Waste APPLICATION: Pyrolysis DATE: 2 August 1978

Expenditures			(4) Total Cost 1974$	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			5575	3561	Pump, Compressor Blowers	119	2.60			1
			1180	3567 3569	Industrial Pattern	122	0.86			1
			18	3572 3576	Other Office	124	0.0083			0
			20	3590	Service Ind. machines	126	0.0092			1
			24100	3511	Engines & Turbine	111	11.06			1
			138	3623	Welding Apparatus	133	0.063			0
			3322	3621	Motor & Gen	131	1.52			1
			12880	3484 3435	Materials Handling Machinery	114	5.91			1
			4055	3569	Gen Indus Machine	122	1.86			1
			320	3820	Mechanical Meas.	157	0.15			0
			22830	3999	Misc. Manufact.	166	10.48			0
Material - Sub Total			116458							
Transportation			9433		Trucking	169	4.33			0
Labor(Dies)	4.279X10^6hr	$11.95/hr	50708		Labor	19	23.27			0
OH Wages			15212		New Construction	19	6.98			0
OH Other			5071		New Construction	19	2.33			0

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

3 of 3

TECHNOLOGY CAPITAL COSTS: WORK SHEET

TECHNOLOGY: Municipal Solid Waste APPLICATION: Pyrolysis DATE: 2 August 1978

Expenditures			(4) Total Cost 1974$	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
Profit			19688		Profit	19	9.135			0
Total Cost			216,570				99.043			0
Land	10 acres		370							

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

TECHNOLOGY CAPITAL COSTS: WORK SHEET 1 of 2

TECHNOLOGY: Municipal Solid Waste APPLICATION: Pyrolysis-Annual Operation DATE: 8 August, 1978

Expenditures			(4) Total Cost 1974$	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			30	281	Industrial Chem	64	1.92			0
			6	3272	Cement, Concrete Gypsum	89	0.38			0
			4	321	Glass	86	0.27			0
			10	3293	Other Stone, Clay, Glass	90	0.64			0
			4	3331	Copper	92	0.26			0
			2	3334	Aluminum	95	0.13			1
			16	3339	Other, Non-Ferrous	96	1.03			1
			15	3441 3443	Fab. Structural	104	0.96			1
			15	3494 3498	Pipes, valves fittings	109	0.96			1
			10	-	Other misc mat.	-	0.64			1
			100	3561 3563	Pumps, Compressor	119	6.42			1
			210	353	Materials handling Equipment	114	13.47			1
			65	3622	Industrial Control	157	4.17			0
			1	3572	Other office	124	0.064			0
			90	3511	Engines & Turbine	111	5.72			1
			90	3621	Motor & Gen	131	5.72			1

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

TECHNOLOGY CAPITAL COSTS: WORK SHEET

2 of 2

TECHNOLOGY: Municipal Solid Waste APPLICATION: Pyrolysis-Annual Operation DATE: 8 August, 1978

Expenditures			(4) Total Cost 1974$	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			10	371	Motor Vehicles	145	0.64			0
			30	382	Mech. Measure.	157	1.92			1
	Total Equipment & Materials		698							
			18.5	494	Water & Sewer	179	1.14			0
			5	494	Heating Fuel	178	0.32			0
	Transportation		56	-	Trucking	169	3.59			0
	Labor (direct)									
		47,090 hr $11.85	558	-	Labor	20	35.70			0
O.H. Wages			167	-	New Construction	20	10.72			0
O.H. Other			56	-	New Construction	20	3.49			0
		Total	1558.5				100.094			

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

Attachment (E)

1 of 1

Residuals Data Sheet

Technology Municipal Solid Waste
Application Pyrolysis
Date Submitted 15 July 1978
Submitted by Lawrence Berkeley Lab

Level of Regionalization:
National
Federal all
State all

Code # [Use Regional
Code # Code Taxonomy]

Residual Category/ Component	Taxonomy 4 digit #	Medium of Transport	Hazardous	Gross Residuals per 10^{12} BTU end-use Energy	Gross Residuals 10^{12} BTU Input	Abatement Removal Efficiency	$ Abatement/10^{12} BTU		Secondary Residuals		Secondary Residual Characteristics	Footnotes
							Capital	Operating	Residual Category/ Component	4 digit Taxonomy		
23	07	land	3	56.69	29.64							
01	00	air	2	3.51	1.56							
37	00	water	3	1.29×10^5 T	5.75×10^4 T	-						
38	99	land	1	61.3 acres	27.3 acre	-						
19	00	air	5	--	--	0						
43	00	--	1	1.486×10^5 hr	6.62×10^4 hr	0						
08	00	air	5	--	--	0						
21	78	water	2	3.17×10^{11} Btu	1.41×10^{11} Btu	0						
15	20	water	2	1.23×10^3 T	5.48×10^2 T	0						
20	47	water	2	1.26×10^{-2} T	5.62×10^{-3} T	0						
20	80	water	2	3.99 T	1.78 T	0						
20	44	water	2	2.84 T	1.27 T	0						
20	88	water	2	1.29 T	5.75 T	0						
20	14	water	2	1.26×10^{-2} T	5.62×10^{-3} T	0						
22	00	water	2	3.93×10^3 T	1.75×10^3 T	0						
23	69	land	3	8.88×10^4 T	3.96×10^4 T	0						
20	78	water	1	4.34×10^4 T	1.935×10^4 T	0						

CAPITAL EXPENDITURES AND MATERIALS REQUIREMENTS SUMMARY REPORTING FORM

TECHNOLOGY	Cogeneration	REGIONAL APPLICABILITY OF DATA:	
APPLICATION	Fluidized Bed	NATIONAL:	X
DATE SUBMITTED	8 August 1978	FEDERAL REGION NOS	all
SUBMITTED BY	LBL	STATES:	all

	$1977	DEFLATOR	$1972
A. CAPITAL COSTS			
1. MATERIALS	5,616.400	1.43	3,927,550
2. TRANSPORTATION	443,700	1.43	310,280
3. CONSTRUCTION LABOR	4,588,000	1.43	3,208,400
4. PROFIT & OVERHEAD	828,500	1.43	579,370
A.1 TOTAL	11,476,600	1.43	8,025,590

B. ANNUAL SYSTEM 10^{12} BTU OUTPUT	0.726(10^{12} Btu/yr)[1]
C. ANNUAL SYSTEM FOSSIL FUEL EQUIVALENT/10^{12} BTU OUTPUT	1.43
D. TOTAL CAPITAL COST/10^{12} ANNUAL BTU $\left[\frac{A.1}{B}\right]$	11,054,540
E. NUMBER OF YEARS TO CONSTRUCT FACILITY	2

F. PHASING OF CONSTRUCTION COSTS ($ EACH YEAR):

YEAR	1	2	3	4	5	6	7	8	9	10
%	50	50								

G. EXPECTED LIFE OF FACILITY (YEARS)	40
H. MAN YEARS TO CONSTRUCT FACILITY	173
I. MAN YEARS/10^{12} BTU ANNUAL OUTPUT $\left[\frac{H}{B}\right]$	238
J. ESTIMATED LAND USE	0

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[1] See Appendix I or Application Section for details on product mix and fossil fuel equivalence

TECHNOLOGY CAPITAL COSTS: WORK SHEET

TECHNOLOGY: Cogeneration APPLICATION: Fluidized Bed DATE: 8 August 1978

Expenditures			(4) Total Cost 1977 $×$10^3$	Inforum Sector Designation			(8) Fraction of Total Cost[d]×100	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			439.0	3441	Other Structured Prod.	104	3.83	assumed		0
			240.7	3564	Pump, Compressor	119	2.10	equal to		1
			1040.0	331	Steel	91	9.07	one for all		1
			139.0	3494, 3495	Pipes, valves, fittings,	109	1.21	year through		1
			335.0	3433	Plumbing & Heating	102	2.92			1
			44.0	3821	Mech.Measuring Dev.	157	0.38	2000		0
			196.0	3561	Pumps, Compressors	119	1.71			1
			60.0	3569	Industrial Pattern	122	0.52			1
			1681.0	3511	Engines & Turbine	111	14.65			1
			85.3	3443	Boiler shop	103	0.74			1
			46.0	3273	Cement, Concrete, Gypson	89	0.40			0
			11.0	3536	Material Handling Equipment	114	0.096			0
			169.3	3444	Other structural prod.	104	1.74			1
			83.0	3821	Mech. measuring Dev.	157	0.72			1
			86.0	3612	Transformer Switches	130	0.75			1
			82.0	3613	Transformer Switches	130	0.71			1

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

(1) 1 = yes, 2 = no Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual BTU output are contained in the list of side equations.

TECHNOLOGY CAPITAL COSTS: WORK SHEET

TECHNOLOGY: Congeneration APPLICATION: Fluidized Bed DATE: 8 August 1978

Expenditures			(4) Total Cost 1977$x10	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			20.3	3532	Const. Mining, mech	113	0.18			0
			413.8	3555	Special Ind. machine	118	3.61			1
			65.0	3622	Indus. Controls	132	0.57			1
			3.0	3621	Motor & Gen	131	0.026			1
			80.0	3273	Cement, Concrete	89	0.70			0
			8.0	1794	New Construction	19	0.07			0
			230.0	3498	Pipes, Valves	109	2.00			1
			13.0	3292	other stone, clay glass	90	0.11			0
			46.0	1621	New Construction	19	0.40			0
Total Equipment			5616.4							
			443.7	-	Trucking	169	3.87			0
	352,900 hrs.	@ 13.00	2072.	-	Labor	19	18.02			0
			621.3	OH (wages)	New Construction	19	5.41			0
			207.2	OH (other)	New Construction	19	1.81			0
			2516.0	-	Architect & Eng.	19	21.70			0
	Total	Cost	11,476.6				100.02			

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

TECHNOLOGY CAPITAL COSTS: WORK SHEET / ANNUAL COSTS 1 of 1

TECHNOLOGY: Cogeneration APPLICATION: Fluidized Bed Combustion DATE: 21 September 1978

Expenditures			(4)	Inforum Sector Designation			(8)	(9)	(10)	(11)
(1) Category[a]	(2) Quantity & Units	(3) Price[b]	Total Cost 1976$ x 10^3	(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #	Fraction of Total Cost[d] %	Scale Factors And Year Applicable	Footnotes	Recycle[e]
			0	2431	Millwork - wood	46	0	Assumed		0
			5	281	Indus. Chem.	64	0.53	Equal to 1		0
			1	321	Glass	86	0.11	For all Costs		0
			1	3293	Other stone & Clay	90	0.11			0
			30	331	Iron and steel	91	3.15			1
			1	3339	Non-Ferrous metal	96	0.11			1
			20	3441 3443	Fabricated Structural	104	2.10			0
			50	3499	Fabricated Metal	110	5.25			1
			10	3494	Pipes, valves, Fittings	109	1.05			1
			2	3569	Gen. Indus. Equip.	122	0.21			1
			20	3434, 3435	Material handling Equipment	114	2.10			1
			5	3561	Pump, comp., blower	119	0.53			1
			4	3622	Control Equip.	132	0.42			0
			20	3670	Electrical Equip.	139	2.10			0
			13	9433	Trucking	169	1.37			0
			550	-	Labor	20	57.76			0
			165	-	Overhead (wages)	20	17.33			0
			55	-	Overhead (other)	20	5.78			0
		Total Cost	952				100.01			0

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding. (e) 1 = yes, 2 = no. Items not recycled may be considered to be operational residuals.

Attachment (1)

Residuals Data Sheet

Technology Cogeneration
Application Fluidized Bed
Date Submitted 8 August 1978
Submitted by Lawrence Berkeley Lab

Level of Regionalization:
National yes
Federal all
State all
Code # ______ [Non Regional
Code # ______ Code Taxonomy]

Residual Category/ Component	Taxonomy 4 digit #	Medium of Transport	Hardness	Gross Residuals per 10^{12} BTU end-use Energy	Gross Residuals 10^{12} BTU Input	Abatement Removal Efficiency	$ Abatement/10^{12} BTU		Secondary Residuals		Secondary Residual Coordinates	Footnotes
							Capital	Operating	Residual Category/ Component	4 digit Taxonomy		
02	00	air	3	94	37.6							1
03	00	air	3	68	27.2							2
01	00	air	3	250	100							1,3,4,
23	07	land	3	3500	1400							1
02	00	land	3	5800	2320							1
23	09	land	3	4.2 acre ft	1.68 acre ft							2,3
27	00	land	3	4750	1900							

1. Yaverbaum, Lee, FBC of Coal and Waste Materials NOYES, Park Ridge, N.J., 1977, p.144.
2. Ibid., p. 107.
3. Reigel, S.A., Bundy; "Why the Swing to Baghouses" Power, 121,(1):68,Jan.1977.
4. Noll, K. et al. Air Pollution Control and Industrial Energy Production, Ann Arbor, Ann Arbor Science, 1975.
5. Output is 55% steam and 45% electric power.

CAPITAL EXPENDITURES AND MATERIALS REQUIREMENTS
SUMMARY REPORTING FORM

TECHNOLOGY Cogeneration

APPLICATION Diesel

DATE SUBMITTED 8 August 1978

SUBMITTED BY LBL

REGIONAL APPLICABILITY OF DATA:

NATIONAL: X

FEDERAL REGION NOS. all

STATES: all

		$1977	DEFLATOR	$1972
A.	CAPITAL COSTS			
	1. MATERIALS	5,359,100	1.28	4,186,800
	2. TRANSPORTATION	418,000	1.28	326,560
	3. CONSTRUCTION LABOR	1,656,500	1.28	1,294,140
	4. PROFIT & OVERHEAD	600,000	1.28	468,750
A.1	TOTAL	8,033,600	1.28	6,276,250

B.	ANNUAL SYSTEM 10^{12} BTU OUTPUT	0.544 (10^{12}BTU/yr) *1
C.	ANNUAL SYSTEM FOSSIL FUEL EQUIVALENT/10^{12} BTU OUTPUT	1.207 (10^{12}BTU/yr)
D.	TOTAL CAPITAL COST/10^{12} ANNUAL BTU $\left[\frac{A.1}{B}\right]$	11,537,225
E.	NUMBER OF YEARS TO CONSTRUCT FACILITY	1

F. PHASING OF CONSTRUCTION COSTS ($ EACH YEAR):

YEAR	1	2	3	4	5	6	7	8	9	10
%	100									

G.	EXPECTED LIFE OF FACILITY (YEARS)	20
H.	MAN YEARS TO CONSTRUCT FACILITY	60.5
I.	MAN YEARS/10^{12} BTU ANNUAL OUTPUT $\left[\frac{H}{B}\right]$	111.21
J.	ESTIMATED LAND USE	0

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[1] See Appendix I for details on product mix and fossil fuel equivating calculations

TECHNOLOGY CAPITAL COSTS: WORK SHEET

TECHNOLOGY: Cogeneration APPLICATION: Diesel DATE: 8 August, 1978

Expenditures			(4) Total Cost 1977$ $\times 10^3$	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			3530.1	3510	Engine & Turbine	111	43.94			1
			243.0	3621	Motors & Generator	131	3.02			1
			151.2	3443	Boiler	103	1.88			1
			126.0	3480	Misc Fab Wire	108	1.57			0
			591.9	3494	Pipes, Valve, Fitting	109	7.37			1
			46.9	3622	Indu. Control Eqpt	132	0.58			1
			40.0	3611	Mech. Measuring	129	0.48			0
			630	3444	Other structural	104	7.84			1
			418.0	-	Trucking	169	5.20			0
	123,460 hr	12.15/hr	1500.0	-	Labor	-	18.69			0
			450.0	OH (wage)	New Construction	19	5.60			0
			150.0	OH (other)	New Construction	19	1.87			0
			156.5	8911	Architect & Engr	19	1.95			0
			8033.6				99.99			

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

Attachment (B)

Residuals Data Sheet

Technology Cogeneration
Application Diesel Engine
Date Submitted 8 Aug. 1978
Submitted by Lawrence Berkeley Lab

Level of Regionalization:
National x
Federal all
State all
Code # ________ [Use Regional
Code # ________ Code Taxonomy]

Residual Category/ Component	Taxonomy 4 digit #	Medium of Transport	Hardness	Gross Residuals per 10^{12} BTU end-use Energy	Gross Residuals 10^{12} BTU Input	Abatement Removal Efficiency	$ Abatement/10^{12} BTU		Secondary Residuals		Secondary Residual Coefficient	Footnotes
							Capital	Operating	Residual Category/ Component	4 digit Taxonomy		
01	00	air	3	50	91.9							1
23	07	land	3	950	1746.3							
02	00	air	3	0.014	0.026							1
03	00	air	3	1600	2941.2	40%	$8E4		27	00	2.3	2
04	00	air	3	545	1001.8							1
27	00	land	3	0.663	1.22							

1. From EPA, Air Pollution Emission Factors, AP-42.
2. Thomson, S.J. and Crow, "Energy Costs of NOX Control" Hydrocarbon Processing, May 1976

CAPITAL EXPENDITURES AND MATERIALS REQUIREMENTS
SUMMARY REPORTING FORM

TECHNOLOGY Cogeneration

APPLICATION Enhanced Oil Recovery

DATE SUBMITTED 8 August 1978

SUBMITTED BY LBL

REGIONAL APPLICABILITY OF DATA:

NATIONAL: X

FEDERAL REGION NOS. all

STATES: all

A. CAPITAL COSTS	$1977	DEFLATOR	$1972
1. MATERIALS	188,005,000	1.43	131,472,000
2. TRANSPORTATION	14,600,000	1.43	10,209,800
3. CONSTRUCTION LABOR	108,910,000	1.43	76,161,000
4. PROFIT & OVERHEAD	39,540,000	1.43	27,650,000
A.1 TOTAL	351,115,000	1.43	245,534,800

B. ANNUAL SYSTEM 10^{12} BTU OUTPUT 15 (10^{12} BTU/yr)

C. ANNUAL SYSTEM FOSSIL FUEL EQUIVALENT/10^{12} BTU OUTPUT 25 (10^{12} BTU/yr)

D. TOTAL CAPITAL COST/10^{12} ANNUAL BTU $\left[\frac{A.1}{B}\right]$ 16,369,000

E. NUMBER OF YEARS TO CONSTRUCT FACILITY 4

F. PHASING OF CONSTRUCTION COSTS ($ EACH YEAR):

YEAR	1	2	3	4	5	6	7	8	9	10
%	25	25	25	25						

G. EXPECTED LIFE OF FACILITY (YEARS) 20 years

H. MAN YEARS TO CONSTRUCT FACILITY 3730 years

I. MAN YEARS/10^{12} BTU ANNUAL OUTPUT $\left[\frac{H}{B}\right]$ 248.5 years

J. ESTIMATED LAND USE 8 acres

TECHNOLOGY CAPITAL COSTS: WORK SHEET

1 of 3

TECHNOLOGY: Cogeneration APPLICATION: Enhanced Oil Recovery DATE: 8 August 1978

Expenditures			(4) Total Cost 1977$×10^3	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			1170	2432	Veneer & Plywood	45	0.33	assumed		0
			2360	2431, 2433	Millwork & Wood	46	0.67	equal to		0
			5495	281	Industrial Chem	64	1.57	one for all		0
			3990	299	Petroleum Refin.	76	1.14	years		0
			4320	3272	Cement, Concrete Gypsum	89	1.23	through		0
			75	321	Glass	86	0.021	2000		0
			1780	3293	Other Stone, Clay, Glass	90	0.51			0
			41,200	331,332	Steel	91	11.73			1
			410	3331	Copper	92	0.12			1
			180	3334	Aluminum	95	0.051			1
			500	3339	other non-ferrous	96	0.14			1
			25,700	3443, 3444	Fabricated Structural	104	7.32			1
			15,800	3494, 3498	Pipe, Valve, Fittings	109	4.50			1
			17,145	3441	Other Structural	104	4.88			1
			1040	3450	Machine Products	105	0.30			1
			12,430	-	Other misc. Mat.	110	3.54			0
			30,000	3511	Engines & Tubine	111	8.54			1

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

TECHNOLOGY CAPITAL COSTS: WORK SHEET

2 Of 3

TECHNOLOGY: Cogeneration APPLICATION: Enhanced Oil REcovery DATE: 8 August 1978

Expenditures			(4) Total Cost 1977$×10³	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			2000	3434 3435	Materials Handling Machine	114	0.57			1
			3100	3820	Mechanical Measuring	157	0.88			1
			230	3541	Machine Tools, Cutter	116	0.066			0
			230	3542	Machine Tools, Form	117	0.066			1
			2300	3623	Welding Apparatus	133	0.65			0
			6250	3621	Motors & Gen.	131	1.78			1
			8630	3561	Pumps, Compressor Blower	119	2.46			1
			775	3567 3569	Industrial Pattern	122	0.22			1
			50	3569	Gen. Ind. Mach.	122	0.014			1
			845	3999	Misc. Manufacture	166	0.24			0
			188,005							
			14,660		Trucking	169	4.18			0

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

TECHNOLOGY CAPITAL COSTS: WORK SHEET

3 of 3

TECHNOLOGY: Cogeneration APPLICATION: Enhansed Oil Recovery DATE: 8 August, 1978

Expenditures			(4) Total Cost 1977$×$10^3$	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
Labor	7,603,850 hr	13.00	98,850	-	-	19	28.15			0
Mngmnt & Service			10,060	-	New Construction	19	2.87			0
OH (Wages)			29,655	-	New Construction	19	8.45			0
OH (Other			9,885	-	New Construction	19	2.82			0
			351,115				100.01			
Land			5,150	-	-	-				

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

TECHNOLOGY CAPITAL COSTS: WORK SHEET / ANNUAL COSTS

1 of 2

TECHNOLOGY: Cogeneration APPLICATION: Enhanced Oil Recovery DATE: 21 September 1978

Expenditures			(4) Total Cost 1976 $x1	Inforum Sector Designation			(8) Fraction of Total Cost[d] (%)	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[e]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			740	2431	Millwork - wood	46	0.32	Assumed Equal to 1 For all Costs		0
			18,000	281	Industrial Chem.	64	7.77			0
			150	321	Glass	86	0.07			0
			950	3293	Other stone, clay	90	0.41			0
			10,100	331,332	Iron and steel	91	4.36			1
			16,600	3339	Non-Ferrous metal	96	7.17			1
			200	3441 3443	Fabricated Structural Mat'ls.	104	0.09			0
			25,400	3449	Fabricated metal N.E.C.	110	10.97			1
			12,200	3494	Pipes, valves, fitting	109	5.27			1
			10,600	3569	Gen. Indus.Equipt.	122	4.58			1
			1,700	3434 3435	Material handling Equipment	114	0.73			1
			1,600	3561	Pump, compressor, Blower	119	0.69			1
			2,700	3622	Control equipment	132	1.17			0

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding. (e) 1 = yes, 2 = no. Items not recycled may be considered to be operational residuals.

TECHNOLOGY CAPITAL COSTS: WORK SHEET/ANNUAL COSTS

TECHNOLOGY: Cogenerator APPLICATION: Enhanced Oil Recovery DATE: 21 September 1978

Expenditures			(4) Total Cost 197 \$x10^3	Inforum Sector Designation			(8) Fraction of Total Cost[d] %	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[e]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			21,100	3670	Electrical Equip.	139	9.12			0
Material	& Equipment	Sub-Total	122,040							
			9,520	9433	Trucking	169	4.11			0
			71,400	-	Labor	20	30.84			0
			21,420	-	Overhead (wages)	20	9.25			0
			7,140	-	Overhead (Other)	20	3.08			0
							100.00			
	Total	Cost	231,520							

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding. (e) 1 = yes, 2 = no. Items not recycled may be considered to be operational residuals.

Attachment (2)

Residuals Data Sheet

Technology Cogeneration
Application Enhanced Oil Recovery
Date Submitted 15 July 1978
Submitted by Lawrence Berkeley Lab

Level of Regionalization:
National
Federal 9
State California
Code #
Code # [Use Regional Code Taxonomy]

Residual Category/ Component	Taxonomy 4 digit #	Medium of Transport	Hardness	Gross Residuals per 10^{12} BTU end-use Energy	Gross Residuals 10^{12} BTU Input	Abatement Removal Efficiency	$ Abatement/10^{12} BTU		Secondary Residuals		Secondary Residual Quantities	Footnotes
							Capital	Operating	Residual Category/ Component	4 digit Taxonomy		
Gas Turbine												
03	00	air	2	70.0	28.	40%	$\$3.5 \times 10^9$	$\$5 \times 10^4$	27	00	2.3	7,8
04	00	air	2	7.1	2.84							7
05	00	air	2	19.0	7.6							7
01	00	air	2	0.12	0.048							7
02	00	air	2	4.8	1.92							7
23	07	land	3	2.28	0.91							

7. Air Emissions from the combustion turbine are for natural gas combustion and were obtained from Air Pollution Emission Factors, EPA publication #AP-42. Note that the energy output used in this calculation includes the oil marketed which does not get burned in the turbine.

8. Balzhiser, Richard, "R&D Status Report: NO_x Control Technology" EPRI Journal, 2(X3): 43, April 1977.

APPENDIX B

CHARACTERIZATION OF MUNICIPAL SOLID WASTE (MSW) AND MSW CONVERSION TECHNOLOGIES

The concept of MSW energy and resource recovery was presented in the Introduction section of this report. This appendix will characterize the input municipal solid waste, will briefly contrast energy and resource recovery with landfill systems, and will expand on the description of general MSW recovery systems provided in the Introduction section.

Conceptual Comparison of Landfill and Recovery

Approximately 600,000 tons of solid wastes are generated daily within commercial, residential and industrial sectors in the United States. By the most common current practices, these wastes are collected at the site of generation by two- and four-ton trucks, hauled to a central transfer station, compacted, loaded on to large (10-ton) transfer trucks and hauled to a landfill site. National average costs for this type of operation range from \$4 to \$8 per ton and may be approximated by the following regression equation (Nuss *et al*., 1975):

$$C_{LF} = 2.35 + Q96(L)$$

where

C_{LF} = cost of collecting and landfilling one ton of MSW

2.35 = national average haul cost (includes collection, transfer and haul)

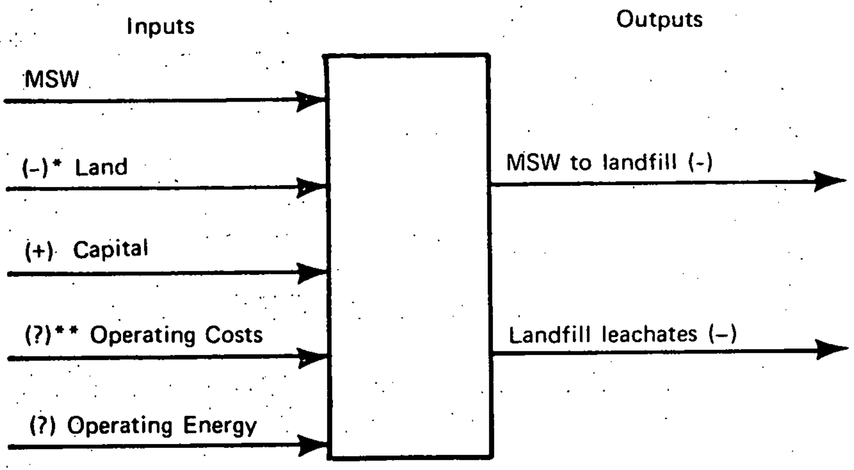
L = landfill land costs (\$1000/acre)

In addition to variations in land costs, C_{LF} varies significantly as a function of the deviation of haul costs from the national norm. For example, in San Francisco, California, where both land costs are high and haul distances are long (approximately 30 miles), the actual haul cost is approximately \$10 per ton and the total cost is approximately \$16 per ton (California Solid Waste Management Board, 1977). In many locations waste incineration is added to this process before the haul to a landfill as a weight and volume reduction measure.

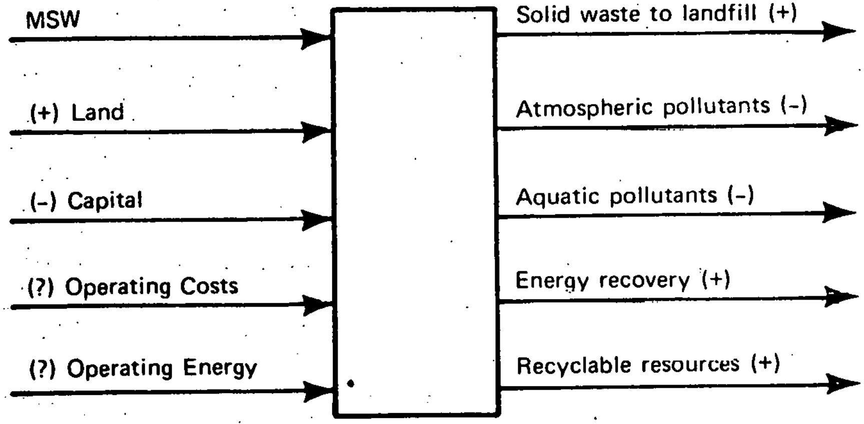
As a alternative to direct landfill disposal, a variety of resource recovery schemes are currently being investigated. In general these schemes convert a certain portion of the solid waste stream combined with varying amounts of additional input energy into usable energy or energy fuel, basic recoverable resources, an air pollution stream, a water pollution stream, and a substantially reduced solid waste stream. While resource recovery processes can recover energy resources and valuable recyclable resources (iron, aluminum, glass and paper) and do substantially reduce landfill requirements, they also generate these pollutant flows released into the atmosphere and into municipal water systems. General schematic diagrams for a landfill system and for an energy and resource recovery system are shown in Figure B-1. This figure shows the basic categories of inputs and outputs associated with each system and qualitatively compares them. A positive rating (+) indicates that the use of or generation of that category on that system is preferable (provides a net benefit) relative to the other system. As is evident, energy and resource recovery systems provide significant benefits by producing energy and recyclable materials and by reducing landfill operations and land requirements for landfill. However, several significant additional costs are also incurred. Aquatic and atmospheric pollutants are generated and large initial capital investments are required.

In addition to the qualitative systemic comparison shown in Figure B-1, a determination to shift from landfill to a resource recovery system involves a wide spectrum of technical, engineering, social and institutional issues not depicted in Figure B-1. As examples, these include the state-of-the-art of the various technologies (will it work?), the question of public or private ownership and operation, the financing and marketing of the facility and its products, and the municipal organization required to adequately support and promote the facility. To emphasize the last issue, Bartolatta (1975) stated that the principal difference between resource recovery facilities and other municipal facilities and operations is the unique organization required to finance and operate the facility and competitively market the products.

A. Landfill System



B. Energy and Resource Recovery System



*(-) indicates a less desirable parameter value than with the opposing. Thus, land is (-) for landfill systems as more land is required for these systems than for Resource Recovery Systems.

**(?) indicates that neither system has a clear, consistent advantage.

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Fig. B-1. Systemic Schematics for a Landfill and for a Resource Recovery System

Thus the shift toward energy and resource recovery systems involves complex, long-term economic analysis, environmental tradeoff analyses, institutional adjustments, and risk analyses both for the new emerging technologies, for future MSW supply and composition, and for future product market conditions. While the local importance of one factor in this analysis (such as stringent atmospheric discharge standards or a lack of available land for landfills) may dominate the decision making considerations between these two general types of solid waste disposal systems in some communities, for many others the many individual costs and benefits associated with resource recovery systems must each be addressed and analyzed.

Characterization of Municipal Solid Waste

Municipal Solid Waste is that waste collected on a routine basis from the residential and commercial sectors within a populated area. In general MSW does not include either industrial solid wastes or agricultural solid wastes as these are typically segregated from residential and commercial wastes through a separate collection and processing system (Kaiser, 1967; West Virginia University, 1976). It should also be noted that at the rates of production considered for energy recovery, MSW is a product of urban rather than rural areas.

A large number of studies have analyzed the rate of production and composition of urban residential and commercial wastes for individual communities. The rate of production of MSW, as characterized by these studies, varies from a low of 2.75 to 3 pounds per day per person (Stephens, 1925; Golueke and McGaukey, 1976) to a high of 4.5 to 5 pounds per day per person (Wilson, 1971; Mathematical Sciences Northwest, 1974; Levy, 1975). To approximate the mean of all studies, a value of four pounds per person per day, is used which can act as a good "ballpark" rate of production for planning purposes. Several studies (e.g. Quimby, 1975 or Golueke and McGanhey. 1976) have suggested MSW production rates have increased over time on a per capita basis. However, this increase is slight and is not included here.

The composition of MSW has also been well studied and is of greater importance than the rate of production for energy and resource recovery. Table B-1 shows the composition of MSW by major material components as reported by the indicated selected studies. Several of the annual average percentage values shown in Table B-1 (e.g. yard wastes) are, in fact, highly variable over a one-year period. The high variance in percent composition of paper goods results, in part, from source separation of paper goods practiced in some but not all communities. Table B-2 shows the basic chemical composition of MSW reported for the same general group of studies. Of particular interest to this study is the energy content of MSW. The mean energy content of MSW in the reported studies is 9.08×10^6 Btu/ton. The variance between any specific sample and this mean value can be significantly higher than that shown in Table B-2 as Table B-2 data are on time-averaged values and thus do not reflect either variations over the year or spatial variations (e.g. central city and suburban collections). It should be noted that, while significant between samples were found over time of year and size of community, significant regional variations were not found.

The analysis by Wilson (1971) suggests that the methods used to calculate heat content tend to significantly underestimate actual heat content and that values of 1.4×10^7 Btu to 1.8×10^7 Btu per ton are more accurate. The use of approximately 9×10^6 Btu/ton as a mean MSW heat content would then represent a somewhat conservative estimate of heat input and thus an overestimate of overall system efficiency. However, the preponderance of available information suggests that 9×10^6 Btu/ton to 9.1×10^6 Btu/ton is as reasonable an estimate as can be made.

The nomographs shown in Figure B-2 provide a simple means of assesing the impact of the use of average rates of production and MSW energy content (or of actual local variations from these means) on the total energy supplied to the MSW energy recovery process. Starting with the lefthand scale of Figure B-2 for the example shown, a generation rate of 4 lb/person/day and a local population of 200,000 are connected with a straight line which is extended to the center scale to determine total local MSW generation rate. This point is then connected with the assumed

Table B-1
MSW Material Components from Various Studies

Source	Year Analyzed	Paper	Glass	Metal Total	(Ferrous Metal)	(Aluminum)	(Other)	Plastic	Rubber and Leather	Textiles	Wood	Food	Wastes	Misc.	Total
US EPA, 1976	1972	31.8	10.1	9.5	(8.5)	(0.7)	(0.3)	3.5	2.6	1.5	3.6	17.0	18.9	1.5	100
US EPA, 1977	1975	30.6	10.5	9.6	(8.5)	(0.8)	(0.3)	4.1	2.7	1.5	3.7	16.7	19.1	1.5	100
W. Virgina Univ.	1975	48.0	14.0	8.0				1.1	0.9	1.0	2.0	16.0	9.0		100
CA State Solid Waste Board, 1976	Average	46.0	9.6	7.5	(6.0)	(1.0)	(0.5)	2.1	2.1	2.1	4.2	6.4	20.0		100
CA State Solid Waste, Mgmt. Board, 1977	Average	33.0	10.0	9.5	(8.0)	(0.8)	(0.5)	3.5	4.0	2.0	4.0	14.5	17.5	2.0	100
Preston, 1975	1974-75	41.5	7.6	8.1	(7.0)	(0.7)	(0.4)	2.3	2.5	1.1	2.0	14.0	19.1	1.8	100
Levy, 1975	Average	35.5	8.2	13.4	(12.0)	(1.0)	(0.4)	2.2	2.9	1.8	2.0	14.5	18.5	1.0	100
Sussman, 1974	Average	38.0	10.0	10.0	(8.0)	(1.0)	(1.0)	4.0	3.0	2.0	4.0	14.0	14.0	1.0	100
Kaiser, 1967	Average	41.9	10.3	8.3				3.1	0.9	2.6	3.1	12.2	17.5		100
Cho, 1975	1972-74	44.9	13.05	12.9				4.1	1.2	3.2	2.2	10.9	6.45	1.1	100
Livingston, 1976	Average	38.0	10.0	10.0	(8.0)	(1.0)	(1.0)	4.0	3.0	2.0	4.0	14.0	14.0	1.0	100
US EPA, 1976a	Average	34.9	10.5	9.8	(8.6)	(0.8)	(0.4)	3.8	2.6	1.7	3.8	14.9	16.3	1.6	100
Lawler, 1975	Average	43.0	8.0	8.5	(7.0)	(1.0)	(0.5)	2.0	2.0	2.0	3.0	15.0	13.0	3.5	100
Schnelle and Yamamoto, 1975	Average	44.2	8.5	8.7				1.8	1.1	2.3	2.5	16.6	12.6	1.7	100
Mean		39.41	10.02	9.55	(8.16)	(0.88)	(0.53)	2.96	2.25	1.91	3.14	14.05	15.43	1.29	
Standard Deviation		5.61	1.78	1.72	1.58	0.13	0.26	1.02	0.93	0.57	0.86	2.77	4.10	0.90	

Table B-2

MSW Chemical Composition from Various Studies

Source	Btu Per Ton (10^6)	Organics	Moisture	Ash	Glass	Al	Fe	S	N	O	C	H
W. Virginia, 1976	9.2											
Sessler & Cuha, 1975	9.1		25.0	8.5	8.0	0.4	6.0	0.1	0.4	24.0	24.4	3.2
Preston, 1975	9.5	52.0	25.0									
Levy, 1975	9.2	52.0	25.0									
Sussman, 1974		53.0	21.0	9.0	8.0		7.0	0.3	0.7	24.0	25.0	3.0
Kaiser, 1967	8.2		33.0	12.6		1.0	8.4	0.08	0.5	18.0	22.0	2.9
Cho, 1975	8.8		25.5	6.0	12.1	0.8	7.9	0.1	0.5	18.9	24.7	3.3
Livingston, 1976	9.5		21.0	10.0	9.0	0.5	6.5	0.3	0.7	24.0	25.0	3.0
Schenelle & Yamamoto, 1975	9.4		25.0		9.0	1.0		0.1	0.58	22.08	26.18	3.51
Mean	9.08	52.5	24.57	9.22	9.28	0.72	7.06	0.17	0.56	21.40	24.38	3.08
Standard Deviation	0.59	0.58	4.00	2.40	1.94	0.27	0.11	1.13	3.06	1.26	1.26	0.16
Variance	0.22	0.25	13.74	4.59	2.83	0.06	0.78	0.61	0.01	7.47	1.28	0.02

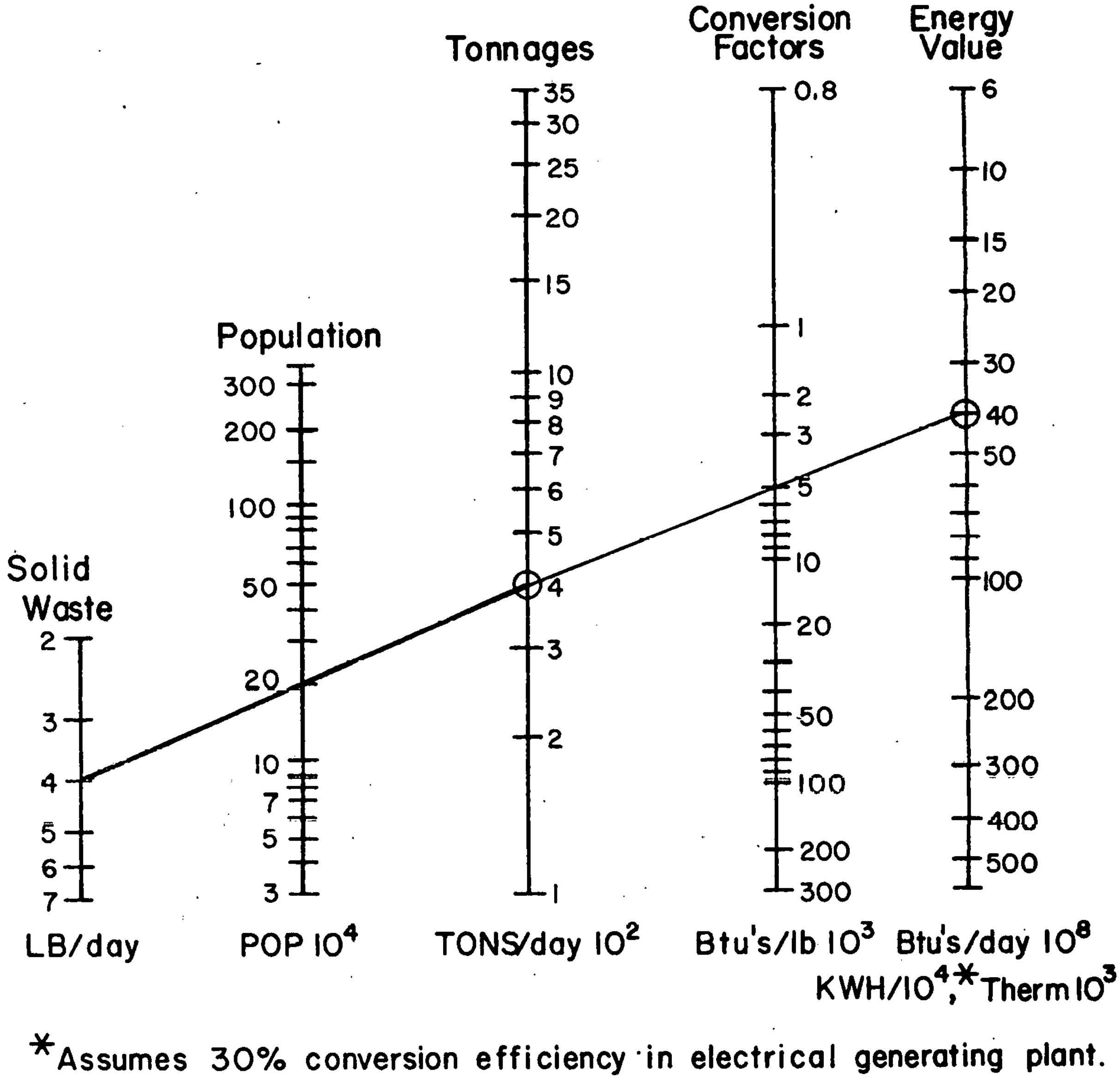

Fig. B-2. Nomograph for Calculation of Total Energy Value of MSW (from California State Solid Waste Management Board, 1976) heat content (5 x 10^3 Btu/lb or 10 x 10^6 Btu/ton as used in this example) and extended to the far right scale to find total heat content of the MSW in Btu/day.

General Characterization of MSW Energy Recovery Systems

All of the MSW energy recovery systems which are addressed in this study follow the general schematic shown in Figure B-3. As used here, front end systems are those involved with the preparation of MSW for an actual recovery process (energy recovery or resource recovery), while rear end systems perform the transformation of MSW into an energy product. Conversion systems are used to convert a basic energy product into some other energy end use form. It is generally true that the selection of a given process or set of processes within one box on Figure B-3 does not restrict the choice of processes in subsequent boxes. Thus, a wide variety of specific facility designs are possible with each being tailored to local characteristics and requirements.

Figure B-4 shows the general Resource Recovery Module in greater detail. The processes and products listed on Figure B-4 are typical of most MSW resource recovery systems and are used in this study as a standard design for all energy recovery systems. The selection of specific components for this module does not affect the outcome of the energy recovery systems except by varying facility total capital requirements and operational auxilliary energy requirements. This resource recovery system does not include paper recovery nor is it based on a analysis to maximize profitability or to ensure net energy efficiency of the recovered material. Rather, this portion of the total MSW recovery system is based on the most common on-line technology in U.S. plants.

Table B-3 lists the major categories of residuals associated with the operation of one or more of the MSW energy recovery systems. Not all pollutant flows listed on Table B-3 are produced by each MSW energy recovery technology. However, the potential for this spectra of residuals should be systematically assessed for each step within an MSW recovery process.

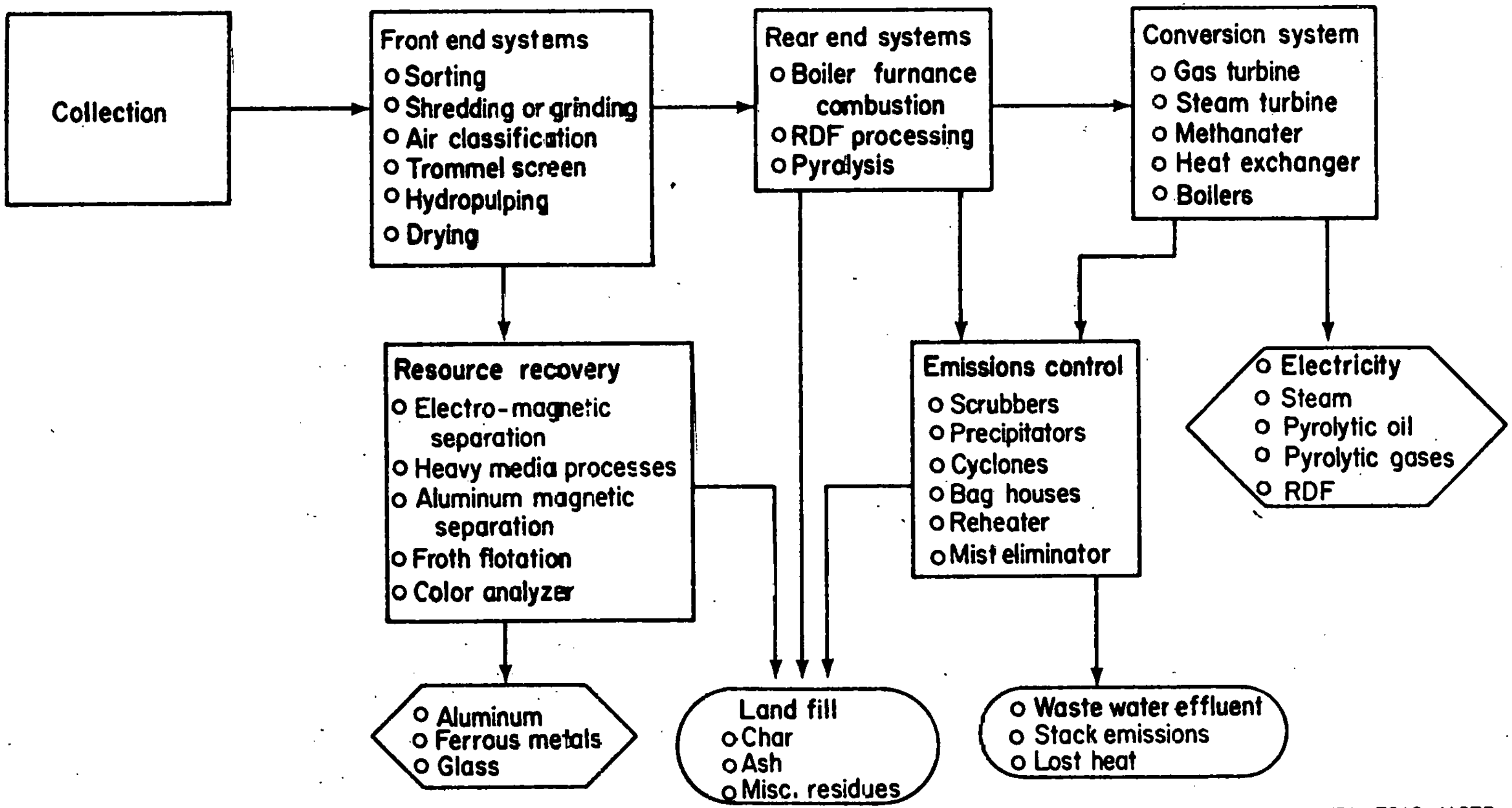

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Fig. B-3. Municipal Solid Waste Resource Recovery

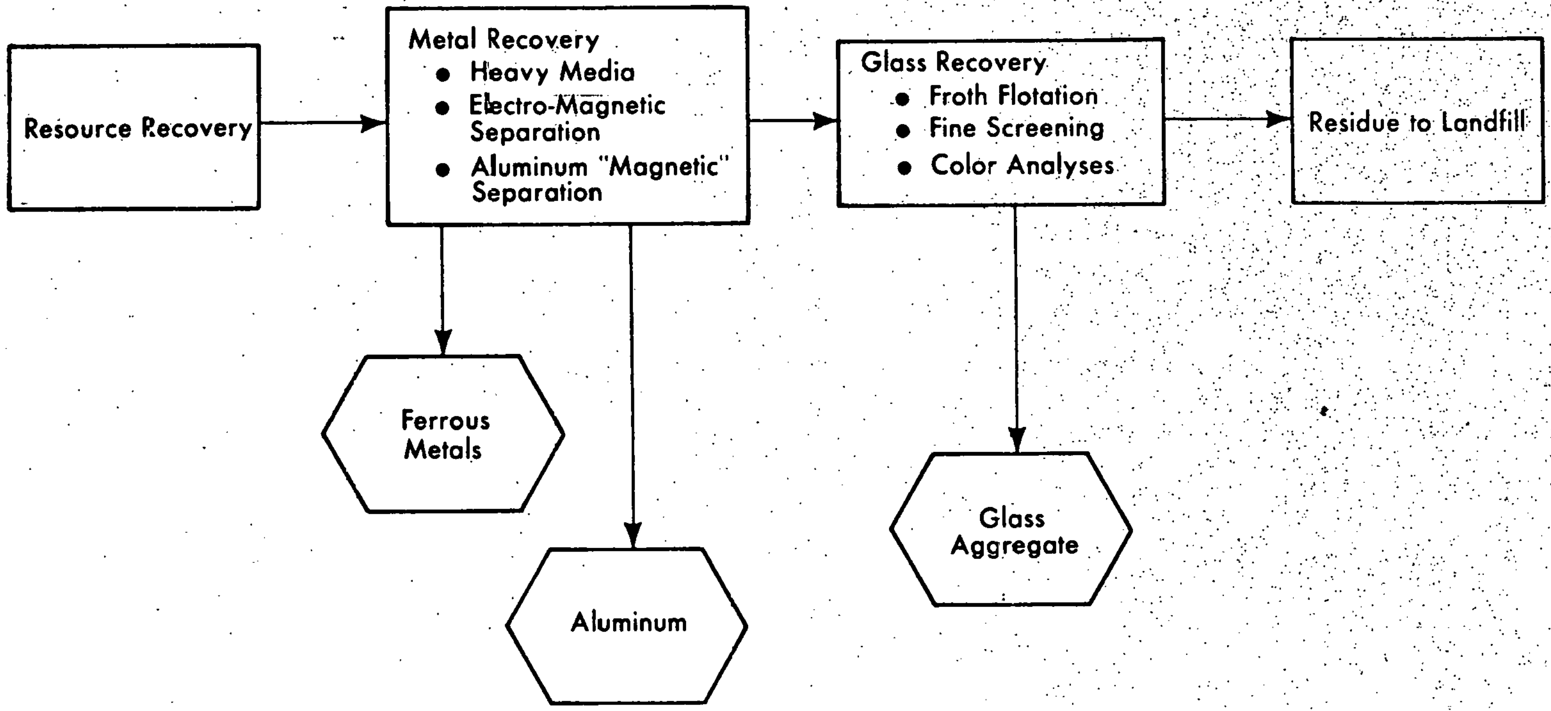

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Fig. B-4. Resource Recovery Module

Table B-3

Major Residuals Generated by a Municipal Solid Waste Processing Facility[1]

Emissions to air	Discharges to water	Residuals to land
NO_x and SO_x	Suspended solids	Metals
HCl	Ash	Inorganics
H_2S	Trace metals and salts	Nondecomposed organics
NH_3	Organics	Bacteria, virus
Particulates	Acids	
Fly ash		
Bacteria, virus		
Trace metals		
Noise and dust		
Organic components (phenols, halides, aldehydes, and unknown organics)		

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[1] From Aerospace Corp., 1975 and 1976.

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APPENDIX C

CURRENT STATUS OF MSW ACTIVITY

This appendix contains three tables which depict various aspects of the present level of national activity in municipal solid waste energy recovery. Table C-1 lists existing MSW energy recovery plants, those which have operated but are not now operational, and future plants for which firm commitments have been made. Table C-2 lists U.S. private companies and public sector agencies involved in the design, research construction or operation of MSW energy recovery facilities. Table C-3 lists existing funded research activity in MSW energy recovery by source of funding. Finally, Table C-4 lists system conversion efficiencies for existing MSW energy recovery systems.

Table C-1

Current Operational Activity in MSW Energy and Resource Recovery[1]

1. Direct Combustion						
Location/Developer	Type	Capacity	Products	Start Up Date	Capital Cost (10^3 $)	Comment
Nashville, Tn./TVA	waterwall	760 TPD	steam	Aug. 1976 after system modification	27,000	Engineering & Emission problems forced extensive system modification
Saugus, MA/	waterwall	1200 TPD	steam	Nov. 1975	35,000	-
Chicago (NW), Ill./	waterwall	1600 TPD	steam	1972	30,000	market difficulties with steam, excessive stack emission
Harrisburg, Pa./	waterwall	720 TPD	steam	Oct. 1973	8300	marketing steam as of mid 1976
Norfolk, Va./	waterwall	360 TPD	steam	1976	2135	cost does not include retrofitted ESP
Braintree, Ma./	waterwall	240 TPD	steam	1977 after modification	2300	ESP required to meet EPA emission guidelines
Blytheville, Ark./	modular combustion unit	50 TPD	steam	Nov. 1975		
Chicago (SW), Ill./	refractory wall	1200 TPD	steam	1963		
Groveton, N.H.	modular combustion unit	30 TPD	steam	1975		
Merrick, N.Y.	refractory wall	600 TPD	electricity	1952		

Table C-1 (continued)

Location/Developer	Type	Capacity	Products	Start Up Date	Capital Cost (10^3 $)	Comment
Miami, Fla./	refractory wall	900 TPD	steam	1956		
Oceanside, N.J./	refractory wall/ waterwall	750 TPD	steam	RWI - 1965 WWC - 1974		
Sloan Springs, Ark./	modular combustion unit	20 TPD	steam	Sept. 1975		
Portsmouth, Va./	waterwall combustion	160 TPD	steam	Dec.,1976		
Akron, Ohio/	waterwall combustion	1000 TPD	steam	late 1978 planned		
Haverhill, Mass./	waterwall combustion	3000 TPD	electricity	NA[2]		
Jacksonville, Fla./	modular combustion unit	50 TPD	steam, iron	NA		US Navy plant
Lexington, Ky./	waterwall combustion	1050 TPD	steam, iron	NA		
Mayport, Fla./	refractory wall incinerator	40 TPD	steam	NA		US Navy plant
Minneapolis, Minn./	waterwall combustion	1200 TPD	steam	1980		steam to support papermill operation
New Haven, Conn./	waterwall combustion	1800 TPD	steam, iron	NA		
North Little Rock, Ark./	modular combustion unit	100 TPD	steam	early 1978		

Table C-1 (continued)

Location/Developer	Type	Capacity	Products	Start Up Date	Capital Cost ($\$10^3$)	Comment
Onondaga County, N.Y./	waterwall conbustion	1000 TPD	steam, iron	NA		
Menlo Park, Ca./ Combustion Power Co. (CPU 400)	direct combustion	90 TPD	electricity, glass, ferrous and non-ferrous metals	1976-1977 System testing conducted		Emission control and operational problems when operating with MSW.
US Recycle Corp. (Consumat)/	direct combustion	12-25 TPD modules	steam	---		many now in commercial/ industrial use
Los Angeles, Ca./ Watson Energy Systems	waterwall combustion	1000 TPD	steam	NA		steam to be used in refinery operations. A Awaiting atmospheric emissions permits
Weber, Utah/Clean Air, Inc.	waterwall combustion	300 TPD	steam	1966		
Cuyahoga County, Ohio/	waterwall incineration	1200 TPD	steam, metal	1979	33,000	
2. RDF						
St. Louis, Mo./ Union Elec.	RDF	325 TPD	RDF, ferrous metals, glass	May 72 to 1977	2500	closed due to economic and institutional constraints
Ames, Io./	RDF	200 TPD	electricity, ferrous metal, aluminum	Fall 1975	5600	
Hempstead, N.Y./	RDF fired waterwall	750 TPD	steam, ferrous metal, glass, aluminum	Jan. 1974	6000	

Table C-1 (continued)

Location/Developer	Type	Capacity	Products	Start Up Date	Capital Cost (10^3 $)	Comment
Chicago (Crawford), Ill.	RDF	1000 TPD	RDF, ferrous metals, glass	June 1976	17,500	RDF for use by local utility
Milwaukee, Wi./ American Can Co.	RDF	1000 TPD	RDF, ferrous metal, glass aluminum	Nov. 1976	18,000	
Bridgeport, Conn./ Occidental Research	RDF	1800 TPD	RDF, ferrous metal, glass aluminum	under construction	29,300	
Berlin, Ct./CRRA	RDF	1400 TPD	RDF, ferrous metal, glass aluminum	under construction	22,000	
Wilmington, Del./	RDF	500 TPD	RDF, ferrous metal, glass	NA	25,000	
Baltimore County, Md./	RDF	550 TPD	steam, ferrous metal, glass	1975		steam for use in cement plant
Dade County, Fla./	wet pulp RDF field waterwall incinerator	3000 TPD	steam, ferrous metal, glass aluminum	NA		steam for use by local utility
Monroe County, N.Y./	RDF	2000 TPD	RDF, ferrous metal, glass aluminum	NA		RDF for use by local utility
Bridgewater, Mass./	RDF	160 TPD	RDF, ferrous metal, glass aluminum	1974		ECO-FUEL-11 plant
N. Washington, D.C./	RDF	80TPD	RDF, ferrous metal, glass aluminum	1974		

Table C-1 (continued)

Location/Developer	Type	Capacity	Products	Start Up Date	Capital Cost (10^3 $)	Comment
Albany, N.Y./	RDF	1200 TPD	RDF, ferrous metal, glass	NA		
Central Contra Costa County, Ca./	RDF	1000 TPD	RDF, ferrous metal, glass aluminum	1979		RDF for use in sludge incinerator
Chemung County, N.Y./	RDF	300 TPD	RDF, ferrous metal, glass	NA		
Detroit, Mich./	RDF fired waterwall incinerator	3000 TPD	steam, ferrous metal, glass, aluminum	NA		
Hackensack, N.J./	RDF	2500 TPD	steam, ferrous metal, glass aluminum	NA		
Lane County, Ore./	RDF	750 TPD	elec., ferrous metal, glass aluminum	NA		
Memphis, Tenn./	RDF fired waterwall incinerator	2000 TPD	electricity, Fe, Al, glass	NA		
Montgomery County, Ohio/	RDF	1600 TPD	RDF, Fe, Al, glass	N/A		
Palmer Township, Pa./	RDF	150 TPD	RDF, ferrous metal, glass	NA		for use in cement kiln
Portland, Ore./	RDF	200 TPD	RDF, Fe, glass	NA		
Tacoma, Wash./	RDF	undecided	steam, Fe, al, glass	NA		

Table C-1 (continued)

Location/Developer	Type	Capacity	Products	Start Up Date	Capital Cost (10^3 $)	Comment
New Britton, Conn./ Eco-Fuel II	RDF	undecided	electricity, Fe, Al, glass	NA		
Los Gatos, Ca./ Sira Corp.	RDF	100 TPD	fuel pellets, glass, ferrous and non-ferrous metals	1976		pilot plant undergoing active testing
Akron, Ohio/	RDF	1000 TPD	steam, ferrous and nonferrous metal, glass	start date delayed	25,400	
Brockton, Mass./ Eco-Fuel II	RDF	400 TPD	RDF, ferrous and nonferrous metals, glass	1973	12,000	expanded to 400 TPD in 1977
Madison, Wisc./	RDF	200 TPD	RDF, glass, paper, ferrous and non-ferrous metals	1979		RDF for use in utility boilers
Montgomery County, Md./	RDF	1200 TPD	RDF, glass, ferrous and non-ferrous metals	1979-1980		
New York, N.Y./	RDF	1500 TPD	RDF, glass, ferrous and non-ferrous metals	1980		
Scranton, Pa./	RDF	600 TPD	steam, aluminum, ferrous metals	1980	16,000	
Toledo, Ohio/	RDF	1000 TPD	ferrous metals, RDF, glass	NA		

Table C-1 (continued)

Location/Developer	Type	Capacity	Products	Start Up Date	Capital Cost (10^3 $)	Comment
3. Pyrolysis						
Baltimore, Md./ Monsanto (Landguard System)	gas pyrolysis	1000 TPD	steam, ferrous metal, glass	late 1975 (shakedown)	26,000	numerous system technical problems have delayed start-up
South Charleston, W.V./Union Carbide (Purox System)	gas pyrolysis	200 TPD	fuel gas	1974 (pilot plant)	13,000	
San Diego, Ca./ Occidental Research	flash pyrolysis	200 TPD	pryolytic oil, glass, ferrous & nonferrous metal	late 1976 with 4 month shakedown	14,000	
Seattle, Wash./	pyrolysis	1500 TPD		facility still in planning phase		
Riverside, Ca./ Pyrotek X-50 Pyrolysis System	pyrolysis	approx. 50 TPD	low Btu gas	1977 begin testing		
Irvine, Ca./Deco	pyrolysis	50 TPD	gas, oil, charcoal	1977		test plant only
Erie County, N.Y./ Carborundum (Torrax System)	pyrolysis	75 TPD	steam or low Btu gas	1969-1973		
East Grandby, Conn./ Urban Research & Development	gas pyrolysis	120 TPD	fuel gas	1978		plant used primarily for technology testing
Richland, Wash./ Battelle Northwest Lab	gas pyrolysis	3-5 TPD	pyrolytic gas	1975		test plant only

Table C-1 Footnotes

1. Sources: Weinstein and Toro, 1976; Levy, 1975; Wentworth, 1970; USEPA, 1976 and 1977; California State Solid Waste Management Board, 1976 and 1977; Council on Environmental Quality, 1976 and 1977; McEwan and Levy, 1977.

2. Not Available.

Table C-2

U.S. Companies Currently Active in MSW Energy Recovery System Operation, Manufacturing, or Design[1]

COMPANY	RESOURCE RECOVERY	ENERGY RECOVERY		
		Direct Incineration	RDF	Pyrolysis
All-American Engr. Co.	X			
Allis-Chalmers Corp.	X		X	
American Can Co. (Americology Div.)	X		X	
Automated Disposal Sys.	X	X		
Battelle Pac. Northwestern Lab	X			X
Blach-Dawson Co.	X		X	
Browning-Ferris	X			X
Carborundum Env. System				X
Clear Air, Inc.	X	X		
Combustion Equip. Associates	X		X	
Combustion Power Co.	X	X	X	
Conservation International	X			
Continental Can	X		X	
Devco Mngt.	X			X
Ecologenics, Inc.	X	X		
Engineered Waste Control	X		X	
Environomotrix, Inc.	X			X
Gruneman Ecosystems Corp.	X		X	
Henningson, Durham and Richardson	X		X	
Los Angeles By-Products	X			
Monsanto (Environ-Chem)	X			X
Nashville Thermal Transfer Corp.	X	X		
Ovitron Corp.	X	X		

Table C-2 (continued)

COMPANY	RESOURCE RECOVERY	ENERGY RECOVERY		
		Direct Incineration	RDF	Pyrolysis
Pollution Control, LTD	X			X
Process Systems	X	X		
Pyrotek (X-50 Pyrolysis Systems)	X			X
R and M Associates	X			
Raytheon Corp.	X	X	X	
Research-Cottrell	X		X	
SCA Services, Inc.	X		X	
Sira Corporation	X		X	
Simplex Industries	X			
Systems Associates	X		X	
Titan Environmental Systems	X	X		
Torrax Systems, Inc.	X			X
Union Carbide Corp.	X	X	X	X
Union Electric Co., St. Louis, Mo.	X		X	
Universal Oil Producers	X	X		
Urban Research & Development	X			X
University of California, Berkeley	X			
U.S. Navy	X	X	X	
U.S. Recycle Corp., (Consumat)	X	X		
Vista Chemical & Fiber Products	X		X	
Waste Management, Inc.	X		X	
Wheelabrator-Frye	X	X		
Williams Brothers	X		X	

1. From: Wentworth, 1970; California State Solid Waste Management Board, 1975 and 1976; USEPA, 1977; Weinstein and Toro, 1976; Sheridan, 1976; U.S. Council on Environmental Quality, 1977 and 1978.

Table C-3

Current Research Projects in MSW Energy Recovery[1]

Projects Funded by Department of Energy

Project Title	Contact/Performing Organization
Study of Technical Problems of Nashville Incinerator	R.B. Engdahl (ret.) Battelle Columbus Laboratories
Environmental Control Requirements in Solid Waste Processing and Energy Recovery Facilities	Ames Laboratory Iowa State University
Support of Equipment Test and Evaluation Facility (and Energy Conservation through Resource Recovery)	Dr. Harvey Alter National Center for Resource Recovery
European Assessment	H.C. Baille Resource Planning Associates
Co-firing in Cement Kiln	Ron Jones Environmental Equipment Corp.
Tests of Gases from 200 TPD Pyrolysis Reactor	W. Plant Union Carbide, Linde Division
Pompano Beach: Advanced System Experimental Facility	Peter Vardy Waste Management, Inc.
Digester Mixing Tests	J. Schwartbaugh Systems Technology Corporation
High Rate Anaerobic Digestion	C.D. Finney Natural Dynamics
Utilization of Waste Carbon Monoxide as a Chemical Feedstock	N.G. Wittenbrock Battelle Pacific N.W. Laboratories
Regional Study - Characterization and Waste Quantification	H.C. Baille Resource Planning Associates
Amonia from Urban Wastes	Ms. C. Shreve City of Seattle
Partial Home Heating and Cooling from Household Wastes	R. Murray General Electric Company

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[1] from: Hunt, Franklin and Franklin, 1978.

Table C-3 (continued)

Project Title	Contact/Performing Organization
Enzymatic Hydrolysis	Leo Spano U.S. Army Laboratories Pollution Abatement Division
Application of SGFM Technology	Dr. W.J. Huffman Texas Tech University
Plug Flow Vs. Complex Mix Reactors for Methane Formation	Dr. John T. Pfeffer University of Illinois
Biological Conversion of Organic Refuse to Methane	Dr. John T. Pfeffer University of Illinois
Feedlot Energy Reclamation Demonstration	Warren Coe Hamilton Standard
Recovery of Fuel Gas from Waste	Dr. Don Wise Dynatech
Bench Scale Research in the Thermochemical Conversion of Biomass	Paul Walkup Battelle Pacific N.W. Laboratories
Construction of Wood Waste-to-Oil Facility	R.J. Lull Marcon, Inc.
Technical Evaluation of Waste-to-Oil Plant	Emile H. Houle Bechtel Corporation
Heat Treatment of Organics for Increasing Biodegradability	Dr. Perry McCarty Stanford University
Conversion of Biomass into Gaseous Products	Dr. Donald E. Garrett Garrett Energy Research and Engineering
Experimental Program for the Albany, Oregon Waste-to-Oil Pilot Plant	Dr. Sabri Ergun Bechtel Corporation

Table C-3 (continued)

Project Title	Contact/Performing Organization
Concepts for Improving the Fuel Quality of RDF	Dr. N. Norman Hecht University of Dayton Research Institute
Preparation, Use and Cost of Densified RDF	Dr. Harvey Alter National Center for Resource Recovery, Inc.
Waste as a Supplementary Fuel	Arnold Chantland Public Works Director, City of Ames (Iowa)
Firing Densified RDF in a Stoker Boiler	Dr. Gregor Rigo Systems Technology Corporation
Utilization of Solid Waste as Fuel	Dale A. Vaughn Battelle-Columbus Laboratories
St. Louis/Union Electric Supplementary Fuels Studies	Paul Gorman Midwest Reserach Institute
Technical/Economic Assessments of Waste-as-Fuel Processes	E.M. Wilson Ralph M. Parson Co.
Coincineration of MSW with Agricultural Wastes (Hawaii)	W.H. Hirai County of Hawaii
Preliminary Environmental Assessment of the Production and Use of Methanol from Non-Coal Sources	W. Ballantyne Battelle Columbus Laboratories
Ethanol Fuel Via Enzymatic Hydrolysis	Leo G. Spano U.S. Army Natick Laboratories
Materials Recovery, RDF, Aluminum, Glass and Air Classification Research and Development	Dr. Harvey Alter National Center for Resource Recovery
Preprocessing Systems Evaluation	David Bendersky Midwest Research Institute
Acid Hydrolysis for Biological Conversion	Dr. W. Brenner New York University
Environmental Effects of Utilizing Solid Waste as a Supplementary Power Plant Fuel	Dale A. Vaughan Battell Columbus Laboratories

Table C-3 (continued)

Project Title	Contact/Performing Organization
Technical Assessment of Air Pollution Control at the Baltimore Demonstration Gas Pyrolysis Facility	Tony E. Eggleston TRW Systems Group, TRW, Inc.
Pilot Pyrolysis of Mixed Waste to Fuel	Dr. Richard Stephens Energy Resource Co., Inc.
Preliminary Environmental Assessment of Biomass Conversion to Synthetic Fuels	S.T. DiNovo Battelle Columbus Laboratories
Fine Grinding Technology Assessment	M. Schrag Midwest Research Institute
Environmental Assessment of Waste-to-Energy	M. Schrag Midwest Research Institute
Disposal of Sludge from Fluidized Bed Combustion Processes	Ralph Stone Company
Combustion and Emission Tests on Portable Pyrolysis Char and Oil	ERDA-Pittsburgh Energy Research Center
Glass Recovery Technology	Raytheon Company
Technical and Economic Analysis of Materials Recovery System - New Orleans Recovery I	J.F. Bernheisel National Center for Resource Recovery
Technical Assessment Support	Systems Technology Corporation
Construction and Demolition Wastes Survey	J. Commins JACA Associates

Table C-3 (continued)

Projects Funded by Other Governmental Agencies	
Project Title	Contact/Performing Organization
Anaerobic Conversion of Organic Wastes into Methane by Thermophilic Bacterial Associations (USDA)	J.G. Zeikus University of Wisconsin
Heat Treatment of Refuse for Increasing Anaerobic Biodegradability (NSF)	P.L. McCarty Stanford University
Biological Conversion of Organic Refuse to Methane (NSF)	Dr. J.T. Pfeffer University of Illinois
Syngas from Coal & Municipal Solid Waste (NSF)	Dr. H.W. Schulz Columbia University
Preparation for Conversion of Cellulose to Glucose (DoD)	T.L. Reiling Reiling Industries, Inc.
Secondary Resource Recovery Programs (Including Pilot) Plants (BoM)	P.M. Sullivan U.S. Department of Interior
Environmental Impact Evaluation of Municipal Refuse as an Energy Resource (BoM)	Bureau of Mines College Park Metallurgy Research Center
Investigation on the Utilization of Peanut Hulls in Feed and Non-Feed Products (USDA)	D. Burdick Department of Agriculture
Technological Problems Inhibiting the Increased Use of Recovered Materials (NSF)	Dr. Harvey Alter National Center for Resource Recovery
Methane Fermentation of Feedlot Wastes (USDA)	R.A. Rhodes U.S.D.A.
Alternate Sources of Heat Energy for Rural Maine (USDA)	N. Smith University of Maine
Pyrolytic Conversion of Cellulosic Materials (NSF)	F. Shafizadeh University of Montana
Pretreatment of Cellulosic Materials to Increase the Rate of Enzymatic Hydrolysis by Partial Acid Hydrolysis (NSF)	H.E. Grethlein Dartmouth College

Table C-3 (continued)

Project Title	Contact/Performing Organization
Alternatives to the Conventional Use of Petroleum (DoD)	J.M. Slaminski U.S. Navy
Uses of By-Product Polymeric Wastes Generated in Arkansas (DoT)	W.V. Wyatt Arkansas State University

*The letters in parenthesis indicate the funding agency. USDA = U.S. Department of Agriculture; NSF = National Science Foundation; DoD = Department of Defense; DoT = Department of Transportation; BoM = U.S. Bureau of Mines

Table C-3 (continued)

Projects Funded by Non-Federal Public Organizations

Project Title	Contact/Performing Organization
Energy Recovered from Processed Municipal Solid Waste (City of Los Angeles)	J.E. Bigger Los Angeles City Department of Water
Fuel Gas Production from Municipal Solid Waste (University of Massachusetts)	E.E. Lindsey University of Massachusetts
Studies in Methanogenesis (Production of Methane, Sludge) Fertilizer and High Protein Feed for Agricultural Wastes (University of Hawaii)	R. Ross University of Hawaii

*Funding agency is listed in parenthesis.

Table C-3 (continued)

Projects Funded by Private Industry

Project Title	Contact/Performing Organization
Pilot Plant for Resource Recovery from MSW	Art Tschannen Adolph Coors Co.
REF-Fuel (RDF)	Bruce Hendrickson Browning-Ferris Industries, Inc.
Storage and Retrieval Bins	T.A. Johnstone American Sheet Metal, Inc.
Disc Screens	Frank G. Hamilton Rader Systems, Inc.
Lyndhurst, N.J. Process Municipal Waste Into Briquette Fuel (Eco-Fuel)(Eco-FuelII)	Robert M. Beningson Combustion Equipment Associates
Solid Waste Utilization	H.L. Koenig Commonwealth Edison Company
Upgrading of Low Grade Fuels Through Pretreatment Processes	T.E. Ban McDowell Wellman Engineering Company
Heat to Energy Conversion	Robert E.S. Thompson Environment, Inc.
Heat Recovery from Waste Products	U.R. Ryffel Dow Chemical Company
Scrap Tire Tyrolysis Project for Recycle of Carbon Char and Oil	V.A. Snow Goodyear Tire & Rubber Company
Burning of Tires in a Furnace to Generate Steam	E.R. Moats Goodyear Tire & Rubber Co.
Retorting of Oil Shale and Other Low Grade Fuel Resources for Recovery of Oil	T.E. Ban McDowell Wellman Engineering Company
Conversion of Organic Wastes to Oil	L.G. Donaruma Clarkson College of Technology
Scrap Tire Utilization	G. Alliger Firestone Tire & Rubber Company
Waste Product Utilization	S.G. Holt Consolidated Papers, Inc.
Energy Conversion and Increased Production Systems	M.D. Robison Weyerhaeuser Company

Table C-4

MSW Energy Recovery System Efficiency Comparison

METHOD	Percent Efficiency* (Energy Recaptured)														
	MSW to Fuel					MSW to Steam					MSW to Electricity				
Estimate**	a	b	c	d	Mean Value	a	b	c	d	Mean Value	a	b	c	d	Mean Value
Waterwall	100	100	100	100	100		59	67		63			29		29
Fluff RDF	70	74		85	76.3	48	58			53	19			29	24
Dust RDF		80			80		63			63					---
West RDF		76			76		43			43					---
Purox		64	64	66	64.7		58			58				22	22
Landguard	78	78		66	74	42	42	54		46	16.8			22	19.4
Occidental	26	26		46	32.7	23	23			23	9.2			16	12.6
Torrax	34	65			74.5	58	37			47.5	23				23

$$^{*}\text{Efficiency} = \frac{\Sigma \text{ energy in}}{\Sigma \text{ available energy out}}$$

** Estimate:

a. U.S. EPA 1976(b)
b. U.S. EPA 1977
c. Golueke and McGanhen, 1976
d. Oak Ridge National Laboratory, 1976

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APPENDIX D

CURRENT STATUS OF COGENERATION SYSTEMS

A great variety of individual cogeneration systems is currently available on the open market. Three general types of cogeneration systems are characterized in this report; however, these systems by no means cover the entire spectrum of potential systems. Cogeneration systems are generally small-scale, are employed to support a single industrial activity rather than a general service system, and are tailored system by system to meet the specific product mix required by the industry.

Despite the flexibility and efficiency of cogeneration systems, their contribution toward national electrical energy production has declined from 15 percent in 1950 to four percent in 1970. The impediments to expanded use of cogeneration which have accounted for this decline are not technical,but rather economic and institutional. These impediments relate to the historical price of electricity, to institutional reluctance to enter into the fixed generation of two energy products, and to the inability of specific industries to profitably sell excess electricity into a utility grid. All of these variables are indirectly affected by the ratio of power output to heat output for a cogeneration system. This ratio determines how much excess electricity, if any, will be available to the utility grid. For example, a steam boiler and turbine system may produce 50 kWh/10^6 Btu of steam heat. A gas turbine-waste heat boiler, however, produces 200 kWh/10^6 Btu of steam heat. Thus, while a gas turbine produces more electricity, it also produces less steam. The importance of this power/heat ratio is in matching the energy demand profile of an industry, especially where it is uneconomical to sell excess electric power.

As mentioned, the variety of cogeneration arrangements currently in use is large in order to match system supply characteristics and the demands of an industrial or commercial application. These systems have different fuel requirements and pollution emissions and can employ a variety of pollution control measures. Major system characteristics for some of the potential cogeneration combinations are shown in Table D-1.

The cogeneration systems described in Table D-1 are typical of industrial plant applications such as the diesel and fluidized bed systems described in this report. A second general application of cogeneration is for enhanced oil

Table D-1

Cogeneration Systems

System	Size (MW elect.)	Fuel	$\frac{\text{Elect}}{\text{Steam}}$ (KW/10^6 BTU)	FCP (BTU/KWH)	Process steam press (psig)	Total Plant installed cost ($/KW)	Pollution	Controls	General system notes
Gas turbine & waste heat boiler	0.5 → 75	• Gas • #2 oil • Treated resid. • SNG (low BTU)	200	5,500	150 - 600	$350-400	NO_x	• Water or steam injection	• 1000°F exhaust can be used as clean hot gas
Diesel engine & waste heat boiler	0.5 → 25	• Gas • #2 oil • Treated resid.	400	6,500	15 - 150	$350-500	• No_x • Part.'s	• Tuning • Steam inject • Baghouse	• Efficient at part load and in small sizes • High power/steam ratio
Steam boiler & turbine	> 1	• Any oil • Coal • Wastes	45 → 75	5,000	15 - 600	$500-600	SO_2 Part.'s NO_x	• Low S fuel, scrubber • Precipitator • Design	• Efficient at part load
Combined cycle & waste heat boiler	1 → 150	• Gas • #2 oil • SNG	150	5,000	15 - 900	$350-450	NO_x	• Water or steam injection	• Variable power/steam ratio • Back pressure steam turbine
Steam bottoming	0.5 → 10	• Waste heat	N.A.	0	N.A.	$400-600	N.A.	N.A.	• Efficient at part load • Uses exhaust >900°F
Organic bottoming	0.6 → 1	• Waste heat	N.A.	0	N.A.	$400-700	N.A.	N.A.	• Efficient at part load • Uses exhaust <900°F • Prototypes avail. • Requires cooling water

recovery. As an example of this type of system, Pacific Gas and Electric Company is negotiating with Getty and Texaco to install combustion turbine cogeneration systems of 280 and 270 MWe capacity, respectively, in Kern County, California oil fields. The oil companies have been blocked from further development of steam injection because of SO_2 and NO_x emissions constraints from crude oil boilers. The economic situation discourages cleanup by the oil companies so they approached PG&E with the offer of inexpensive oil in exchange for steam. Electricity generation in turn allows PG&E to invest in oil gasification and desulfurization equipment to meet emission constraints. This institutional arrangement provides energy, economic and environmental advantages and although no cogeneration systems have been installed at present, there is a significant potential for their installation in the future. As stated above PG&E is presently negotiating for 490 MWe of baseload capacity, supplying 3.6×10^6 lbs/hr steam. This steam capacity is only one-fifth of the present steam generation in the three major Kern County oil fields (Kern River, Midway-Sunset, and S. Belridge). Additionally, there are several other significant heavy oil deposits in California as listed in Table D-2.

The recoverable heavy oil figures given in Table D-2 are conservative with respect to cogeneration potential because they consider only 1975 technologies and economics. This would be steam soak methods of recovering $5.25/bbl oil. Doubling the value of the oil will permit steam drive methods and increase the recoverable reserves by 30-50 percent. On the other hand, two-thirds of this oil will be recovered using steam while one-third will be recovered with CO_2 flooding or detergent drives which do not use cogeneration. Finally, the list only considers the largest fields capable of supporting a 200 MWe cogeneration plant for at least 15 years.

While enhanced oil recovery supports the petroleum drilling operation exclusively, fluidized-bed and diesel cogeneration are particularly attractive to several major industrial sectors. Table D-3 lists projections reported for cogeneration activity in 1985 for six major industries which require both electricity and process heat within the temperature and pressure ranges for which cogeneration is an efficient producer.

Table D-2

Potential for Expanded Enhanced Oil Recovery in California

Field	County	API Gravity	Oil-in-Place 10^9 bbl	Recoverable[a] 1975 10^9 bbl	Project Sponsor
Cat Canyon	Santa Barbara	°11-13	7.3	1.4	ERDA-Getty Oil
Santa Maria Valley	Santa Barbara	°14	5.1	1.0	Union Oil
Kern River	Kern	°13	3.3	0.6	Getty-Standard
Midway-Sunset	Kern	°11	2.5	0.5	ERDA-Chanslor Oil
Kern Front	Kern	°14	1.3	0.3	Several small projects
Cymric	Kern	°12-14	1.2	0.2	Several small projects
San Ardo	Monterey	°11	1.2	0.2	Texaco and Mobil
Poso Creek (Premier)	Kern	°12-13	1.0	0.2	None
Casmalia	Santa Barbara	°10	0.9	0-0.2	None
Oxnard	Ventura	°7-8	0.9	0	None
McKittrick	Kern	°14-15	0.9	0.2	Getty Oil and others
Guadalupe	San Luis Obispo	°11	0.1	0.02	None
Paris Valley	Monterey	°11	0.06	0.01	ERDA-Husky Oil

[a] °15-10 (API): 19% recovery factor; °10-7: 0% recovery factor

Sources: Estimates by Alan Leighton, ERDA-SAN, September 1, 1976; A. Leighton and J. Patek, Combination Thermal Drive to Recovery Very Heavy Oil from Paris Valley Field, California, 2nd Annual ERDA Symposium on Enhanced Oil Recovery, Tulsa, Oklahoma (Sept. 1976).

Table D-3

Cogeneration Projections for 1985

Industry	1985 Cogeneration Capacity,* MW
Food	343
Textiles	98
Pulp and paper	4,861
Chemical	2,677
Petroleum refining	763
Steel	1,423
TOTAL	10,165

*Assuming no government action

APPENDIX E
APPLICATIONS OF COGENERATION SYSTEMS

This appendix describes in some detail two potential applications of cogeneration: fluidized bed combustion in the pulp and paper industry and enhanced oil recovery.

COGENERATION IN THE PULP AND PAPER INDUSTRY: A BRIEF OVERVIEW

Industry Description

The pulp and paper industry in the U.S. consists of over 350 companies together representing over 700 operating mills. The output of this sector totaled about 600 pounds of paper and cardboard products per person in 1975. Total industry capacity is about 200,000 tons per day, almost half of which is located in the southeastern United States (Table E-1). Integrated mills with both pulping and forming facilities account for about 70 percent of industry capacity. These mills have an average annual capacity of about 300,000 tons. Non-integrated mills (forming facilities only) tend to be smaller, with only about 15,000-20,000 tons annual capacity on the average. Industrial plants are thus large and capital-intensive; a new installation can exceed $300 million.

Fuel Consumption

Some 90 percent of the fuels consumed in the industry are used to produce process steam at temperatures between 250-390°F, and between 50 and 175 psig. The industry generates a tremendous amount of biomass fuel in the form of bar, wood chips and spent liquor (the waste product from the pulping process). In terms of Btu potential such wastes accounted for 44 percent of all energy consumption in the industry nationwide (Thermo Electron Corporation, 1976, Table 4.27)*.

Fuel and Energy Uses

While most of the steam is used at relatively low temperatures and pressures, much of it is produced at higher pressures, allowing ample application of steam turbine topping cycle electrical generation. In fact, the

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*Thermo Electron Corp, A study of Inplant Electric Power Generation in the Chemical, Petroleum Refining and Pulp and Paper Industries. Woodham, MASS. NTIS, PB255-659, June 1976.

Table E-1

Region Distribution of the Pulp and Paper Industry

Region	States	Mills (%)	Capacity (%)
New England	Maine, New Hampshire, Vermont, Rhode Island, Massachusetts, Connecticut	15	8
Middle Atlantic	New York, New Jersey, Pennsylvania	18	10
East North Central	Ohio, Indiana, Illinois, Michigan, Wisconsin	22	16
West North Central	Minnesota, Iowa, Montana, North Dakota, South Dakota, Nebraska, Kansas	4	3
South Atlantic	Delaware, Maryland, Washington, D.C., Virginia, West Virginia, North Carolina, South Carolina, Georgia, Florida	12	24
East South Central	Kentucky, Tennessee, Alabama, Mississippi	7	12
West South Central	Arkansas, Louisiana, Oklahoma, Texas	8	12
West	Montana, Indiana, Wyoming, Colorado, New Mexico, Arizona, Utah, Nevada, Washington, Oregon, California, Hawaii, Alaska	14	15

industry consumption of electrical power per ton of product has grown significantly over the years, and the use of higher boiler pressures has followed this trend. During the 1965-1975 period, the largest boiler capacity additions were in the 850-1250 psig range, and significant capacity was added at pressures greater than 1250 psig (Thermo Electron Corporation, 1976, Table 4.40).

Natural gas is used for direct fire hot air dryers and space heating, as well as for some boiling. Residual oil is also used directly in lime kilns to fire the pulping chemical recovery process. Thus residual oil use is roughly proportional to energy generated from liquor. The lime kiln operations require about 2 x 10^6 Btu of oil per ton of paper. Energy generated in spent liquor is about 20 x 10^6 Btu per ton of paper product. It should be borne in mind, however, that boiler/recovery efficiencies are not the same for the biomass fuels and for the purchased fossil fuels. The American Paper Institute (API) estimates an average boiler efficiency of 85 percent from purchased fuels (e.g. 15% stack loss), 70 percent from bark, and 60 percent for spent liquor.

Thermodynamic Potential for Increased Cogeneration

The potential for bottoming of waste heat in the pulp and paper industry is believed to be negligible. The waste heat from stack gases, warm water, heated air, and water vapor ranges from 100°F to 400°F, too low to result in any substantial electrical generation. The remainder of this section will therefore deal with topping potential.

For topping cycles, the maximum potential electrical generation depends on the industry's steam flow requirements (amount of steam per unit time and its pressure and temperature), and the type of topping cycle. In 1975 for the industry as a whole, the amount of steam used was about 1100 x 10^{12} Btu, averaging about 1.421 x 10^8 lbs per hour, most of which is at 50-400 psig, The standard power to steam ratios for steam turbine, gas turbine, and diesel topping cogeneration are about 45 kWh/10^6 Btu, 200 kWh/10^6 Btu, and 400 kWh/10^6 Btu, respectively. Applying figures such as these to the total process steam requirements yields the maximum electrical generation potentials (Table E-2).

We note that even under steam turbine topping, the maximum generation exceeds current implant generation, suggesting substantial increases even at present levels of economic activity and extensive implant generation.

Table E-2

Maximum Potential for Inplant Generation of Electricity in kWh/Year in the Pulp and Paper Industry

Region	Electricity (10^9 kWh/year)						
	Maximum Potential Generation[1]			Total Used[2]	Maximum Potential Export[3]		
	Steam Turbine Topping	Gas Turbine Topping	Diesel Topping		Steam Turbine Topping	Gas Turbine Topping	Diesel Topping
New England	4.4	15	30	4.2	0.2	10.8	25.8
Mid-Atlantic	3.4	12	23	3.6	(0.2)[4]	8.4	19.4
East North Central	7.4	26	52	7.4	--	18.6	44.6
West North Central	1.0	3.6	7.1	1.2	(0.2)	2.4	5.9
South Atlantic	18	65	130	14	4.0	51	116
East South Central	8.5	30	59	7.2	1.3	22.8	51.8
West South Central	9.1	32	64	8.6	0.5	23.4	55.4
Mountain & Pacific	9.7	33	67	10	(0.3)	23	57
TOTALS	61.5	216.6	432.1	56.2	5.3	160.4	375.9

Notes

1. Maximum potential generation - topping process steam (the opportunities for topping of process heat and bottoming of waste heat in the pulp and paper industry are minimal).
2. Purchased plus inplant generation (hydro not included).
3. Maximum potential for export - maximum potential generation minus purchased electrical minus inplant generated electricity.
4. Use greater than maximum potential.

Gas turbine and diesel topping could generate substantial exports of electricity. Several caveats must be mentioned, however. First, gas turbines and diesel systems require more total fuel to generate any given usuable electricity-plus-steam Btu equivalent, due to higher efficiency of the steam turbine. There is more unrecoverable heat output in these systems than in steam turbine systems. Second, the pulp and paper industry requires tremendous amounts of steam, as noted above. Finally, gas and diesel systems require petroleum fuel inputs. Steam generation allows the burning of coal and other solid biomass fuels. This is an important factor for the pulp and paper industry whose waste already comprises between 40 and 50 percent of its fuel inputs.

Economic Potential for Increased Cogeneration

The implementation of cogenerated electricity and steam systems on a wide scale requires additional investment in instances where these products are generated separately. That such investment has been forthcoming only in small amounts in the U.S. is not surprising when historical realities are considered. Low energy costs and rapid postwar expansion of centralized, utility-run power systems, coupled with an emphasis by industry on first costs have selected against cogeneration, as witnessed by the decline in cogenerated electricity as a percent of total generation in the U.S. since 1950. The enormous increases in petroleum fuel costs and the steady growth of industrial plant size have begun to turn cogeneration's economic picture around. In general, the measure utilized to determine the viability of an investment is the level of internal rate of return. Essentially, the internal rate of return (r) is determined for any given investment by the following formula

$$C = \sum_{i=1}^{N} \frac{R_i}{(1 + r)^i}$$

where

c = capital costs

R_i = after-tax returns in year i

N = expected lifetime of investment in years

r = internal rate of return

The rate of return required by a business to justify investment depends many factors, particularly the degree of expected market risk, borrowing costs, and debt/equity ratios. It has been estimated that for the pulp and paper industry, the average rate of return required over all investments is about 15 percent after tax. In general, industries need a higher rate of return for cost saving investments such as cogeneration than for product-oriented investments which are associated with direct profitability, market expansion, and the like. On the other hand, a lower rate is required by utilities (around 13%) because electricity (and steam in some cases) is the utility's primary product. Moreover, as a regulated industry, utilities can usually borrow at lower rates. Thus implementation could depend on generation plant ownership. In fact, the pulp and paper industry generates 55-60 percent of its own electricity in-plant, making it likely that it might invest in cogeneration at return rates fairly close to its industry average.

Another issue facing cogeneration implementation is whether or not it is associated with expansion or replacement of process steam facilities. If cogeneration is considered as industry expands or replaces worn out or obsolete boilers, pipes, pumps, fans, etc., then initial investment capital costs estimates are reduced because the firm will only consider the incremental costs associated with electricity generation (e.g. costs of turbine, generator, etc.). If existing and useful process steam equipment must be replaced, however, the total costs of the new system must be used, including those associated with steam production.

A final consideration influencing rate of return are tax policy and financing options. Both increased investment tax credit (such as are proposed in President Carter's national energy policy) as well as decreased corporate income tax rate would increase expected rates of return. Also, if a company has access to outside capital at interest rates below the expected return rate, its willingness to invest can be expected to increase relative to a base case situation in which it had to generate all its funds internally or dilute its equity.

The Effect of Economic Incentives on Potential Implementation by 1985

To assess the potential for increased cogeneration, one must make assumptions regarding industrial growth. The estimates shown below are based on the following projections: (a) the amount of steam and electricity would increase by 50 percent in the 1975-85 period, implying a conservative 3.2 percent real annual growth rate, and (b) 75 percent of existing (1975) capacity is assumed to be still in place by 1985. The economic incentives considered are increased tax credits (up to 50 percent of new investment in cogeneration), lower corporate tax rates (down to 25% of income) and the availability of up to 50 percent financing at 10 percent.

With steam topping, only very small amounts of electricity will have to be purchased by 1985. Even in the base case of no added incentives (e.g. current tax structures and no debt financing) and industry ownership of facilities, self-generation would amount to about 65 percent of industry needs. With incentives for industry or under a system of utility ownership, cogeneration could account for 82-99 percent of industry's power needs. With gas turbines and diesel cogeneration, given appropriate petroleum, synthetic fuels or adequate fluidized bed combustion technology, substantial electricity could be exported: from a low of 2.2 percent (given gas turbine topping, industry ownership, and no incentives) to a high of 9.6 percent. The latter case assumes diesel topping, utility ownership, all tax incentives, and outside financing options.

Potential fuels savings for 1985 would be about 70,000 bbl of oil per day for the steam systems and 290,000 bbl/day for both gas turbine and diesel topping (Thermo Electron Corporation, 1976, Table 6.31). These estimates assume industry ownership and all economic incentives. For utility ownership, assuming all incentives, the savings are 110,000-135,000 bbl/day, 380,000-420,000 bbl/day, and 480,000-580,000 bbl/day for steam, gas and diesel topping, respectively. The increase in savings listed here for gas and diesel would need to be modified somewhat if their higher heat rate were taken into account.

Fluidized Bed System for the Pulp and Paper Industry

Fluidized bed cogeneration system is suggested for use in the pulp and paper industry because of its ability to burn both coal and waste fuels efficiently and cleanly.

Two significant trends in the energy field today are fuel switching from oil and gas to coal and waste fuels and also decreasing environmental impact. The combination of these trends is largely contradictory on the basis of existing experience with coal combustion. This, however, should change in the near future with the implementation of fluidized bed combustion (FBC) which inherently produces low emissions. Furthermore, it is of small to moderate size scale which makes it well suited to use in cogeneration applications. Cogeneration complements FBC well by maximizing efficiency in the use of waste and fossil fuels to produce both electricity and process heat for use by industry. Unfortunately industries tend to be located where ambient air quality is already poor and where emissions impact on large populations. Thus fluidized bed combustion is expected to be significant in the future and its emissions and their control will be especially important.

The first feature of FBC is the fact that it allows any type of coal or waste fuel to be burned regardless of ash content or caking properties. Furthermore, the coal requires little processing such as washing and pulverization as done in modern coal plants because the ash is easily included in the bed material. Generally the coal is only crushed to 1/4 inch size to ease fuel feeding.

The ability to burn any coal or waste material and to burn it cleanly is a feature because of coal's variability. Coal varies in its physical properties and chemical composition. Some coals produce too much ash or slagging ash and so cannot be used in some boilers. This does not interfere with FBC, however, because of the small fraction of coal in the fluidized bed. Likewise, sulfur content can vary from 0.5 percent to 5 percent by weight. Once again, the large bed or sorbent can easily adapt to varying sulfur removal rates by adjusting flow rates. This is an advantage under proposed New Source Performance Standards which require 90 percent control regardless of sulfur in the fuel rather than simply meeting an emission standard with some combination of low sulfur coal plus a scrubber. Thus an industry with 90 percent sulfur control in FBC will have flexibility in choosing coal supplies. This is particularly important for small industrial users which tend to have greater variability in their coal supplies because they cannot claim an entire mine's production as a utility power plant does.

Combustion

The most important features of combustion for power generation and process heat are combustion temperature, heat transfer and overall efficiency.

In general higher temperatures mean greater efficiency in energy conversion to electricity. The limiting factor, however, is not combustion but rather a problem with materials. For example, high pressure steam pipes can only withstand 566°C. Most gas turbine blades are damaged by temperatures over 950°C. Thus, we do not have the technology to take advantage of the thermodynamic potential of coal combustion flames at 2000°C. To limit temperatures, boilers maintain a large excess air flow to dilute the combustion gases. Fluidized bed burners must also maintain a large working fluid flow to limit temperatures but do so in the combustion zone so that actual combustion temperatures can also be reduced to about 800 or 900°C or less. The bottom limit would be the ignition temperature of 500 to 600°C depending on the fuel.

Fluidized Bed Combustors

The characteristics of fluidized bed combustion are determined by the combustion bed, which has only one to two percent fuel. This bed is fluidized by a flow of combustion air from a gridplate below the bed. These two features are complementary in that the excellent mining of a fluidized bed is what allows such a large amount of inert bed material. In turn, this allows the temperature to be decreased without losing complete combustion by providing a large thermal mass.

It is very convenient for this bed material to be limestone or dolomite. It then can react chemically with sulfur dioxide and allow its removal as a dry solid waste. The low temperature is also important for decreasing thermal NO_x formation. Finally, the low temperature and large amount of bed material serve to minimize the emission of trace metals from the coal combustion.

The large amount of bed material also allows heat transfer pipes to be located directly in the midst of the combustion zone. This gives a much more compact boiler which in turn decreases expenses.

The actual design of an FBC is still experimental. Development appears to be more advanced in England and Sweden where a few units have been placed in regular operation. In the U.S. the prototypes are still experiencing problems with coal feeding while many European units simply pour coal in the top. Nearly all of the American work has been done by Pope, Evans and Robbins, Inc. They have designed and built a DOE-funded conversion of the 30-MW Rivesville plant to a FBC. This boiler will actually have three beds plus a carbon burnup cell. This improves turndown capability by being able to turn one or two cells off. The carbon burnup cell is needed because the Rivesville beds only consume 83 percent of the fuel carbon. At a recent coal conference it was stated that this was inevitable and that industries might not require a burnup cell but that utilities definitely would for maximum efficiency. The problem of elutriation results from the poor American design which uses too high an air velocity. European designs, on the other hand, do not require a carbon burnup cell. Most estimates are that fluidized bed combustion will be available commercially by the middle to late 1930's, which is discouragingly slow, considering the use of fluidized bed reactors in the chemical industry for decades.

ENHANCED OIL RECOVERY

At present the Pacific Gas and Electric Company is negotiating with Getty and Texaco to install combustion turbine cogeneration systems of 230 and 270 MW capacity in Kern County, California oil fields. The oil companies have been blocked from further development of steam injection because of environmental constraints with respect to SO_2 and NO_x emissions from crude oil boilers. The economic situation discourages cleanup by the oil companies so that the utilities were approached with the offer of inexpensive oil in exchange for steam. Electricity generation in turn allows PG&E to invest in oil gasification and desulfurization equipment to meet emission constraints. This institutional arrangement provides energy, economic and environmental advantages and although no cogeneration systems have been installed at present, there is a significant potential in the future. As stated above PG&E is presently negotiating for 490 MW of baseload capacity, supplying 3.6 x 10^6 lbs/hr steam. This steam capacity is only one-fifth of the present steam generation in the three major Kern County oil fields (Kern River, Midway-Sunset and S. Belridge). Furthermore, there are several other significant heavy oil deposits as listed in Table E-3.

The recoverable heavy oil figures given in Appendix D (Table D-2) are conservative with respect to cogeneration potential because they consider only 1975 technologies and economics. This would be steam soak methods of recovering $5.25/bbl oil. Doubling the value of the oil will permit steam drive methods and increase the recoverable reserves by 30-50 percent. On the other hand two-thirds of this oil will be recovered using steam while one-third will be recovered with CO_2 flooding or detergent drives which do not use cogeneration. Finally, the list only considers the largest fields capable of supporting a 200-MW cogeneration plant for at least 15 years.

Obviously the potential for cogeneration is very large. Table D-2 (Appendix D) lists 4.7×10^9 recoverable barrels of heavy oil in California. Assuming that 40 percent is recovered by cogenerated steam drive over 20 years, production will be 96×10^6 bbl/year. If 50 percent is marketed, 15 percent converted to electricity, 25 percent converted to steam and 10 percent lost, then generation will be 5500 MW continuous for 20 years. Nationally the potential might be triple this amount.

The problem which needs to be addressed with respect to enhanced oil recovery cogeneration is whether the oil-fired combustion turbine system assumed in the example above is the most advantageous method. It is presently preferred by those contemplating the installation of the first oil field cogeneration. This, however, has been largely determined by the artificial economics of low first tier oil prices. At this point it is important to take a broader long-term view of the technical options available. Most important among these are combined cycle and closed cycle systems allowing the use of coal or possibly coal gasification. These systems may have slightly lower efficiencies, but more importantly, oil production will be doubled by the substitution of coal.

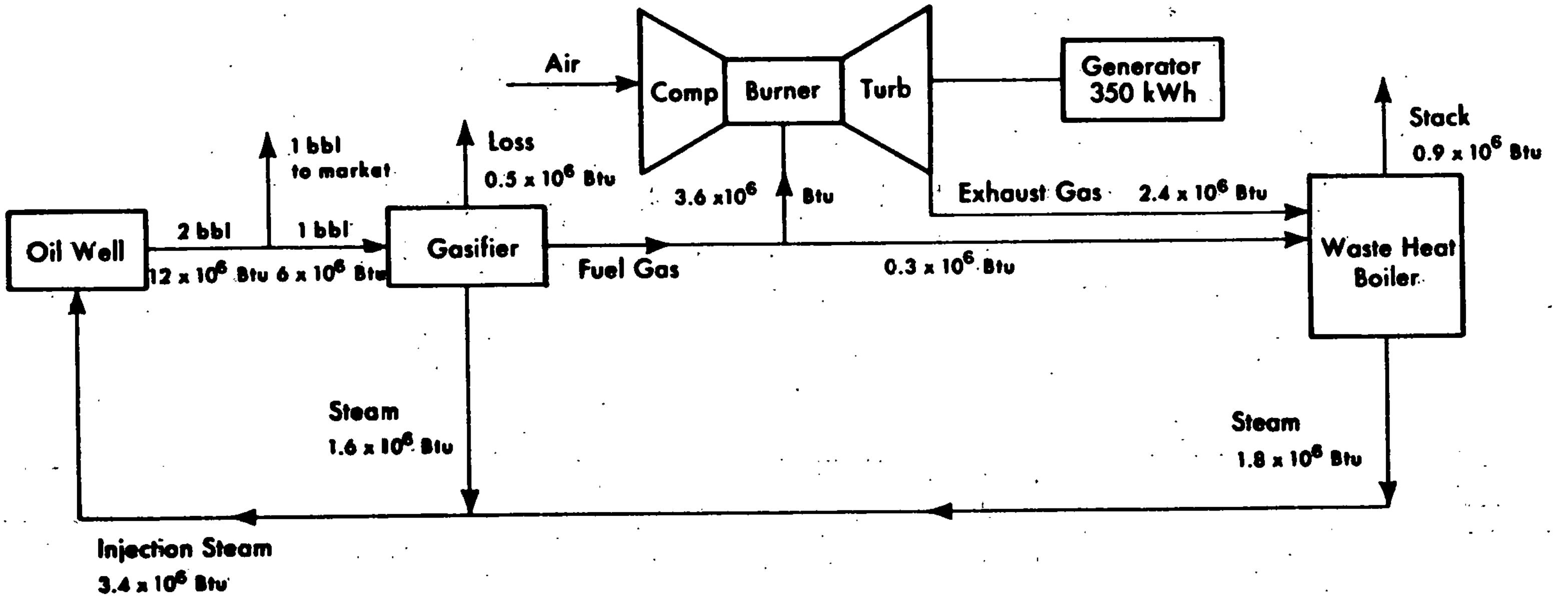
Oil fuel availability is obviously no problem, although at present the artificial pricing of oil has caused lower tier oil to be trucked to distant fields to avoid burning second tier oil for steam.

This institutional arrangement is for the benefit of the companies involved and may not be in the long-term public interest. For example, the large capital investment by the public utility with ratepayers' money depends upon the artificially depressed prices for first tier oil before it enters a refinery and requires entitlement payments to refineries buying foreign oil. This investment in crude gasification will be in jeopardy if the Federal government decontrols the price of first tier oil which in a fair possibility over a period of 20 years.

An energy flow diagram for the oil-based system is presented in Figure E-1 based on preliminary equipment specifications of PG&E. This included large GE frame 7000 turbines rated at 75 MW. In assessing the enhanced recovery industry energy profile, it will be necessary to consider a range of engines including smaller, less efficient ones which may be appropriate in other locations. This information includes empirical data on the performance of various engines as a function of fuel, temperature and load. Fortunately the load characteristics of enhanced recovery are simple and stable over time (years). Thus the duty cycle will be based primarily on the optimum maintenance schedule. The process used in this case allows for daily fluctuations in steam production without interfering with oil production. It is important to maintain a high pressure (900 psi), but steam quality is not critical and 80 percent vapor is considered satisfactory. The water content is important to prevent scaling because of poor water quality.

With respect to environmental constraints, the role of cogeneration is positive compared to the existing boilers burning crude oil without controls. All of the major combustion turbines with gaseous fuels can meet the New Source Performance Standards promulgated by the EPA for gas turbines last fall. At the state and local level, Kern county is a non-attainment area with respect to some ambient air quality standards (NO_x, SO_2). Fortunately New Source Review procedures now allow pollution tradeoffs which are abundantly available from the existing dirty boilers to be retired. Future investigation should indicate the possibilities for increasing steam and oil production while decreasing pollution emissions.

Operational residuals and capital requirements for the described enhanced oil recovery system are listed in Appendix A. Appendix I contains a description of the capital residuals for the cogeneration systems.



[a] For the Getty-Kern Oil Field the proposed installation is 280 MW and 2×10^6 lbs/hr of steam at 900 psi and 80% quality factor.

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Fig. E-1. Energy Flows for Thermally Enchanced Oil Recovery Cogeneration[a]

APPENDIX F
DIRECT COMBUSTION SYSTEMS

This appendix provides additional information on the characteristics of direct combustion systems to that included in the body of the report. Its purpose is to clarify the information contained in the Technology Application section and to provide important information concerning Direct Combustion systems which is not required for SEAS input through the TASE program.

A general schematic diagram for MSW direct combustion systems is shown in Figure F-1. Some systems include coarse shredders, while some screen incoming MSW and shred only oversized material; many systems include no front end processing at all. As briefly described in the Technology Application section of this report, incinerators are either of a refractory wall or of a waterwall type. Refractory wall incinerators require the use of a boiler or of an afterburner to complete combustion followed by a boiler, to produce the basic system product: steam. This steam may either be converted to electricity or used directly for industrial process or district heating applications while the waste gas stream is treated and released from the plant stacks.

A general comparison of waterwall and refractory wall systems is shown in Table F-1. Refractory systems tend to require more excess air and generate a higher volume of H_2O in the off-gasses, both of which decrease the desirability of the refractory wall system. Further, refractory wall incinerators burn at a much lower temperature than waterwall systems. It should be noted that while these temperatures are comparable to RDF systems, they are well below that of pyrolysis systems, which have reaction temperatures of $900^{\circ}F$ - $3000^{\circ}F$.

The simplicity of both of these types of systems and their use of existing technology has accounted for the interest in and adoption of direct combustion systems as indicated in Appendix C. However, there are two major disadvantages to direct combustion systems which limit the future attractiveness of this technology relative to RDF and pyrolysis systems. These are:

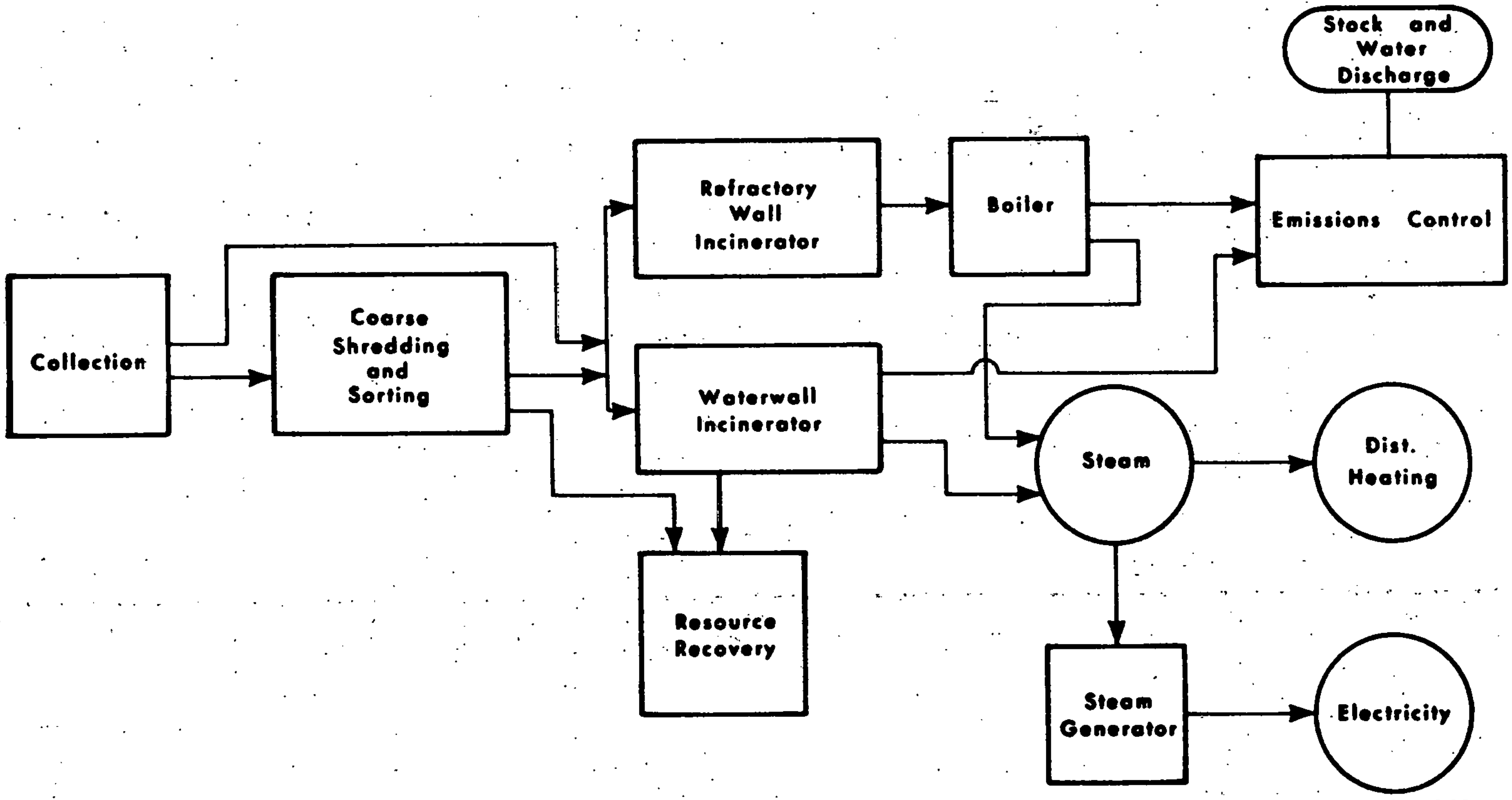

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Fig. F-1. MSW Direct Incineration

Table F-1

Typical Gas Compositions for Conventional and Steam-Generating Incinerators

Type of Incinerator :	Waterwall	Refractory
Refuse Firing Rate, MT/hr (ST/hr)	15.2 (16.7)	8.4 (9.2) (Rating)
Air Cooling/Air Cleaning Method	Boiler/Electrostatic Precipitator	Caustic Scrubber
Excess Air, %	71.7	180 (estimated)
Stack Exhaust		
Temperature, °C (°F)	211 (411)	57-77 (135-170)
Volume % CO_2, wet basis (dry basis)	9.1 (10.5)	3.7-3.2 (4.8)
Volume % O_2, wet basis (dry basis)	7.8 (9.0)	10.1-8.6 (13.
Volume % N_2, wet basis (dry basis)	69.3 (80.5)	64.2-54.2 (82.2)
Volume % H_2O, wet basis	13.3	22-34
Flow, CM/min @ temperature (ACFM @ temperature)	2400 @ 211°C (84,700 @ 411°F)	2119 @ 77°C (74,800 @ 170°F)

1. Large volumes of excess air are required to ensure complete burning and to maintain desired incinernator temperature. As a result, the volume of dry flue gas is dramatically increased as shown in Figure F-2. The required large air flows dictate the use of large fan systems, larger stacks, larger precipitators and/or scrubbers, and decreased precipitator efficiencies (Waste Age, March 1975).
2. MSW incineration tends to increase pipe, refractory and lining fouling and corrosion when compared to other steam-producing fuels (Govan, Martin and Monro, 1974). The high fly ash content of MSW off-gasses tends to coat waterwall and superheater pipes and thus reduce heat transfer efficiency. High PVC and rubber content in MSW will increase chlorine corrosion of metal tubes and pipes (Govan, Martin and Monro., 1974).

A third type of direct combustion systems not shown in Figure F-1 are the modular systems. These systems typically have a capacity of less than 50 TPD and use an incinerator-afterburner-boiler flow rather than a waterwall system. Modular systems therefore closely resemble a refractory wall incinerator in operational characteristics, except that burning is split between the incinerator and a gas-fired afterburner, where sufficient excess air is injected to complete the burning process, and that the modular systems are designed for low flow applications (refractory wall and waterwall incinerators are now being designed in the thousands of tons per day, while modular systems are designed for 30-50 tons per day).

Even though there are differences between the refractory wall and waterwall operation, and between modular systems and each of the other two types, the three systems are similar with respect to conversion efficiencies and to residual generation rates (Schoenberger, Wohlers and Jackson, 1970; Combustion Power Company, 1977). Because of its advantages relative to refractory wall systems and because of its greater system simplicity, a waterwall incinerator system has been selected for model application in this study. A material, capital and energy input/output summary for a typical waterwall incinerator is included in the Technology Application section. A material balance is shown in Figure F-3. The system energy balance is shown in Figure F-4. Data for Figures F-3 and F-4 were obtained from a critical synthesis of the data contained in:

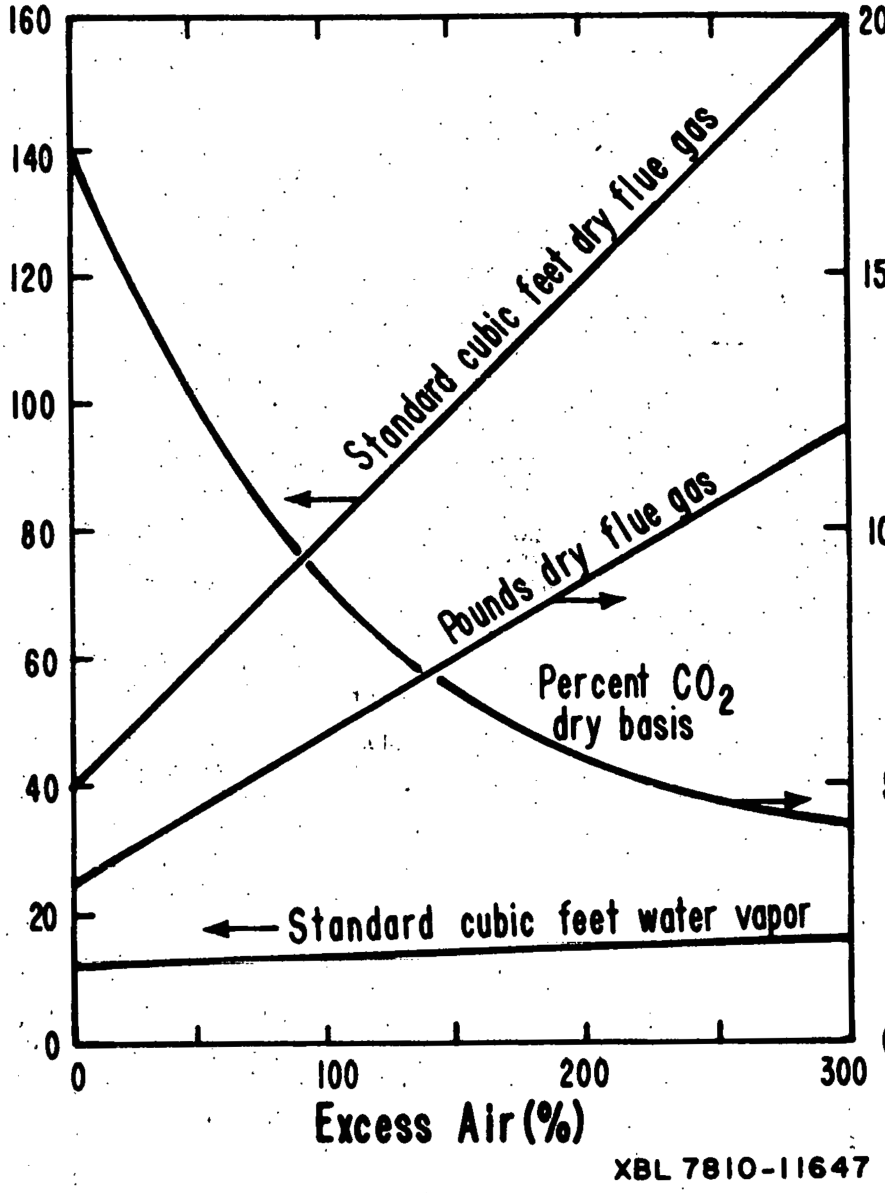


Fig. F-2. Incinerator Flue Gas Volume as a Function of % Excess Air (from Weinstein and Toro, 1976)

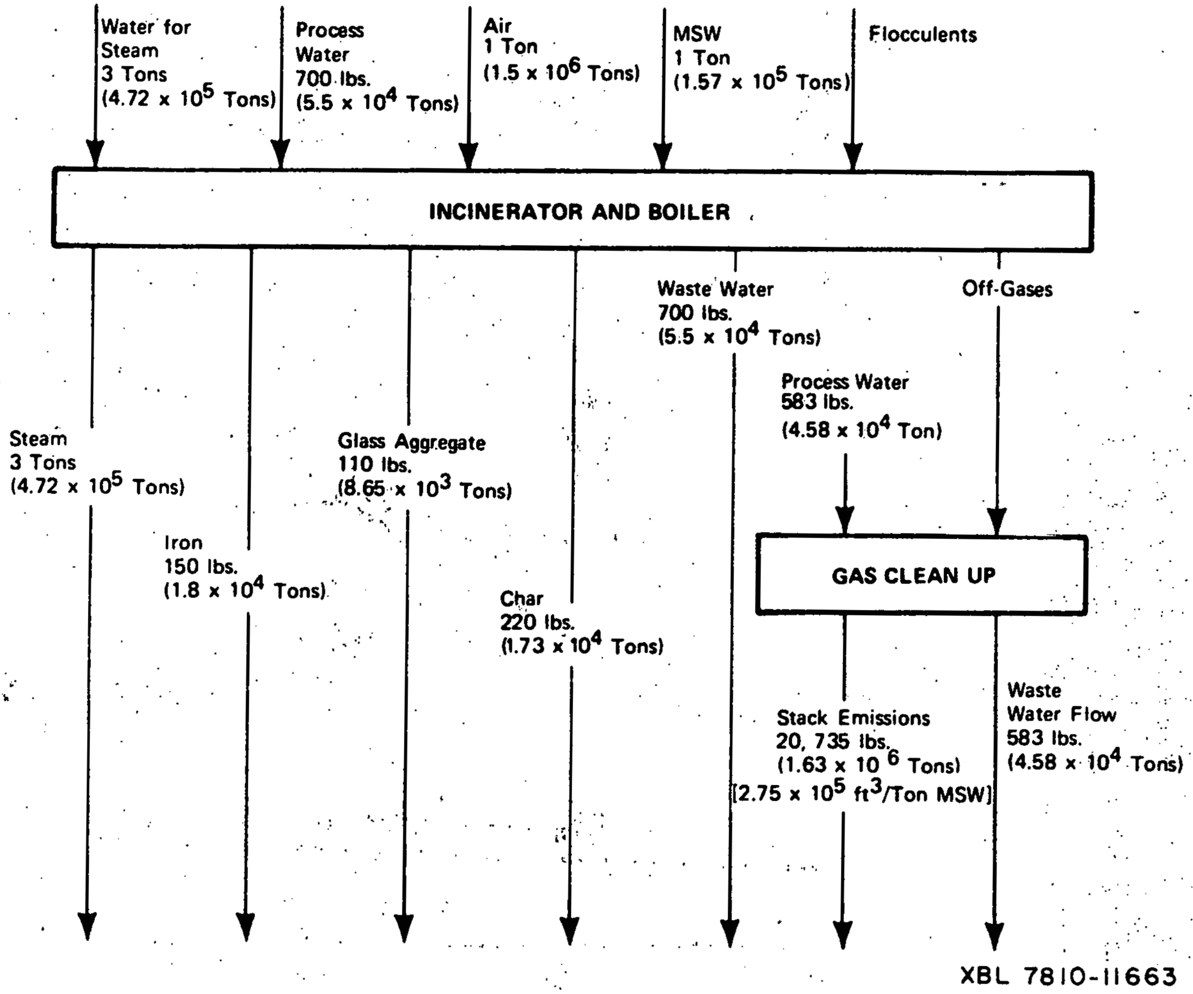
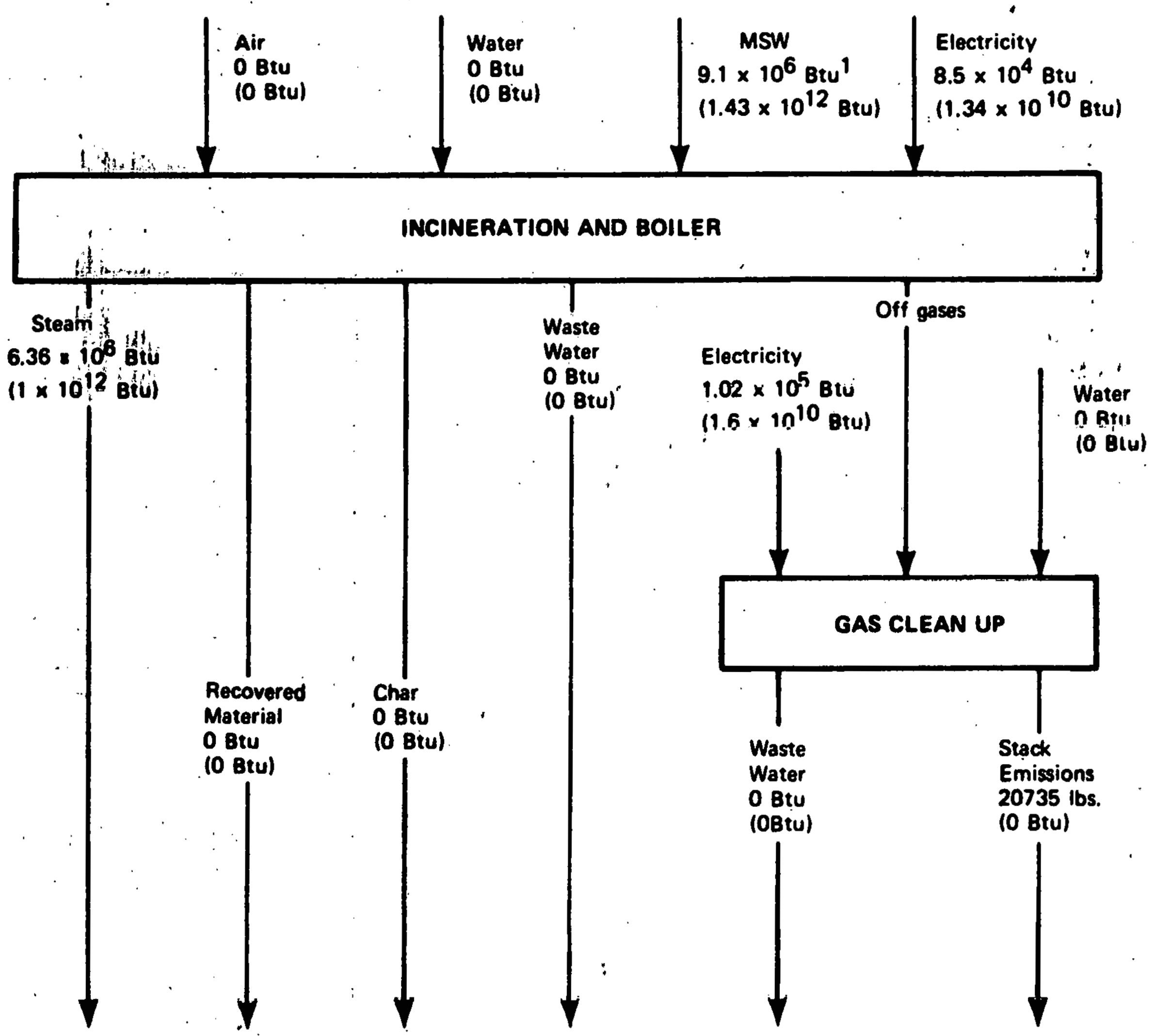


Fig. F-3. Direct Combustion Material Balance



$$\text{Efficiency} = \frac{\text{Energy out}}{\text{Energy in}} = \frac{1 \times 10^{12}\ \text{Btu}}{1.46 \times 10^{12}\ \text{Btu}} = 68\%.$$

[1] Numbers give amount per ton of MSW and (amount per 10^{12} Btu output).

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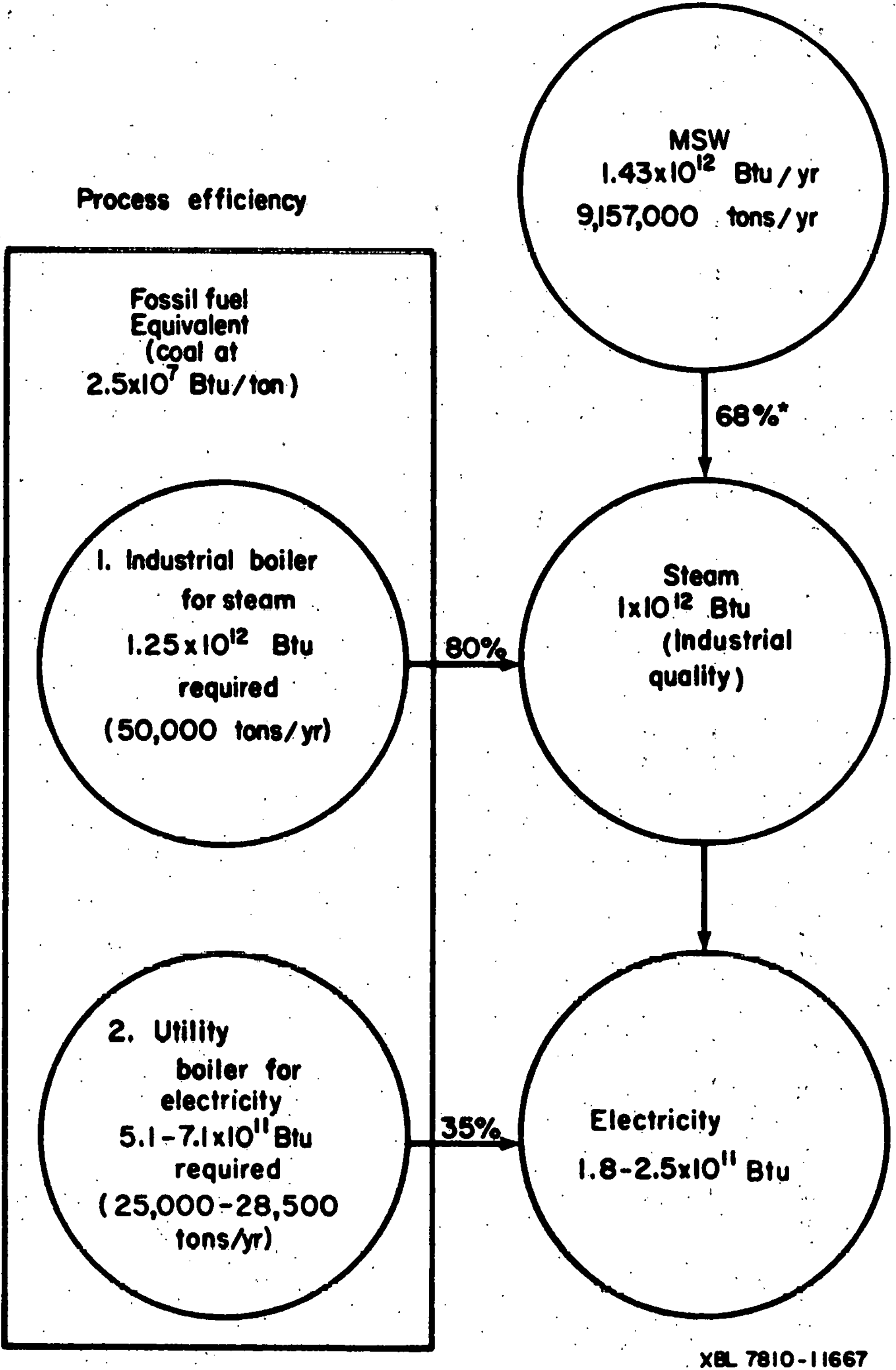
Fig. F-4. Direct Combustion Energy Balance

Gowan, Martin and Monro, 1974; Moore, 1967; Lawler, 1975; Kaiser, 1976 and 1976a; University of California, 1951; Ongerth and Tucker, 1970; Bishop and Deming, 1967; and Hahn, 1970. A 1000 TPD plant following the schematic shown in Figures F-3 and F-4 will produce 1.946 x 10^{12} Btu of steam per year working at an 85 percent on-line rate. This MSW would then replace approximately 97,500 tons of coal per year which would otherwise be required to produce industrial quality steam.

Determination of the fossil fuel equivalency of MSW for a direct combustion system is depicted in Figure F-5. The design end use for the direct combustion energy product is industrial process steam. Direct MSW combustion incinerators produce relatively low pressure (150 psi to 500 psi) and low temperature (400-600°C) steam. In order to produce the same 1 x 10^{12} Btu of industrial steam, 1.25 x 10^{12} Btu of fossil fuel would be required. If, however, MSW-produced steam is converted to electricity as an end use product, only 5.1 x 10^{11} to 7.1 x 10^{11} Btu of coal will be replaced by the MSW system. Assumed system efficiencies for all processes are shown in Figure F-5. MSW conversion efficiency is calculated from Figure F-4.



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*process efficiency

Fig. F-5. Fossil Fuel Equivalency for MSW Direct Time Systems

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APPENDIX G
CHARACTERIZATION OF RDF

The chemical composition of RDF determines not only its heating value but also its emission control problems. Table G-1 provides a comparison of the typical composition of raw refuse and RDF using reasonable estimates for non-site specific analysis. The chemical composition for air-classified RDF (as used by Union Electric at St. Louis and by the city of Ames) and the wet-pulped RDF (Black Clawson fuel) is shown in comparison with coal in Table G-2.

The pollution problems of sulfur, nitrogen, ash and chlorine prevail for each fuel. The amount of sulfur in refuse fuels is significantly lower than coal. It is expected that there will be no difficulty in achieving the sulfur standards established for stationary sources. Nitrogen levels are also lower than those of coal and should pose no serious problems that could not be controlled. There is typically twice the ash content in RDF as there is in coal. The overall effects of ash are to increase operating and capital costs due to handling of bottom and fly ash. Increased ash levels may result in additional residuals in the air emission and boiler residue which will require further process control. The chlorine content of RDF is also enhanced because of the presence of plastics in the combustible fraction. The potential environmental impacts related to the pollutants listed above are discussed in another section (Environmental Data).

The materials and energy balance for a typical RDF system are shown in Figures G-1 and G-2. The values shown are amount per ton MSW input. In addition, in the materials balance diagram the amount-per-10^{12}-Btu of output is also included.

Table G-1
Comparison of Raw Refuse and RDF

Category	Raw Refuse	Refuse Fuel
Ultimate Analysis of Refuse (1% weight)		
Carbon	26.18	32.73
Hydrogen	3.51	4.33
Oxygen	22.08	28.79
Nitrogen	0.58	0.55
Sulfur	0.10	0.11
Chlorine	0.08	0.01
Noncombustibles	22.47	9.29
Moisture	25.00	24.14
Proximate Analysis of Refuse		
Moisture	25.00	24.14
Volatile matter	45.89	58.50
Fixed carbon	6.64	8.07
Noncombustibles	22.47	9.29
Heating Value		
Organic	4,622	5,858
Partial oxidation of metal	78	8
Total Btu's per Pound	4,700	5,866

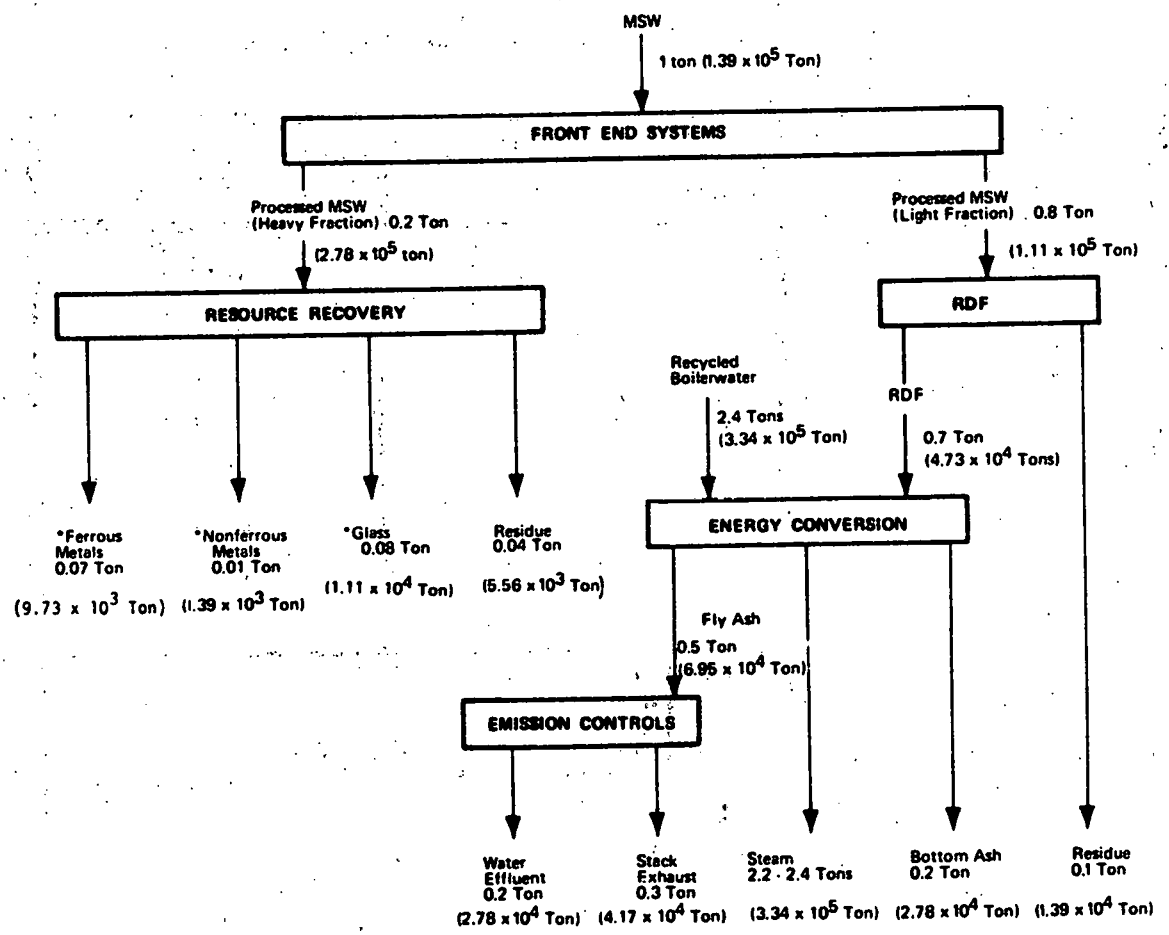
Source: Barnett, S.M. <u>et al.</u>, <u>Energy From Solid Waste Utilization</u>, Proceedings of the Sixth Annual Northeastern Regional Anti-Pollution Conference, University of Rhode Island, July 8-9, 1975.

Table G-2

Comparison of the Chemical Composition of Fuels

	Coal	Air Classified RDF	Hydropulped RDF
H_2O moisture	8.96	26.04	50
C_2 carbon	63.31	27.23	23.26
H_2 hydrogen	4.75	3.85	3.3
N_2 nitrogen	1.02	0.28	0.33
Cl chlorine	0.12	0.20	0.72
O_2 oxygen	9.98	21.49	17.26
Ash	11.28	20.63	5.6
S_2 sulfur	3.38	0.26	0.09

Source: Environmental Science & Technology, May 1975.



[a] Values shown as amount per ton MSW input and (amount per 10^{12} Btu of output).

*Potentially recoverable materials.

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Fig. G-1. RDF System—Materials Balance[a]

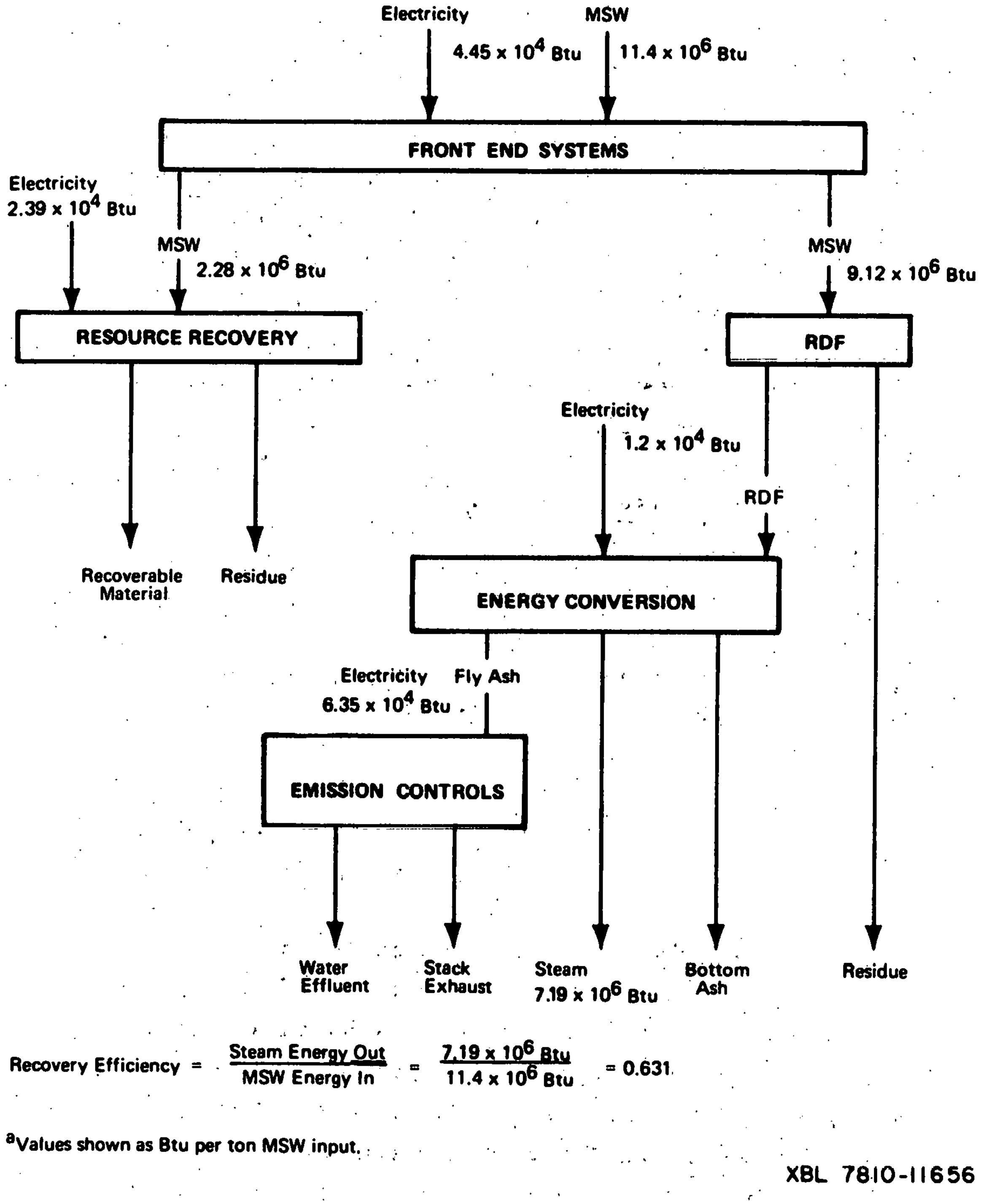

Fig. G-2. RDF System Energy Balance[a]

APPENDIX H
PYROLYSIS CONVERSION OF MSW

This appendix contains additional information on pyrolysis energy recovery systems to that contained in the Application and Environmental Data section of the report. Specifically, limited information on the basic chemistry of pyrolytic reactions, an expansion of the advantages and drawbacks to pyrolytic systems, additional description data on the PUROX sytems, and general descriptions of the Landguard and Garrett Research processes are included.

Chemistry of Pyrolysis

The elemental composition of the organic fraction of MSW roughly approximates that of cellulose which can be chemically represented as $(C_6H_{10}O_5)_n$, where n indicates the number of basic chemical units (Weinstein and Toro, 1976). With this approximation a simple pyrolytic reaction can be represented as (Weinstein and Toro, 1976):

$$\text{MSW} \equiv C_6H_{10}O_5 \xrightarrow{\text{heat}} \text{fuel gas with } CO_2 \text{ and } H_2O + \text{pyrolytic oil}$$
$$+ \text{ other condensibles} + \text{carbonaceous solid residue}$$

The relative yield of each of these basic product components is dependent upon the specific characteristics of the input MSW and upon the control conditions of the pyrolysis reaction. The primary control conditions include temperature, pressure and the use of catalysts or oxydizing agents. The relative product mix is most sensitive to the reaction temperature, and, in fact, this control is used to separate gas-producing from oil-producing pyrolytic systems. The effects of temperature variation on the resulting product mix and product gas composition are shown in Table H-1 and Figure H-1, respectively. The relative product mix from a typical pyrolytic reaction is shown in Table H-2.

Table H-1

The Effect of Temperature on Pyrolysis Yields
(Weinstein and Toro, 1976)

Pyrolysis Temperature, °C (°F)	482 (900)	649 (1200)	816 (1500)	927 (1700)
Product Yields, weight %				
Gases	12.33	18.64	23.69	24.36
Volatile Condensibles[a]	43.37	29.20	47.99	46.96
Other Condensibles	17.71	9.98	11.68	11.74
Char	24.71	21.80	17.24	17.67
	98.12	99.62	100.60	100.73

Pyrolysis System Advantages and Drawbacks

Pyrolysis systems have several key general advantages over other systems. Briefly, these include: fuel compataibility (pyrolytic fuel can be varied between oil and gas and can be subsequently converted to methanol, ammonia or other end use products); gaseous emissions can be minimized by collecting the off-gasses as an energy fuel; the processes are efficient and economical to run. General drawbacks include high capital costs and high corrosion and deposition rates on refractory walls and waterwall boiler tubes.

Advantages and disadvantages of specific pyrolysis systems are shown in Table H-3. Based largely on this tabular comparison, the PUROX system was selected as the model application.

PUROX System

A basic description of the PUROX system is contained in the Applications section of the report. This section presents supplemental information on the characteristics of the systems, its products and on the mass and energy flows through the systems.

An average analysis of the PUROX product gas is shown in Table H-4, and a comparison of this fuel with other common gaseous fuels is shown in Table H-5. Average composition of the slag aggregate is shown in Table H-6. This aggregate is suitable for sale to various industries including road construction.

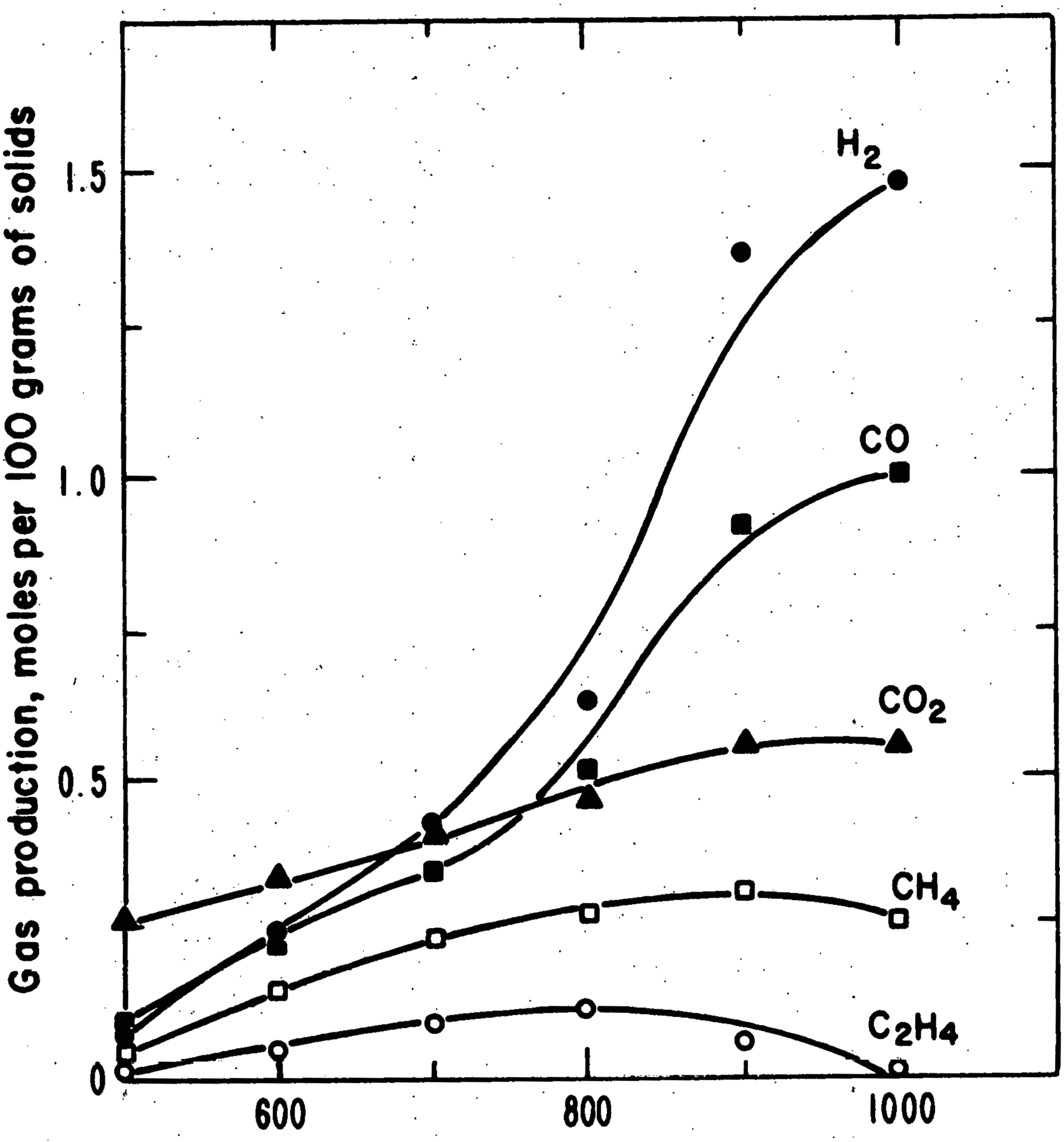

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Fig. H-1. Gas Production—Laboratory Pyrolysis of Municipal Solid Waste[1]

[1] from McFarland, J.M., 1972

Table H-2

Simple Pyrolysis

Fraction	Char	Pyrolytic Oil
Yield, weight %	20	45
Composition, weight %		
Carbon	48.8	57.5
Hydrogen	3.9	7.6
Nitrogen	1.1	0.9
Sulfur	0.3	0.1
Ash	31.8	0.2
Chlorine	0.2	0.3
Oxygen (by diff.)	13.9	33.4
	100.0	100.0
Heating Value, cal/g (BTU/lb)	5000 (9000)	5830 (10,500)

Fraction	Gas	Water
Yield, weight %	20	15

	Volume %		Contains
	0.1	Water	Acetaldehyde
	42.0	Carbon Monoxide	Acetone Formic Acid
	27.0	Carbon Dioxide	Furfural
	10.5	Hydrogen	Methanol
	0.1	Methyl Chloride	Methyl Furfural
	5.9	Methane	Phenol
	4.5	Ethane	Etc.
	8.9	C_3 to C_7 hydrocarbons	
	99.0		

Table H-3

Advantages and Drawbacks of Pyrolysis Systems

System	Advantages	Disadvantages
Garrett flash	Over 2 years operating experience with pilot plant Does not require auxiliary fuel for preheat Produces oil -- storable and transportable (8500-10, 500 Btu/lb) Potential for recovery of clean glass and iron Process flexible -- can produce oil (1 barrel/ton) or gas (6000 scf/ton) Produces dry char -- heating value 9000 Btu/lb	Requires ultrafine size reduction of refuse -- 0. 015 in. Refuse must be predried -- 2 to 3% moisture Agglomerating noncombustibles, especially glass, may contaminate fluidized bed Char highly alkaline and corrosive Fuel oil -- low flash point ~ 130°F; objectionable odor, highly alkaline, and high viscosity Requires extensive water purification Entire process -- especially front end equipment -- very expensive
Monsanto	Operating experience with pilot plant since 1969 Produces gas -- burned to produce low-pressure steam (1 ton/day refuse produces 200 lb/hr steam) Potential for recovery of iron Does not require predrying of refuse	Shredding of refuse to -6 in. Restricted to normal municipal refuse Char is wet, as produced: requires drying Char -- highly alkaline pH12: low heating value Gas scrubber required Auxiliary fuel for preheat
Union Carbide	Some operating experience with 5-tons/day pilot plant Generally accepts normal refuse without size reduction Gas produced -- high heating value 300 Btu/scf, relatively clean, and can be upgraded by methanation NO_x production virtually precluded Fuel gas requires less air per scf or per 1000 Btu than natural gas Molten residue -- potential for metals recovery Does not require auxiliary fuel	Considerable investment in a large O_2 plant Requires size reduction of bulky refuse Requires gas cleaning train -- electrostatic precipitator, acid absorber, and condenser Water purification for condenser and cooling tower water
Urban Research and Development	Some operating experience with pilot plant Generally accepts normal municipal refuse without size reduction Uses air with a more conventional degree of preheat Gas produced by the process is fired for preheat, no auxiliary fuel needed Air heater -- a normal boiler	Produces low-grade gas -- 200 Btu/scf Cleaning of flue gas required Requires glass and iron in refuse to permit proper fluxing for slag flow Size reduction -- 4 ft required for bulky waste
Torrax	Longest operating experience -- 3 to 4 years, with 75-ton/day pilot plant Accepts normal municipal refuse as received. No shredding Shaft furnace problems -- material hangup and gaseous reactant medium flow through the bed appear to have been resolved	Requires separately fired, expensive ceramic preheater Auxiliary fuel -- about 20% of the heating value of refuse -- required Produces low-Btu fuel gas Size reduction of bulky waste required
City of Charleston	Long operating experience, 2-3 years, on bench scale Fuel gas has high heating value -- half of natural gas	Requires size reduction of normal municipal refuse Progress appears slow -- project still in early research phase

Table H-4

Typical PUROX Fuel Gas Analysis

	Volume %
H_2	26 - 30
CO	40 - 50
CO_2	17 - 23
CH_4	4 - 5
C_2+	3 - 5
N_2, A,	.5 - 1
	approximately 100

From: Bonnet, 1975

Table H-5

Comparison of PUROX Gas and Other Gaseous Fuels[1]

Property	PUROX Fuel Gas	CH_4	C_3H_8	C_4H_{10}
Btu/scf	300-310	950	2400	3100
Compression Power[2] (Kwhr/mm Btu)	4.3-5.2	1.4	0.5	0.35
Combusion air requirement (SCF/mm Btu)	8000-8200	10,600	10,400	10,400
Volume of Combustion Products (SCF/mm Btu)	10,100-10,300	11,100	10,800	10,800
Heat Released/Volume of Combustion Products (Btu/SCF)	95-101	90	92	92

1. From Marple, 1974; and Donnegan, 1975.
2. Gas compressed to 35 psig from 1 atm., 100 F with 75% efficiency

Table H-6

Average Slag Analysis

MnO	0.3
SiO_2	50.7
CaO	10.3
Al_2O_3	10.5
TiO_2	0.6
BaO	0.2
P_2O_5	0.1
FeO	6.2
MgO	2.2
Na_2O	8.0
K_2O	1.0
CuO	0.2
Misc.	0.7
	100.0

From: Bonnet, 1975

Detailed mass and energy balances for the process are contained in Figures H-2 and H-3, respectively. The PUROX process as described in this study does not include conversion of the fuel gas to any other end use fuel. However, processes exist to convert pyrolytic gas to several common products including ammonia and methanol. Figure H-4 shows material and energy flows through a methanol subsystem designed to act as an add-on to the PUROX process. A schematic diagram for such a conversion process is shown in Figure H-5. A summary of the overall PUROX system inputs and outputs is shown in Table H-7.

Landguard System

The Monsanto Landguard plant installed at Baltimore, Maryland, is a 1000-TPD plant sited on a 10-acre panel and costing a total of $19 million. Six million of this total was provided to the city by a Section 208 EPA grant, and $4 million by the Maryland Environmental Services. The plant has been designed and constructed by Monsanto Enviro-Chem Systems, Inc. Initial construction of the plant was completed in June of 1975 and production testing was begun. Immediate major problems which arose included the inability of the scrubber system to meet state and federal emission standards, premature failure of the kiln refractory, and various mechanical problems. While these problems were basically corrected by mid-1976, new problems caused Monsanto to abandon the project as of January, 1977. The City of Baltimore still plans to operate the plant on a reduced scale (Solid Wastes Management, March 1977).

In defense of the Landguard system it should be noted that two 35-TPD test plants (one in St. Louis, Missouri and one in Kobe, Japan) both have met all design specification and emission standards (Sussman, 1974; Hamabe *et al.*, 1975). MSW tested at the Kobe plant was high in both moisture and plastics content. In addition, various industrial wastes and sewage sludge were tested. Both air and water emission standards were met in all tests (Hamabe *et al.*, 1975).

The major inputs to this system in addition to MSW are labor (the Baltimore plant uses 31 employees for 24 hr/day operation), water at a rate of 638 gallons per ton of MSW, electrical energy at a rate of 225 kW-hr

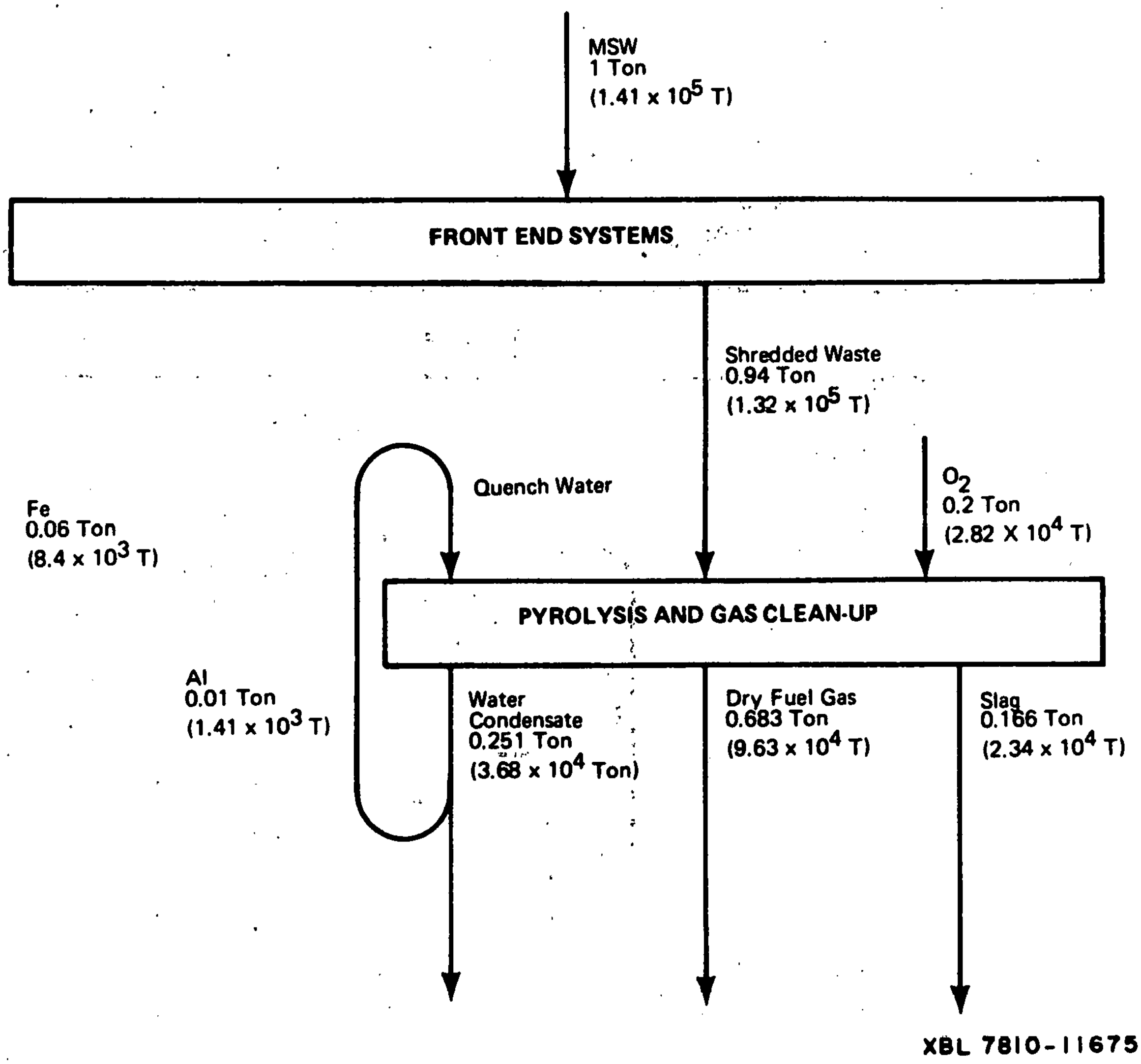
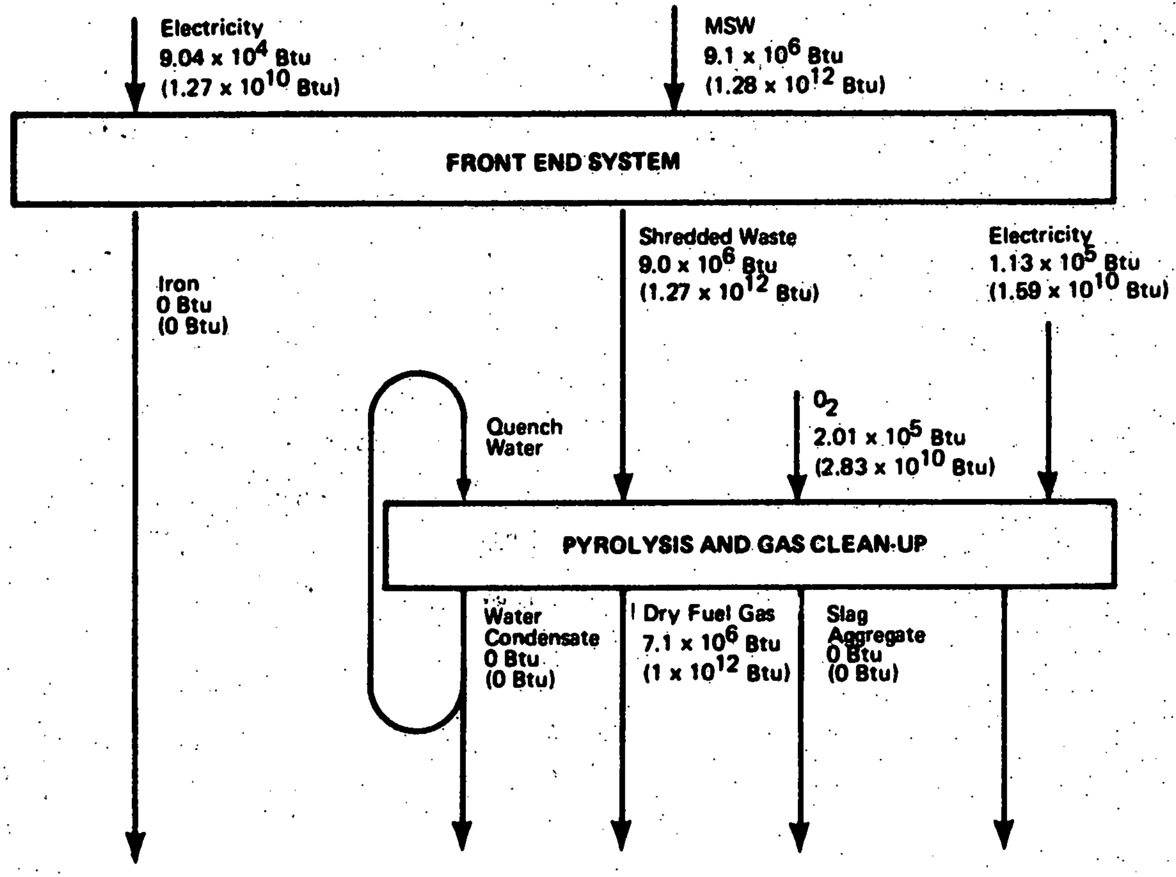


Fig. H-2. PUROX System Material Balance



$$\text{Efficiency} = \frac{\text{Energy Out}}{\text{Energy In}} = \frac{1 \times 10^{12}\ \text{Btu}}{1.34 \times 10^{12}\ \text{Btu}} = 0.748$$

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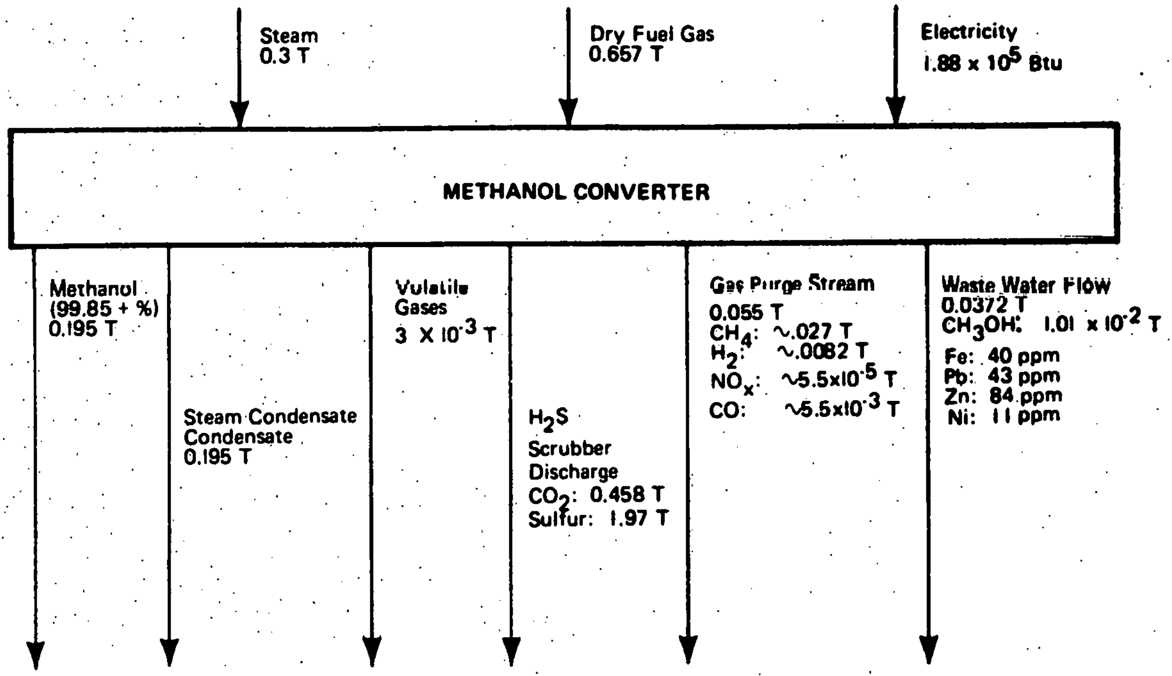
Fig. H-3. PUROX System Energy Balance



From: Mathematical Sciences Northwest, 1974

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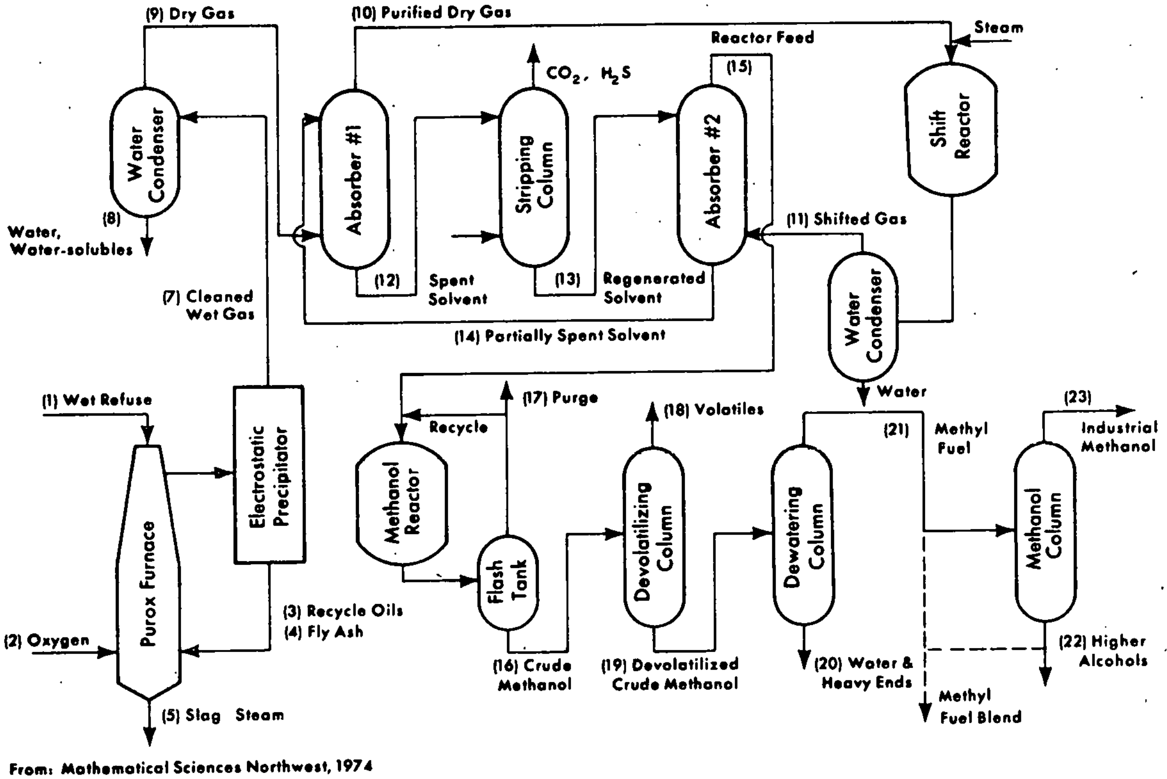
Fig. H-4. Methanol Converter System Input/Output Diagram (per ton of MSW input)



From: Mathematical Sciences Northwest, 1974

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Fig. H-5. Methanol from Refuse~~-~~Flow Diagram

Table H-7

PUROX Inputs and Outputs per 10^{12} Btu Output

Inputs	Quantity per 10^{12} Btu Output per year*
Land	20.71 acres
Capital	\$36.82 x 10^6
MSW	1.45 x 10^5 Tons (1.28 x 10^{12} Btu)
Electricity	1.59 x 10^{10} Btu
Oxygen	2.82 x 10^4 Tons (2.83 x 10^{10} Btu)
Outputs	
Iron	8.45 x 10^3 Tons
Slag Aggregate	2.96 x 10^4 Tons
Water Condensate	4.3 x 10^4 Tons
Dry Fuel gas	9.65 x 10^4 Tons (1 x 10^{12} Btu)

---

*Capital residual (Land and Capital are calculated as in Table H-8 based on an annual PUROX system output of 4.345 x 10^{11} Btu.

per ton of MSW and miscellaneous oils and liquid fuels at a rate of 7.3 gallons per ton of MSW.

The basic products of the system are steam at a rate of 2.4 tons per ton of MSW, glass, ferrous metals and aluminum for recycling, and a 94-percent reduction in the volume of the solid wastes to be land filled (Sussman, 1974; California State Solid Wastes Management Board, 1975). The one intermediate product, pyrolysis gas, is a low Btu gas (approximately 120 Btu/cubic ft) and on a dry basis consists of approximately 69.3 percent nitrogen, 11.4 percent CO_2, 6.5 percent CO, 6.6 percent hydrogen and minor amounts of methane, ethylene and oxygen (Sussman, 1974). This gas is burned in an afterburner to generate product steam.

As a rotary kiln process, the Landguard system requires only coarse shredding of incoming MSW. This waste is then stored and ram fed directly into the kiln where fuel oil is added to drive the pyrolysis reaction. Char produced in the kiln is quenched and sorted in accordance with the assumed design of the basic resource recovery module. Gasses produced in the kiln are burned to completion in an afterburner at 1400°F. Gas turbines are not employed in this system. Waste heat is directed into two parallel boilers to generate 200,000 pounds of steam per hour. Waste gasses are scrubbed and are passed through a cooling dehumidifier prior to discharge. Scrubber waste water passes through a settling tank where flocculent is added, with the overflow being recycled to the scrubbers and the underflow being used as quench water for the solid char.

A basic mass balance for this system is shown in Figure H-6. The system energy balance is shown in Figure H-7. Data for these figures were compiled from a joint analysis of work by: Mallan and Titlow, 1975; Sussman, 1974; California State Solid Waste Management Board, 1977 and 1975; Quimby, 1975; Weinstein and Toro, 1976; Malin, 1971; Hamabe _et al._, 1975; Livingston, 1976; Sessler, 1975; Schnelle and Yamamoto, 1975. Basis efficiency parameters are shown in Figure H-8. Total projected output of a 1000-TPD Languard plant is 1.701×10^{12} Btu (7.34×10^{5} tons of steam per year). A summary of the overall system inputs and outputs is shown in Table H-8.

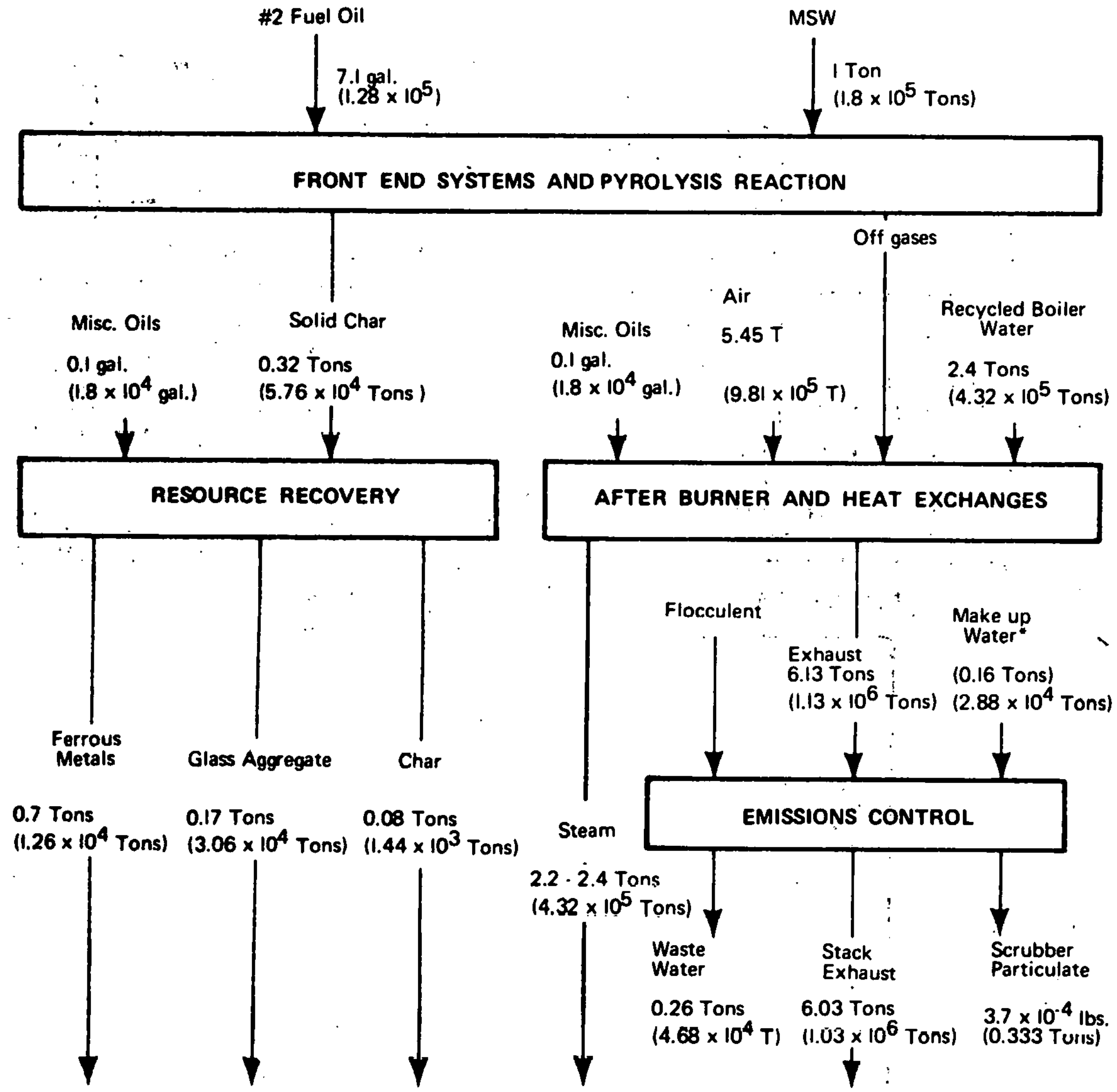

Figure shown as amount per ton of MSW input and (amount per 10^{12} Btu of steam output)

*Water makeup assigned to emission control module; however, some of this water is used in char waterquench.

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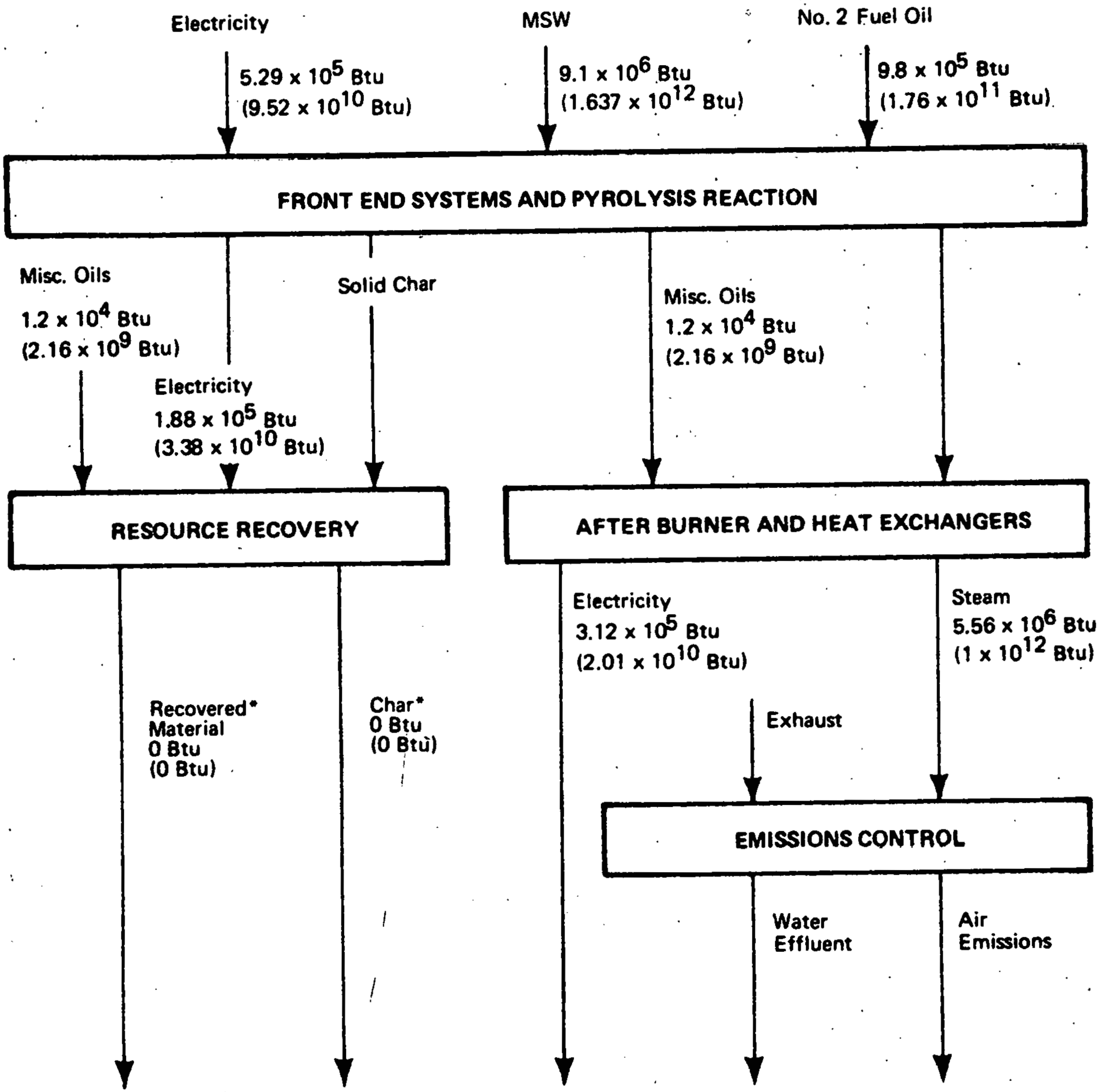
Fig. H-6. Landguard Pyrolysis System Mass Balance



$$\text{Recovery Efficiency} = \frac{\text{MSW Energy Out}}{\text{Steam Energy In}} = \frac{1.000 \times 10^{12}\ \text{Btu}}{1.637 \times 10^{12}\ \text{Btu}} = 0.611$$

$$\text{System Efficiency} = \frac{\text{Total Energy Out}}{\text{Total Energy In}} = \frac{1.0 \times 10^{12}\ \text{Btu}}{1.97 \times 10^{12}\ \text{Btu}} = 0.508$$

*Energy content of recycled material and of char is defined as zero since all energy is unrecoverable.

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Fig. H-7. Landguard Pyrolysis System Energy Balance

Table H-8

Landguard System Input/Output Summary

Inputs	Amount per 10^{12} Btu steam output per year*
Land	5.9 acres
Capital Costs	\$11.2 x 10^6
MSW	1.8 x 10^5 Tons (1.637 x 10^{12} Btu)
Air	1.78 x 10^5 Tons
#2 Fuel Oil	1.28 x 10^6 gal (1.76 x 10^{11} Btu)
Water	1.15 x 10^8 gal (353 acre ft)
Electricity	4.05 x 10^4 Mwhr (1.38 x 10^{11} Btu)
Misc. Fuels and Oils	3.6 x 10^4 gal (4.32 x 10^9 Btu)
Outputs	
Steam	4.32 x 10^5 Tons (1 x 10^{12} Btu)
Ferrous Metals	1.26 x 10^3 Tons
Glassy Aggregate	3.06 x 10^4 Tons
Char	1.44 x 10^3 Tons
Waste water discharge	4.68 x 10^4 Tons
Stack exhaust	1.103 x 10^6 Tons
Scrubber particulate recovery	33.3 Tons

*For capital resources figures given as input per 10^{12} Btu annual output. Thus if plant output = 2 x 10^{12} Btu annual output = total required input divided by 2.

Effluent flows for the Landguard system are summarized in Table H-9. Table H-10 summarizes mean residual generation rates per 10^{12} Btu of steam output. SEAS input forms for residuals are contained in the Appendix to this report. Waterborne effluent flows are less than 75 gpm. To date no data on residual concentration are available. However, this pollutant flow is though to be relatively free of particulate BOD and COD concentrations.

Projected system operating economics are shown in Table H-11. Greater detail on capital and operating input is contained in the Capital Requirements section of this report.

Garrett Flash Pyrolysis

The Garrett flash pyrolysis system differs from the previous two systems in that it is an oil-producing system. It also has the most extensive front end system of the three pyrolysis plants described in this report. This plant uses a low temperature (900°F - 1300°F) flash pyrolysis to produce the product mix described in Table H-12. As described, this pyrolytic oil is a direct substitute for Bunker C oil (Preston, 1976). The flash pyrolysis process was developed privately by the Garrett Research Corporation on a 4 TPD test plant. Following successful testing of that system, a 200-TPD prototype was completed in 1976 for San Diego County under partial funding by U.S. Environmental Protection Agency and by San Diego Gas and Electric Company at a total cost of between $18 and $20 million. System tests evaluations and adjustments have been made over the 1976-1978 period, including both MSW tests and tests on various industrial waste streams.

The front end system for this plant includes resource recovery of ferrous metals, aluminum and glass as well as both coarse and fine shredding of the organic wastes. The specific flow diagram for this front end process is shown in Figure H-8. While this system provides expanded resource recovery, it does so by incurring a significant capital and operational cost. Estimated capital cost of this expanded front end system is between $1.5 million and $2.5 million. The added operational cost is primarily an added electrical energy requirement (approximately 40 kW-hr/ton of MSW or 1.37×10^5 Btu/ton of MSW) and a

Table H-9

Landguard Stack Effluents per 10^{12} Btu Output

Pollutant	Residuals per 10^{12} Btu System Output
NO_x	77.2 Tons
SO_2	127 Tons
Particulates	7.6 Tons
HCL	306 Tons
Hydrocarbons	12 Tons
Chlorides	55.2 Tons

Table H-10

Landguard System Stack Residuals

Pollutant	Source of Estimate					Mean
	CA State Solid Waste Mgmt. Board, 1976	Boss, 1974	Sussman, 1974	Malin, 1971	Weinstein and Toro, 1976	
NO_x	100 ppm		50 ppm	50 ppm	65 ppm	70 ppm
SO_2	$\sim$100 ppm			100 ppm	100 ppm	115 ppm
Particulates*	.02 gr/scf	.03 gr/scf	.03 gr/scf	.03 gr/scf	.02 gr/scf	.03 gr/scf
HCl	3.4 lb/ton					3.4 lb/ton
Hydrocarbons					10 ppm	10 ppm
Chlorides					25 ppm	25 ppm

*corrected to 12% CO_2

Table H-11

Landguard System Economics ($per ton of MSW)

Amortization		$5.55
Operating Cost		
Material inputs	4.00	
Manpower	1.10	
Maintenance	1.80	
Miscellaneous	.60	
		$7.60
Total Cost		$13.15
Revenues		
Steam	6.18	
Iron	1.55	
Glassy Aggregate	.40	
		$8.13
Net Cost per Ton		$5.02

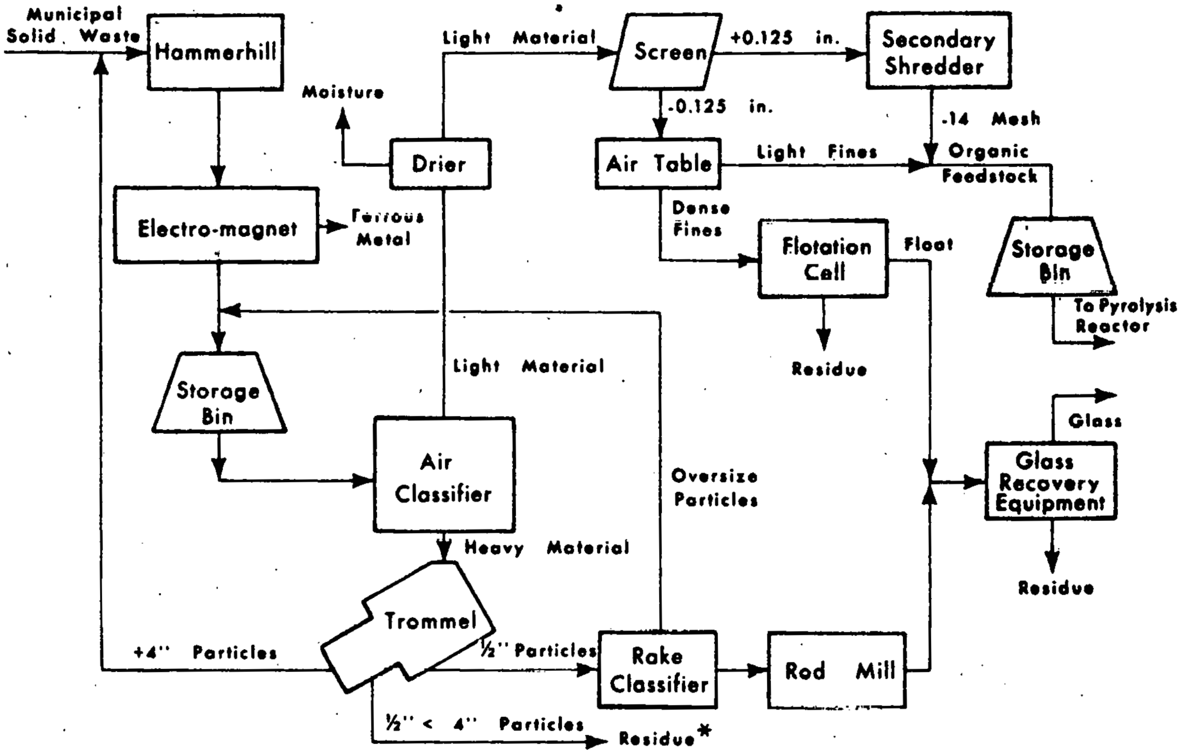
From Cal. State Solid Waste Management Board, 1975; Sussman, 1974.

Table H-12

Garrett Flash Pyrolysis Products

Major Product	% Composition	Major Components	% Composition
1. Char	20%	C	48-50%
		Ash	30-35%
		O	13-14%
		other	4-9%
			100%
2. Oil	40%	C	55-58%
		O	32-35%
		H	6-9%
		N	1-1.5%
		other	2-6%
			100%
3. Gas	30%	H_2	11-13%
		CO	35-40%
		CO_2	35-40%
		CH_4	4-8%
		C_2H_4	2-4%
		other	3-7%
			100%
4. Water	10%		
	100%		

From Preston, 1976; Levy, 1975.



* This would be the feedstock to an aluminum recovery plant.

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Fig. H-8. Garrett Flash Pyrolysis Front End System (Levy, 1975) an increased maintenance requirement. The majority of the added energy cost is for the required fine shredding process. Figure H- 9 shows the energy cost associated with this single process.

The pyrolytic gas and most of the char produced in the pyrolytic reaction are recycled into the pyrolytic furnace. This gas is the driving force for the pyrolytic reaction. A mechanical separator and an oil decanter are used to separate the product oil from char and gas, respectively. After gas cleanup, excess process gas is burned in an afterburner, used to preheat recycled gas and char, and exhausted through a baghouse filter.

The major inputs to this process per ton of MSW include approximately 84 gallons of water (700 lbs), minor amounts (516 units) of No. 2 fuel oil, and 140 kW-hr of electricity. Major products include approximately 41 gallons of oil (338 lbs at 12,390 Btu/lb), 106 pounds of glass aggregate, 165 pounds of ferrous metal, 13.5 pounds of aluminum, 315 pounds of inert material, 500 pounds of waste vapor, 121 pounds of process waste water, and 111 pounds of char. A 200-TPD plant produces 4.188 x 10^6 Btu of oil per ton of MSW for an annual average production of 2.56 x 10^{11} Btu.

The Garrett flash pyrolysis material balance is shown in Figure H-10. The system energy balance is shown in Figure H-12. Data for Figures H-10 and H-11 were obtained from a critical synthesis of data contained in: Preston, 1975 and 1976; Levy, 1974 and 1975; Garbe, 1976; Weinstein and Toro, 1976: International Research and Technology Corporation, 1972; Schnelle and Yamamoto, 1975; and Mallan and Titlow, 1976. Overall energy efficiency of this system as shown in Figure H-11 is 43.3 percent. Major system inputs and outputs are summarized in Table H-13.

Residuals generated by the Garrett process are listed by stream in Table H-14. As can be seen, 100x emissions and COD load in the process waste water stemming from a series of oils and tars formed with, and existing with, the water in the pyrolytic reaction, form major environmental problems for this system.

System economics are listed in the Capital Residual section of this report.

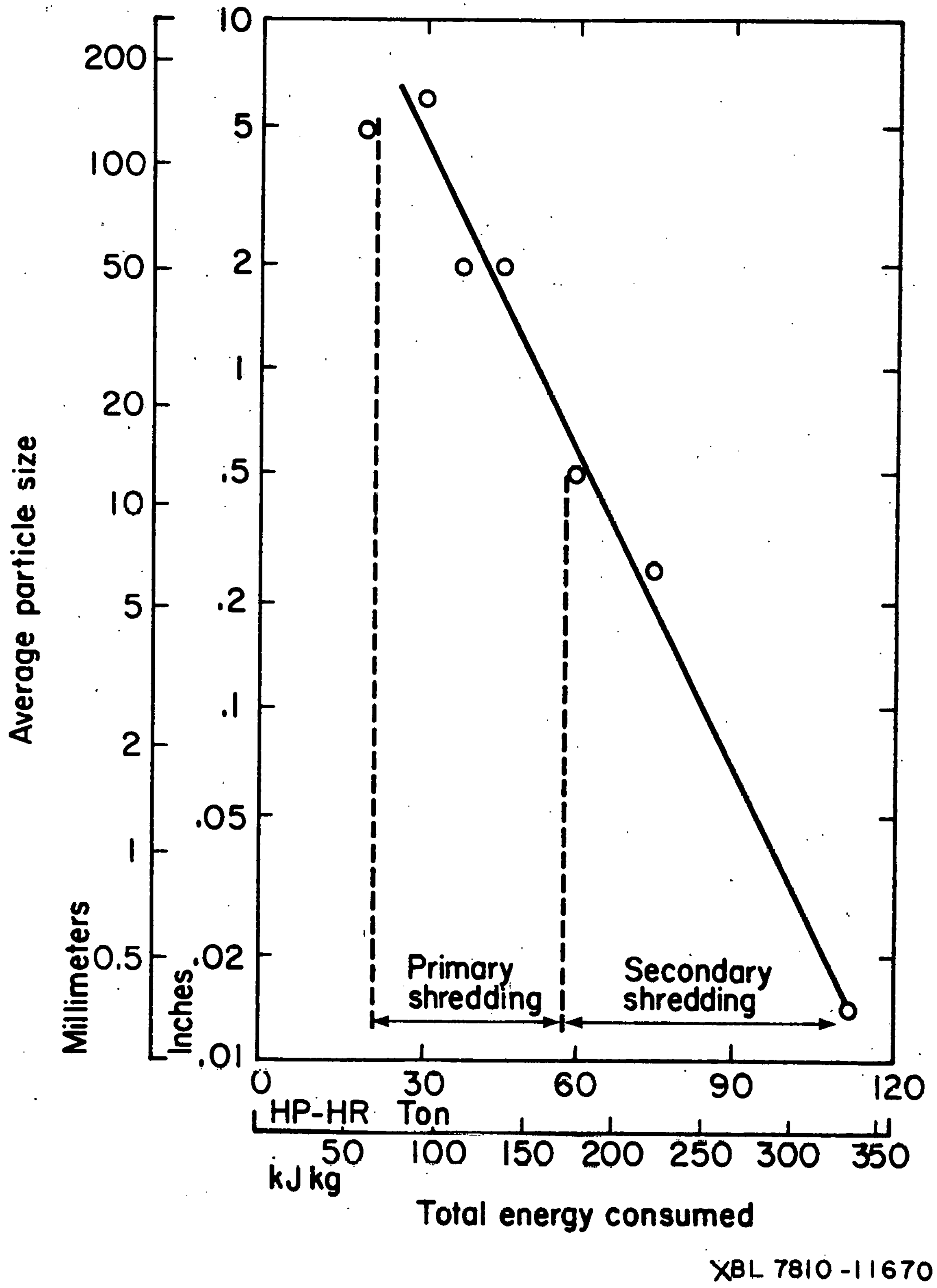


Fig. H-9. Energy Consumption for Primary and Secondary Shredding (Preston, 1976)

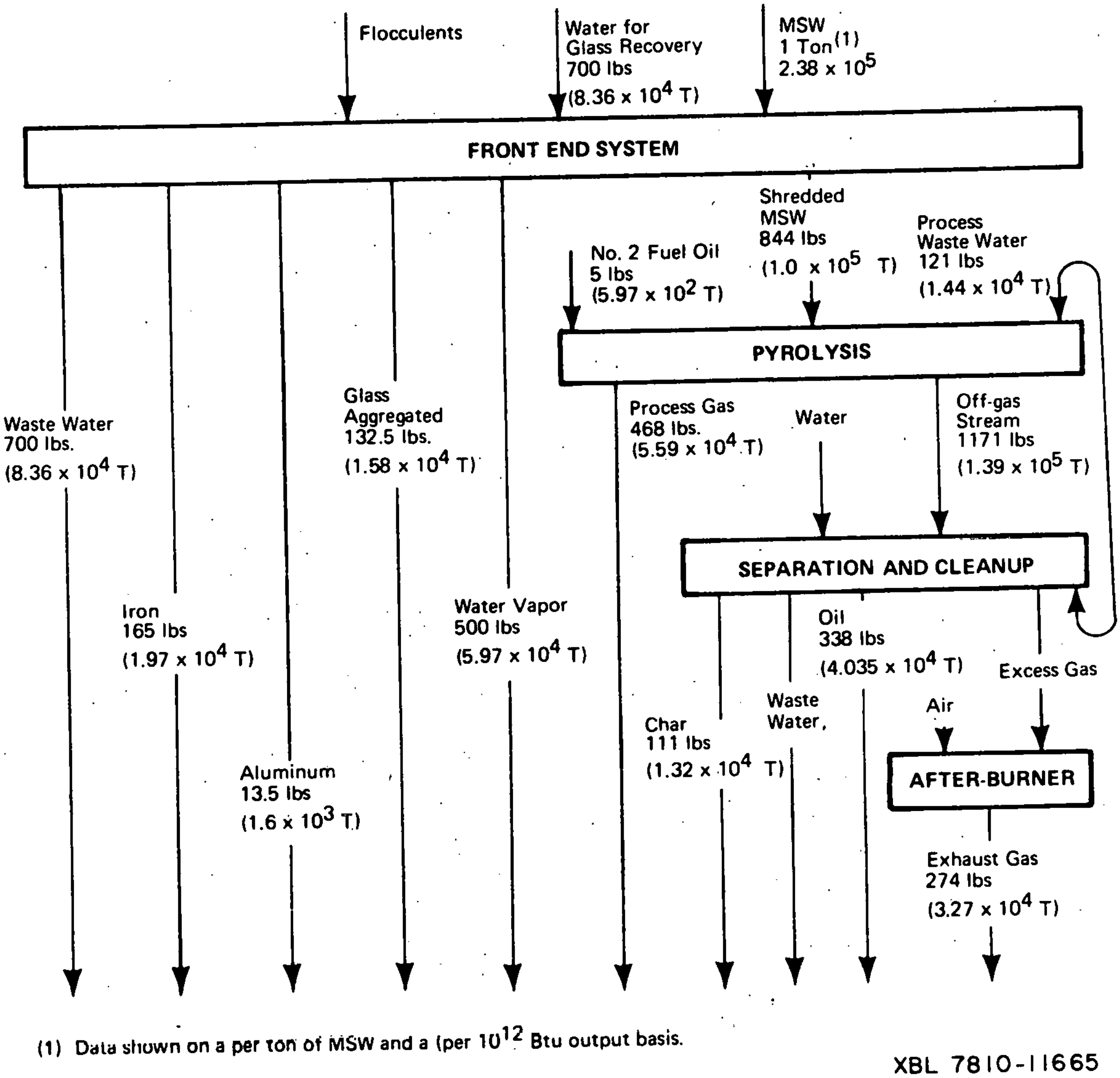
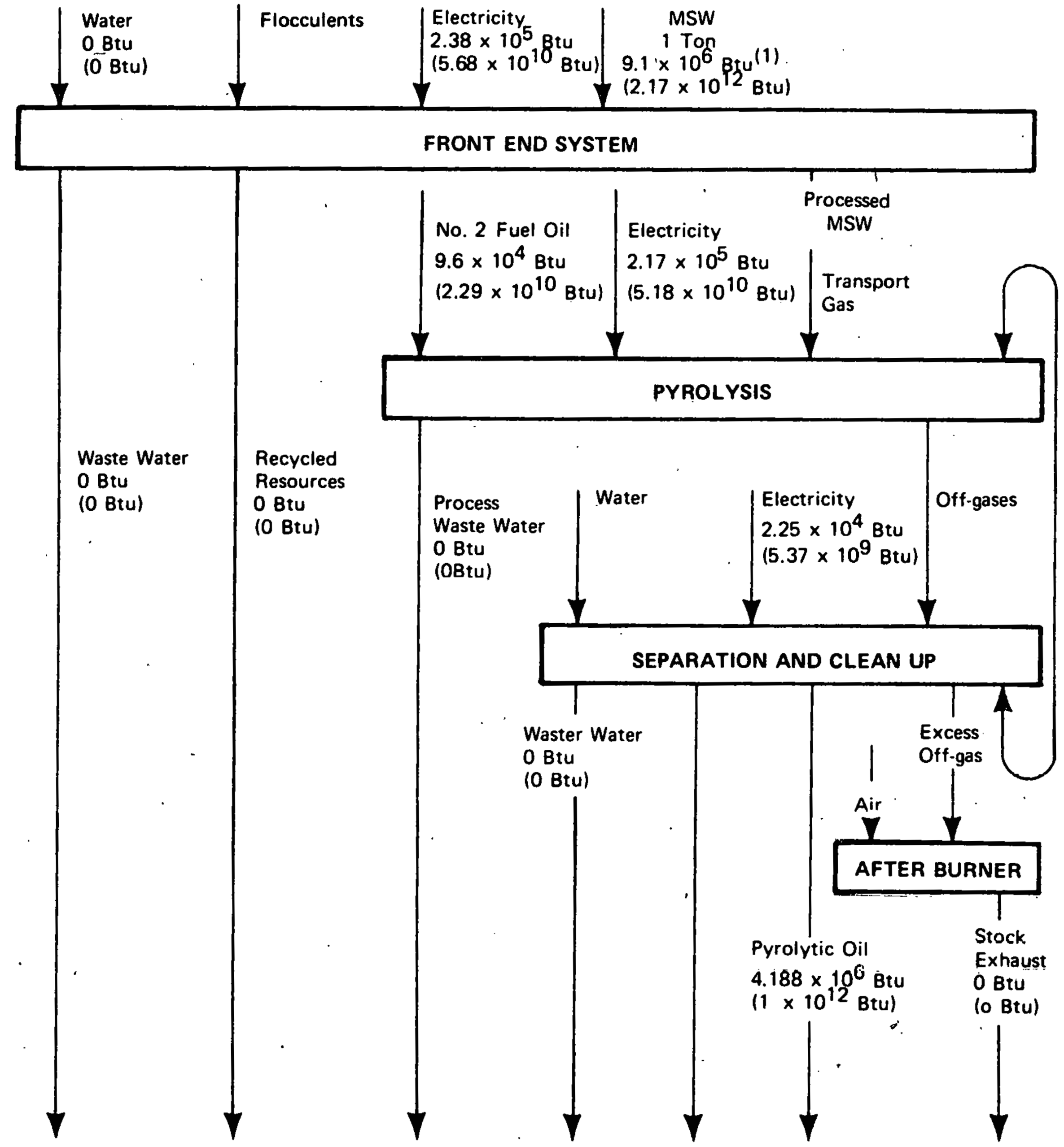


Fig. H-10. Garrett System Material Balance



(1) Numbers describe amount per ton of MSW and amount per 10^{12} Btu output.

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Fig. H-11. Garrett Process Energy Balance

Table H-13

Summary of Major Inputs and Outputs for the Garrett Flash Pyrolysis Process

1. Inputs	Amount Per 10^{12} BTU Output Per Year
Land	35 acres
Capital	\$74.2 x 10^8
MSW	2.38 x 10^5 Tons (2.17 x 10^{12} Btu)
Process water	9.2 x 10^4 Tons
No. 2 Fuel Oil	597 Tons (2.29 x 10^{10} Btu)
Electricity	1.14 x 10^{11} Btu
2. Outputs	
Glass aggregate	1.58 x 10^4 Tons
Iron	1.97 x 10^4 Tons
Aluminum	1.61 x 10^3 Tons
Char	1.325 x 10^4 Tons
Oil	4.035 x 10^4 Tons (1 x 10^{12} Btu)
Exhaust gasses	3.27 x 10^4 Tons
Waste water	1.06 x 10^5 Tons
Water vapor	5.97 x 10^5 Tons

Table H-14

Garrett Process Residuals

Residual	Concentration	Amount per 10^{12} Btu Output
1. Stack Exhaust		
particulates	0.05 grain/scf	
SO_2	700 ppm	22.9 Tons
NOX	250 ppm	8.2 Tons
HCL	100 ppm	3.3 Tons
hydrocarbons	20 ppm	0.65 Tons
2. Process Waste Water Flow		
COD	100,000 ppm	1.44×10^3 Tons
3. Air Classifier and Shredder		
particulates	0.4285 Kg/Ton	112.4 Tons

From Levy, 1975; Preston, 1976; International Research and Technology Corp., 1972; and Sessler and Cukor, 1975.

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APPENDIX I
CAPITAL REQUIREMENTS

INTRODUCTION

This appendix provides background information for the capital costs associated with the technologies listed in Appendix A in the DOE-prescribed format for direct use in the SEAS model.

For each major technology and application, a single plant type is described. Associated with each plant is a specific plant design and plant capacity. The use of a single plant design and material specification to represent a technology as is done in SEAS implies both linearity between plant size (or output) and all major plant inputs, and an independence of plant cost from specific plant design. While the basic SEAS model structure necessitates these assumptions, it is evident that neither is correct and that significant economies of scale can be realized for several technologies. Figure I-1 shows basic unit cost for direct MSW combustion steam recovery system (cost per unit throughput) as a function of plant size. It is evident from this figure that costs for a 1000-TPD plant should not be linearly translated into costs for a 6000-TPD plant or for a 30-TPD plant. Similarly, Figure I-2 shows the non-linear relationship between operational employment requirements for MSW conversion plants and plant size. The use of "average" and mid-range cost figures in this report should minimize the error induced by subsequent linear scaling of plant size and costs by the SEAS model, but will certainly not eliminate the error.

In addition several standard conventions were used to estimate several of the figures listed in Appendix A for capital and operational costs. These conventions are:

- GNP fixed-weighted price indices are used to deflate all data to 1972 dollars.
- 1977 average labor wage rate of $13.00 per hour is used for all labor. Previous year's wage rates are obtained by deflating this rate to other year dollars.

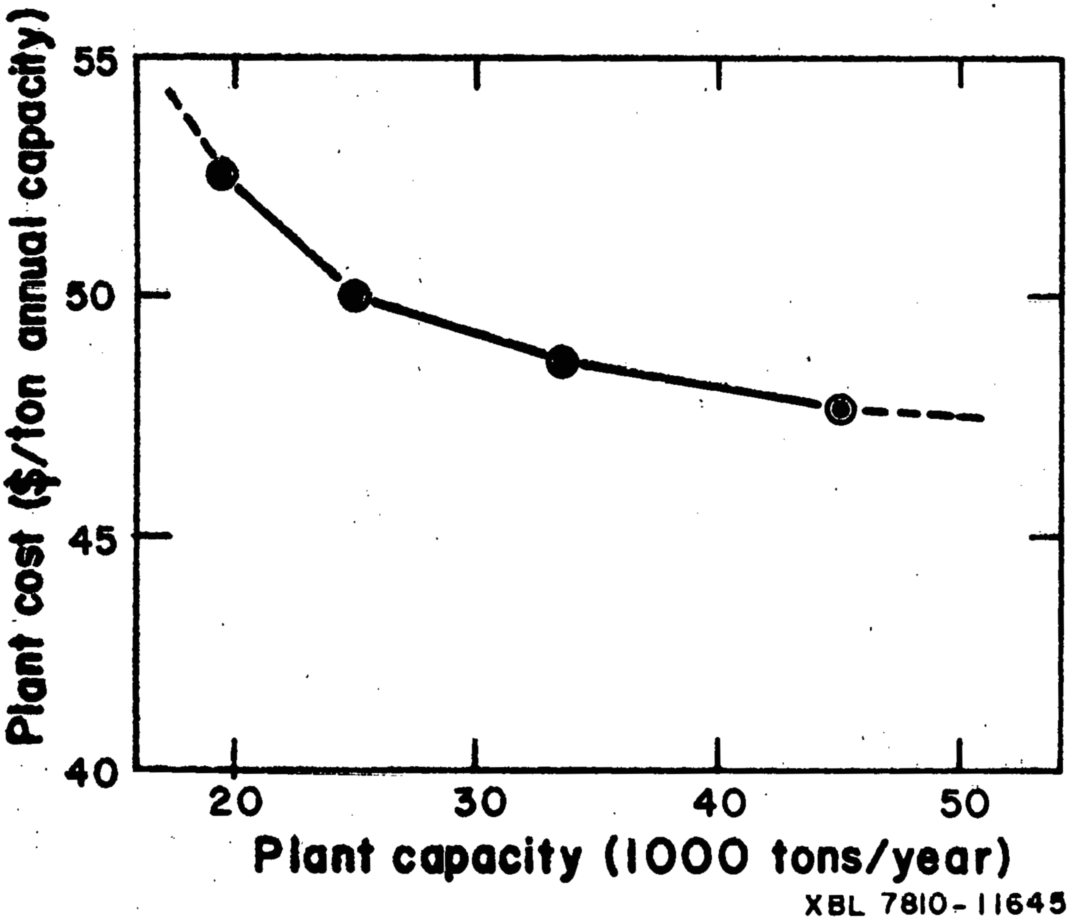
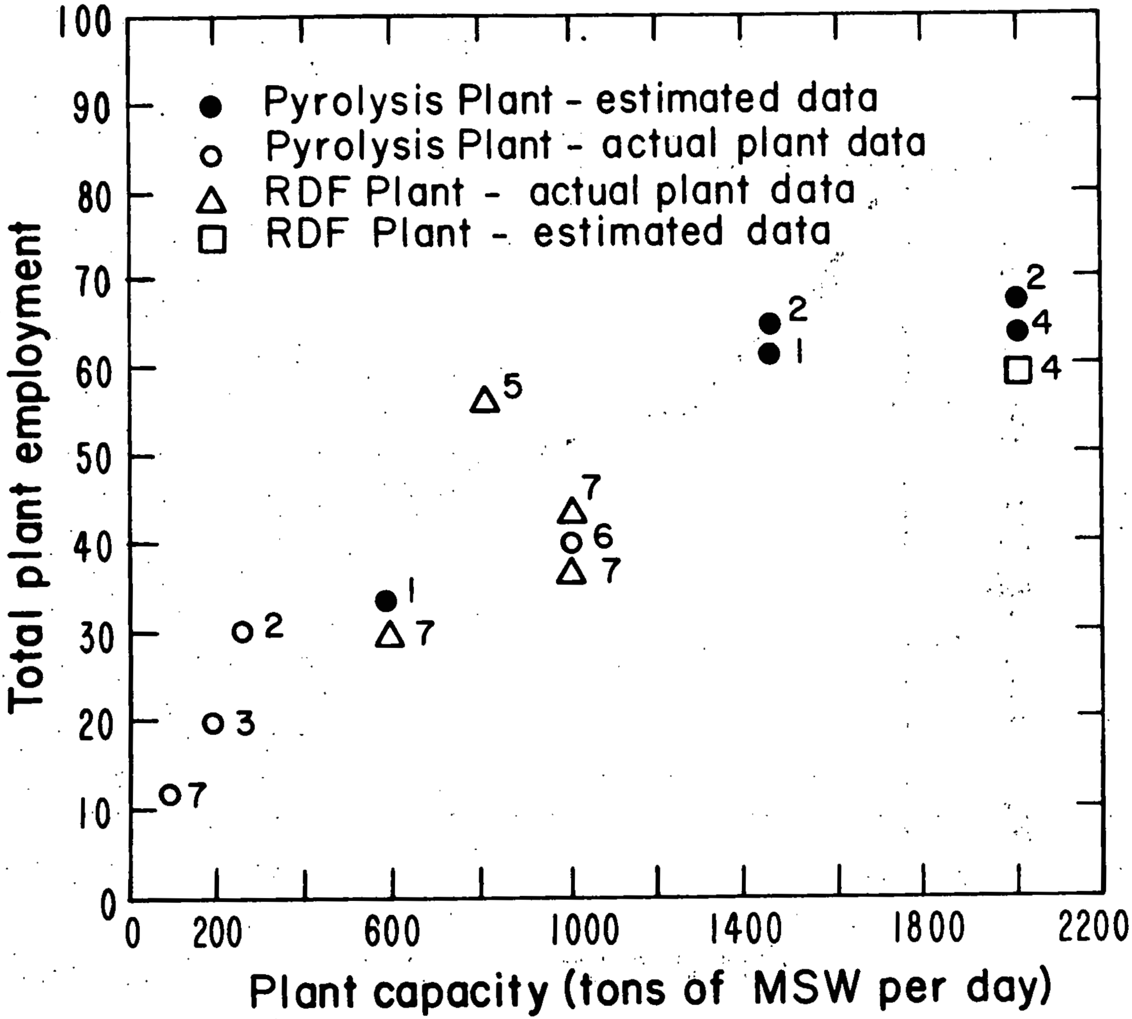


Fig. I-1. Plant Capital Cost as a Function of Plant Size



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2. Sathaye, J. et al., 1977
3. Levy, 1975
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5. Klumb, 1976
6. California State Solid Waste Management Board, 1975
7. General Electric Corporation, 1975

Fig. I-2. Employment Requirements for Various Site Plants

- Overhead on labor costs for construction is assumed to be 30 percent of labor while administrative overhead is assumed to be 10 percent of labor costs. Profit assumed to be 10 percent of total project costs.
- One man-year of labor is assumed equal to 2000 hours.
- In the absence of actual transportation cost estimates, transportation costs (SEAS Sector 169 - Trucking) is assumed equal to 8 percent of actual materials costs.

Cost data for a "typical" plant for each of the following technologies are included in Appendix A: pyrolysis of MSW to electrical energy, generation of RDF from MSW with conversion to electricity, enhanced oil recovery converted to electrical energy, fluidized bed system for the pulp and paper industry, and a diesel system for cogeneration. A brief characterization of each plant for which data is listed in Appendix A is included here so as to document the plant configurations being described.

DIRECT COMBUSTION

The direct combustion system characterized here is based on typical or average data compiled from a large number of municipal furnaces. Not all of these furnaces are used for energy recovery. Data are based on a 1000-TPD system. Ferrous metal, aluminum and glass aggregate recovery systems have been added for labor, capital and ancillary energy requirements. Waterwall boilers are used to produce steam which acts as the primary system product. Recovered resources are sold to local manufacturing markets. Steam is sellable to a variety of manufacturing processes and to electric utilities for electricity.

RDF

A MSW to RDF conversion plant capable of processing approximately 1500 TPD of MSW and a 350-MWe electric power plant using 20 percent RDF and 80 percent coal are included in the capital residual descriptions. The RDF plant design is patterned after Union Electric's

St. Louis RDF plant. Power plant sizing and design are typical of the current generation of intermediate-size plants (<1000 MWe). Electrostatic precipitators are included as an integral element of plant design. RDF products may either be used for electrical generation (as used here) or to support industrial steam production.

PYROLYSIS

The pyrolysis plant described in this report includes both the pyrolysis plants or oxygen production plants and a combined cycle power plant to support a 400-MWe generating capacity. In order to feed the combined cycle with 100 percent pyrolytic gas, 6000-TPD capacity of gas pyrolysis plants are included. These plants are patterned after Union Carbide projections for a 2000-TPD plant paralleling their successful 200-TPD PUROX plant at Charleston West Virginia. Scrubbers and electrostatic percipitators are included as an integral part of the basic plant configuration. Linear scaleup factors are assumed. Gas could support industrial (manufacturing) steam production as an alternate to electricity production. In case final conversion efficiencies are significantly improved (from 32 percent to 80 percent), residuals per 10^{12} Btu output should be adjusted downward by a factor of 2.5.

FLUIDIZED BED

System capital requirement data were derived from Comparative Study and Evaluation of Advanced Cycle Systems by the General Electric Company for the Electric Power Research Institute in February 1978. This work reported a detailed engineering design study on the use of fluidized bed boilers for a utility power plant. That application required 24 FPC cells arranged in six modules. A large number of cells is required due to the small output of fluidized bed boilers. For the pulp and paper cogeneration application considered here, two cells are used in a single module. Each of these cells are scaled to one-third the size of the fluidized beds proposed for utility use. A reduction scale factor of 37 percent is used to account for reductions in module size and number. This scale factor is based on staff judgement but is not supported by industry or other estimates.

ENHANCED OIL RECOVERY

The data for this project are projected from the proposed application in the Kern River Oil Fields which are expected to produce 280 MWe continuous and 1500 bbl/day of oil, half of which will go directly to market. The other half is used as input to the cogeneration system. Data on the gas turbine are from the Bechtel Energy Supply Planning Model. Data on the heat recovery steam generator are from the Westinghouse Energy Conversion Alternatives Study, Volume 5. In each case linear scaling factors were used to match component size to oil field output. Cogeneration system products include both steam and electricity. Steam output is designed to support manufacturing industrial process heat requirements. Electricity can either be used internally within the oil field operations.

DIESEL

The diesel system described here is the most simple of the cogeneration systems included in the study. The system includes only the engine, piping interconnects and transmission interconnects. The application selected is for a municipal sewage disposal plant. Primary engine input fuel for this application is methane derived from municipal sewage sludge and design output capacity is a combined product of 12.6 MWe and 33.8 x 10^6 Btu of steam per hour. Capital residuals and operational residuals are taken from data developed by the Los Angeles Sanitation District and by Williams and Lane, Inc. Operational material input and labor requirements are not available at this time.

FOSSIL FUEL EQUIVALENCY

It is essential that the amount of fossil fuel which would be required to produce the amount of end use energy generated by each energy recovery system were the listed fuel (e.g. MSW) not available, be calculated for use in the SEAS model system. This amount of

Table I-1

System Fossil Fuel Equivalency

System	Product	Output	Efficiency (%)	Fossil Fuel Equivalent Input
Direct Combustion	steam	1x10^{12} Btu	80	1.25x10^{12} Btu
RDF	electricity	2.10^{11} Btu[1]	33	6.06x10^{11} Btu
Pyrolysis (PUROX)	electricity	1x10^{12} Btu	33	3.03x10^{12} Btu
Fluidized Bed	steam	5.54x10^{11} Btu	80	6.93x10^{11} Btu
	electricity	4.46x10^{11} Btu	34	1.31x10^{12} Btu
	Total	1x10^{12} Btu		2.00x10^{12} Btu
Diesel	steam	4.01x10^{11} Btu	80	5.01x10^{11} Btu
	electricity	5.99x10^{11} Btu	34	1.76x10^{12} Btu
	Total	1x10^{12} Btu		2.26x10^{12} Btu
Enhanced Oil Recovery	steam	2.5x10^{11} Btu	80	3.13x10^{11} Btu
	electricity	7.5x10^{11} Btu	34	2.21x10^{12} Btu
	Total	1x10^{12} Btu		2.52x10^{12} Btu

[1] Electricity generated from burning of 20 percent RDF and 80 percent coal. 6.06 x 10^{11} Btu of coal replaces required MSW input. Total system requires 3.03 x 10^{12} Btu of coal.

fossil fuel is the additional amount of fossil fuel which would be consumed if the described solar and conservation systems were not used, and is called the "fossil fuel equivalency" of a system. Table I-1 shows the fossil fuel equivalency of each of the six systems described in this report.

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