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SOLID WASTE UTILIZATION—PYROLYSIS

by

William J. Boegly, Jr., and William R. Mixon

and

Clark Dean and Daniel J. Lizdas

ICES
INTEGRATED COMMUNITY ENERGY SYSTEMS

TECHNOLOGY EVALUATIONS

Prepared by:

Oak Ridge National Laboratory
Operated by Union Carbide Corporation
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August 1977

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The four E's of the cover logo embody the goals of the Community Systems Program of the Energy Research and Development Administration, ERDA, namely:

- to conserve *Energy*;
- to preserve the *Environment*; and
- to achieve *Economy*
- in the design and operation of human settlements (*Ekistics*).

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FOREWORD

The Community Systems Program of the Division of Buildings and Community Systems, Office of Energy Conservation, of the United States Energy Research and Development Administration (ERDA), is concerned with conserving energy and scarce fuels through new methods of satisfying the energy needs of American Communities. These programs are designed to develop innovative ways of combining current, emerging, and advanced technologies into Integrated Community Energy Systems (ICES) that could furnish any, or all, of the energy using services of a community. The key goals of the Community System Program then, are to identify, evaluate, develop, demonstrate, and deploy energy systems and community designs that will optimally meet the needs of various communities.

The overall Community Systems effort is divided into three main areas. They are: (a) Integrated Systems, (b) Community Design, and (c) Commercialization. The *Integrated Systems* work is intended to develop the technology component and subsystem data base, system analysis methodology, and evaluations of various system conceptual designs which will help those interested in applying integrated systems to communities. Also included in this program is an active participation in demonstrations of ICES. The *Community Design* effort is designed to develop concepts, tools, and methodologies that relate urban form and energy utilization. This may then be used to optimize the design and operation of community energy systems. *Commercialization* activities will provide data and develop strategies to accelerate the acceptance and implementation of community energy systems and energy-conserving community designs.

This report, prepared by Oak Ridge National Laboratory, is part of a series of Technology Evaluations of the performance and costs of components and subsystems which may be included in community energy systems and is part of the Integrated Systems effort. The reports are intended to provide sufficient data on current, emerging and advanced technologies so that they may be used by consulting engineers, architect/engineers, planners, developers, and others in the development of conceptual designs for community energy systems. Further, sufficient detail is provided so that calculational models of each component may be devised for use in computer codes for the design of Integrated Systems. Another task of the Technology Evaluation activity is to devise calculational models which will provide part load performance and costs of components suitable for use as subroutines in the computer codes being developed to analyze community energy systems. These will be published as supplements to the main Technology Evaluation reports.

It should be noted that an extensive data base already exists in technology evaluation studies completed by Oak Ridge National Laboratory (ORNL) for the Modular Integrated Utility System (MIUS) Program sponsored by the Department of Housing and Urban Development (HUD). These studies, however, were limited in that they were: (a) designed to characterize mainly off-the-shelf technologies up to 1973, (b) size limited to meet community limitations, (c) not designed to augment the development of computer subroutines, (d) intended for use as general information for city officials and keyed to residential communities, and (e) designed specifically for HUD-MIUS needs. The present documents are founded on the ORNL data base but are more technically oriented and are designed to be upgraded periodically to reflect changes in current, emerging, and advanced technologies. Further, they will address the complete range of component sizes and their application to residential, commercial, light industrial, and institutional communities. The overall intent of these documents, however, is not to be a complete documentation of a given technology but will provide sufficient data for conceptual design application by a technically knowledgeable individual.

Data presentation is essentially in two forms. The main report includes a detailed description of the part load performance, capital, operating and maintenance costs, availability, sizes, environmental effects, material and energy balances, and reliability of each component along with appropriate reference material for further study. Also included are concise data sheets which may be removed for filing in a notebook which will be supplied to interested individuals and organizations. The data sheets are colored and are perforated for ease of removal. Thus, the data sheets can be upgraded periodically while the report itself will be updated much less frequently.

Each document was reviewed by several individuals from industry, research and development, utility, and consulting engineering organizations and the resulting reports will, hopefully, be of use to those individuals involved in community energy systems.

ABSTRACT

As a part of the Integrated Community Energy System (ICES) Program, a number of technology evaluations are being prepared on various current and emerging sources of energy. This evaluation considers the use of pyrolysis as a method of producing energy from municipal solid waste. The energy can be in the form of a gas, oil, chars, or steam.

Pyrolysis, the decomposition of organic matter in the absence of oxygen (or in an oxygen-deficient atmosphere), has been used to convert organic matter to other products or fuels. This process is also described as "destructive distillation".

Four processes are described in detail:

(1) The "Landgard" Svstem (Monsanto Environ-Chem Systems, Inc.);

(2) The Occidental Research Corporation Process (formerly The Garrett Research and Development Company;

(3) The "Purox" System (Union Carbide Corporation); and

(4) the "Refu-Cvcler" (Hamilton Standard Corporation).

"Purox" and "Refu-Cycler" produce a low-Btu gas; the Occidental Process produces an oil, and the "Landgard" Process produces steam using on-site auxiliary boilers to burn the fuel gases produced by the pyrolysis unit. Also included is a listing of other pyrolysis processes currently under development for which detailed information was not available.

The evaluation provides information on the various process flowsheets, energy and material balances, product characteristics, and economics.

Pyrolysis of municipal solid waste as an energy source can be considered a potential for the future; however little operational or economic information is available at this time.

TECHNOLOGY EVALUATION SUMMARY SHEET

SOLID WASTE UTILIZATION-PYROLYSIS

By: W.J. Boegly, Jr. and W.R. Mixon, ORNL, and C. Dean and D.J. Lizdas, Hamilton Standard August, 1977

INTEGRATED COMMUNITY ENERGY SYSTEMS

Pyrolysis - the decomposition of organic matter in the absence of oxygen (or in an oxygen-deficient atmosphere) - has been used to convert organic matter to other products or to fuels. Four variants of the pyrolysis process currently are under active development or are in the demonstration phase. Table 1 compares the four pyrolysis concepts surveyed. These concepts were selected because they are nearest to commercialization and are based on different reactor types. Three of the four systems will handle sludge as well as municipal and industrial solid waste. Of these, the Refu-Cycler and Purox systems are limited to about 40% wet sludge by the amount of waste heat available. The Landgard system is fueled by oil and could handle any percentage of sludge, although about 40% is still probably an economic limit.

Of the products produced, the oil produced by the Occidental process is the most desirable from the standpoint of fuel storage, although its application will be limited to specially designed burners. The steam produced by the Landgard process has the least degree of flexibility. The fuel gas produced by both the Purox and Refu-Cycler is too low in Btu/ft^3 to be economically stored or piped and must be used locally for either heat or electric power generation.

Because the product of most value from a pyrolysis system is energy (fuel), of special interest is the energy yield (or net efficiency) of these processes. Energy yield is the gross output minus the auxiliary input energy divided by the input energy available from solid waste. Input electricity is assumed to require 10,000 Btu/kWh. Analyses indicate that the Purox and Refu-Cycler are about equal in yield. Both are substantially higher in yield than Occidental and Landgard systems.

Table 1. Comparison of Pyrolysis Concepts

	Refu-Cycler	Occidental	Purox	Landgard
Input Capability	Solid Waste and Sludge	Dry Solid Waste	Solid Waste and Sludge	Solid Waste and Sludge
Pre-Processing Requirements	None; some sorting of large objects required	Drying, Shredding Classification Pulverizing	Shredding; needs currently being studied	Shredding
Products	150 Btu/ft^3 gas glassy aggregate	Heavy fuel oil ferrous metals glass	300 Btu/ft^3 gas glassy aggregate	Steam ferrous metals, char, glassy aggregate
Energy Yield	64%	27%	64%	41%
Auxiliary Fuel Required	Propane (startup only)	5 lbs/ton of #2 fuel oil	Propane (startup only)	51 lbs/ton of #2 fuel oil
Electric Power Required	42 kWh/ton	140 kWh/ton	120 kWh/ton	67 kWh/ton
Development Status	10 ton/day unit under construction; evaluation began late in 1976	4 ton/day pilot plant 200 ton/day pilot plant under construction	5 ton/day pilot plant in 1971 200 ton/day pilot plant in operation since 1974	35 ton/day pilot plant in 1972 1000 ton/day pilot plant in 1973; further evaluation to occur during 1977
Capital Cost*	$10,000/ton-day for 100 ton/day size (Sept. 1976)	$56,000/ton-day for 200 ton/day size (June 1976)	$14,000/ton-day for 1,000 ton/day size (Oct. 1974)	$26,000/ton-day for 1,000 ton/day size (June 1976)

*Cost of Refu-Cycler and Purox are engineering estimates, costs for Occidental and Landgard are those incurred in their original installations and include considerable design modification costs and performance guarantees.

Auxiliary fuel and electric power requirements are an indication of operating costs. The Refu-Cycler and Purox systems require auxiliary fuel only for startup. The Occidental system requires a minimal amount of fuel; whereas, the Landgard system requires significant quantities. The Occidental process requires the most electric power because of extensive preprocessing requirements, and the Purox system requires power to produce oxygen.

All of the systems are in the pilot-plant or demonstration stage, and performance and operational data will probably be available on all concepts by the end of 1977. Currently, the most developed of the concepts appears to be the Purox system.

Capital costs for a system range from $10,000 to $56,000/ton-day. The lower half of this range is competitive with incinerators that meet emission standards. The Landgard system capital cost of $26,000/ton-day is somewhat misleading in that it includes conversion of refuse all the way to steam. All capital cost data should be viewed with caution, however, because there are instances where several published reports on the same installation indicate costs that vary by a factor of two, depending on the time the costs were published. Note also that the capital costs for Occidental and Landgard are the actual costs of their pilot plants; whereas the estimates for Refu-Cycler and Purox are capital cost estimates for future commercial plants that are not yet built. Moreover, the costs for Purox and Refu-Cycler do not include land costs or site-specific design requirements; Landgard includes land costs; Occidental may not include land costs, but does include site preparation. The unit capital costs on future Landgard and Occidental plants could be considerably lower than those experienced in the first pilot plant.

Net operating costs reported for all four processes are quite variable and are highly dependent on the estimated value of the products (local market potential and prices) and estimated operating and maintenance costs, which may or may not be site specific. With the operation of the full-scale or pilot-scale plants during 1977, more accurate data on which to estimate net operating costs (or savings) is expected to be developed. Manpower, usually a major part of O&M costs, needs investigation in greater detail because most pilot scale demonstrations tend to use more labor than do follow-up plants.

Depending on costs and operation of the four pilot plants, pyrolysis appears to be a candidate soon for use in the Integrated Community Energy Systems (ICES) Program, managed by Argonne National Laboratory for the Buildings and Community Systems Division of the U.S. Energy and Development Administration. There appears to be no reason at this time to discount pyrolysis as an alternative to incineration with heat recovery as an energy source for ICES.

TECHNOLOGY EVALUATION OF

SOLID WASTE UTILIZATION-PYROLYSIS

Prepared by W.J. Boegly, Jr. and W.R. Mixon, ORNL, and C. Dean and D.J. Lizdas, Hamilton Standard

Date August, 1977

1 INTRODUCTION

Pyrolysis is an emerging technology that meets the ICES objective of conserving energy, because it can extract from solid waste a fuel that can be used in an integrated energy system to reduce primary fuel requirements. The development activities currently being conducted with private and public funds should make pyrolysis a candidate for ICES in the 1980s.

A number of companies and universities, shown in Table 1.1 are actively engaged in the development of pyrolytic processes for municipal solid waste. Most of these organizations are in various stages of process development; however, only three are currently in commercial development.

An attempt has been made here to include at least one example of each of the furnace types listed in Table 1.1. Excluded are the horizontal-shaft furnace and the fluidized-bed type of operation because data are lacking and these types have not yet become commercial.

As of October, 1976, three of the processes described were in the fairly large (200 tons/day or larger capacity) pilot plant stage. One of these (Landgard) currently is undergoing design modifications to correct scale-up factors; another (Occidental) has yet to start operation, and the third (Purox) is reported to be operational in a test bed configuration; but little data on this plant have been published. The fourth system (Refu-Cycler) has been tailored to smaller units (less than 100 tons/day), and a pilot plant will be in operation early in 1977.

1.1 PROCESS DESCRIPTIONS

Pyrolysis can be defined as the decomposition of organic matter in the absence of oxygen or in an oxygen-deficient atmosphere. Pyrolysis has also been described as "destructive distillation" and has been used to convert organic matter to other products or fuels. Four variations of the pyrolysis process currently are under active development or are in the demonstration phase and are being evaluated for ICES. These are: (1) the Landgard system (Monsanto Eviro-Chem Systems, Inc.); (2) the Occidental Research Corporation

Table 1.1 Status of Pyrolysis Projects

Process	Status: Research	Pilot plant (tpd)	Commercial (tpd)
Shaft or vertical			
Union Carbide		5	200
Occidental		4	200
Torrax Systems, Inc.		75	
Urban Research and Development Corp.		120	
Georgia Tech		25	
Battelle		2	
Hamilton Standard		14	
Shaft-horizontal			
Kemp Corp.		5	
Barber-Colman		1	
Rotary kiln			
Rust Engineering			
Monsanto		35	1000
Devco		120	
Pan American Resources Inc.	•		
Fluidized bed			
West Virginia University	•		
Coors		1	
A. D. Little	•		
Others			
Hercules	•		
Bureau of Mines	•		
N.Y. University	•		
Univ. of Southern Calif.	•		
Anti-Pollution Systems, Inc.	•		
University of Calif.	•		
Wallace-Atkins	•		
Resource Sciences		2	

process (formerly the Garrett Research and Development Company); (3) the "Purox" system (Union Carbide Corporation); and (4) the Refu-Cycler (Hamilton Standard). Pyrolysis produces fuels that can be used in a wider range of applications than heat energy recovered from incineration. Moreover, savings may be possible in air pollution controls and capital and operating costs. Three fuel products produced during the pyrolysis reactions are gases (hydrogen, methane, carbon dioxide, and carbon monoxide), organic liquids, and an organic "char", all of which have potential value as fuels. The amount and composition of these three products depend on the initial solid waste composition and the nature of the process being used.

1.2 BACKGROUND

Pyrolysis has been used by industry for the production of producer gas for many years. Currently the pyrolysis of solid waste is being evaluated in one demonstration plant (Landgard) that is in the shakedown phase, and another (Occidental) that expects to start operation in early 1977. In addition, Purox has had a pilot plant operating since 1974, and the Refu-Cycler pilot plant is expected to be operational in the spring of 1977.

Most of the reported information on pyrolysis has been developed from laboratory batch-type units, or from very small pilot plants, using wood wastes, paper wastes, etc., but not much has been reported on mixed municipal refuse. Because the four processes mentioned above are proprietary, most of the laboratory or small pilot plant data have not been reported. However, sufficient data are available to convince EPA to partially fund large demonstrations of the Landgard and Occidental processes. Currently, Purox and Refu-Cycler are being developed with corporate funds only.

1.3 PRODUCTS PRODUCED

There are three main products from the pyrolysis process. Each of the four processes under development tend to favor the production of one product over the other two. For example, Landgard's Baltimore plant is geared to producing a combustible gas that is burned in waste heat boilers to produce steam which is sold offsite. Occidental's system favors the production of an oil-like liquid that can be used as a fuel in combination with No. 6 fuel oil. Purox and Refu-Cycler produce a fuel gas for closely coupled use near the pyrolysis unit.

1.4 TYPES OF PYROLYSIS REACTORS AVAILABLE

Each of the four pyrolysis processes uses a different type of reactor and method of heating. The Landgard Process uses a rotary kiln furnace; the Occidental Process, a vertical reactor; the Purox Process, a vertical shaft furnace with pure oxygen; and the Refu-Cycler Process, a vertical shaft furnace with air.

1.5 PREPROCESSING REQUIRED

Two of the processes include shredding the solid waste; the Occidental process works best when most of the non-organic fraction is removed before entering the furnace; the Refu-Cycler does not require preprocessing. The Purox system does not require, but is investigating the possible use of, shredding for advanced systems.

1.6 ICES CONSIDERATIONS

Pyrolysis systems for municipal solid waste disposal had not been commercially available as of late 1976. Most of the existing plants have been specially designed large plants or pilot plants. However, at least one manufacturer plans to enter the market with relatively small units suitable to ICES application. For ICES systems, it appears that pyrolysis could be used and therefore merits further consideration.

1.7 ECONOMICS

Pyrolysis is presently in the development stage, but the economics are not well defined. Because the costs include various credits for handling the solid waste in the pyrolysis facility versus alternative facilities, they are highly dependent on the estimated revenue from the sale of the end products. In all cases, economic considerations will be a complex analysis of pyrolysis capital and operating costs which are unique to the specific situation as compared to equally specific competitive costs.

Operating costs are only estimates at this time, and the capital costs are confused and inconsistent because of the methods of handling return on the investment. Moreover, most of the capital costs reported do not include land and site preparation work, and many of the reported costs are inflated because of performance guarantees required in demonstration plants. EPA has developed suggested estimating procedures for estimating costs; however, these procedures do not seem to be used. Costs can be anticipated to be reduced in future plants, and commercialization plant unit costs will be lower. Operating costs can be estimated by the auxiliary utilities required, estimates of the operating personnel required, and labor rates.

1.8 CURRENT STATE OF DEVELOPMENT

It seems to be too early to define conclusively the economics and details of performance of pyrolysis techniques in handling and extracting energy from municipal solid wastes. Nevertheless, the obvious potential of pyrolysis techniques has led to significant expenditure of government and private funds in development and evaluation of the various processes. As an advanced technology, pyrolysis is ideally suited to the ICES philosophy, and ICES could be an appropriate vehicle for confirming its applicability to mixed energy systems.

Because all four processes to be described later in this report are in either the pilot plant stage or the initial demonstration phase of development, many operational and maintenance problems have been encountered that were not anticipated. For example, the Landgard Plant has experienced trouble with the refractory lining of the rotary kiln, which may be due to not allowing enough time to bring the kiln up to temperature or to mechanical damage caused by abrasion produced by various constituents in the solid waste. At the time this report was prepared, essentially no information was available on waste water treatment, anticipated equipment life, maintenance, and general operating problems.

1.9 MARKET FOR PRODUCTS

The objective of ICES is energy conservation, and because the primary product of pyrolysis is energy, the market for the pyrolysis energy will be within the ICES Program. However, secondary products must find a market outside the ICES Program. Slag residue from the Purox or Refu-Cycler Process can be used for roadbuilding, and the char from the Occidental or Landgard Process possibly could be used as a source of activated carbon for wastewater treatment. Even if the secondary products are not marketable, their greatly reduced volume drastically reduces the landfill requirement.

1.10 ICES TIME FRAME

Pyrolysis possibly could be developed commercially during 1980 and might be considered for ICES in that time frame. ICES can play a major role in developing operational, performance, and economic data for pyrolytic processing of solid waste.

1.11 ENVIRONMENTAL CONSIDERATIONS

One of the most cited advantages of pyrolysis over incineration is the reduced potential for air pollution provided by such systems. The only pyrolysis process with air pollution problems appears to be the Landgard system; however, these problems seem to be related to emissions from the on-site waste heat boiler. Where chars are produced, they may represent a potential pollution source. Slagging pyrolysis processes, such as Purox or Refu-Cycler, produce a sterile, inert frit which should reduce pollution problems from the disposal of this material. However, quenching of these materials may represent a minor environmental problem in liquid effluent disposal. Because composition of the quench water has not yet been well documented, the application of pyrolysis processes does not seem to cause significant environmental degradation. When more information is available from the first-generation commercial plants, the effect of pyrolytic products on the environment can be evaluated in greater detail.

2 VERTICAL FURNACE - OCCIDENTAL "FLASH PYROLYSIS"

The Occidental Research Corporation (a subsidiary of Occidental petroleum Corporation) is currently building a 200 ton/day pilot plant in San Diego, California. The major objective of the Occidental Process is to produce an oil-like liquid fuel, similar to No. 6 fuel oil, for use in utility boilers. Gas produced is totally used in the process, and studies are underway for utilization of the organic char.

A feature of the Occidental process is extensive pretreatment of the incoming waste to remove metals, glass, and other inorganics. Sale of these materials is expected to offset a large fraction of the operating cost.

2.1 PROCESS DESCRIPTION

The Occidental process is based on earlier research on coal liquifaction. Figures 2.1 and 2.2 show simplified process flowsheets of the pyrolysis system. Methods of processing the solid waste -- both for material recovery and energy recovery -- are illustrated in these two flowsheets. Raw solid waste is first ground in a hammermill to a nominal 3-in. size (90% passing a 3-in. screen), and then fed through an electromagnetic separator to remove ferrous metals. The remainder of the waste is stored to ensure constant feed to the air classifier to allow shredding for 8 hr/day, but to permit the rest of the plant to operate 24 hr/day. In the air classifier, an upward-flowing column of air carries the lighter organic fraction out through the top of the tower; heavy inorganics (mainly glass) fall through the air stream and are removed from the bottom of the classifier. The light fraction is dried to about 4% using gas from the pyrolysis reactor or fuel oil. When the light fraction is dried, additional mechanical processing such as screening, milling, and use of an air table further separate organics from inorganics. A number of other operations also are included for glass recovery.

The resulting light fraction is feedstock to the pyrolysis reactor consisting of a vertical stainless steel vessel into which the feedstock is fed pneumatically. Hot char particles are fed to the reactor to provide the energy needed to pyrolyze the organic matter. Five pounds of char (heated to 1400°F)

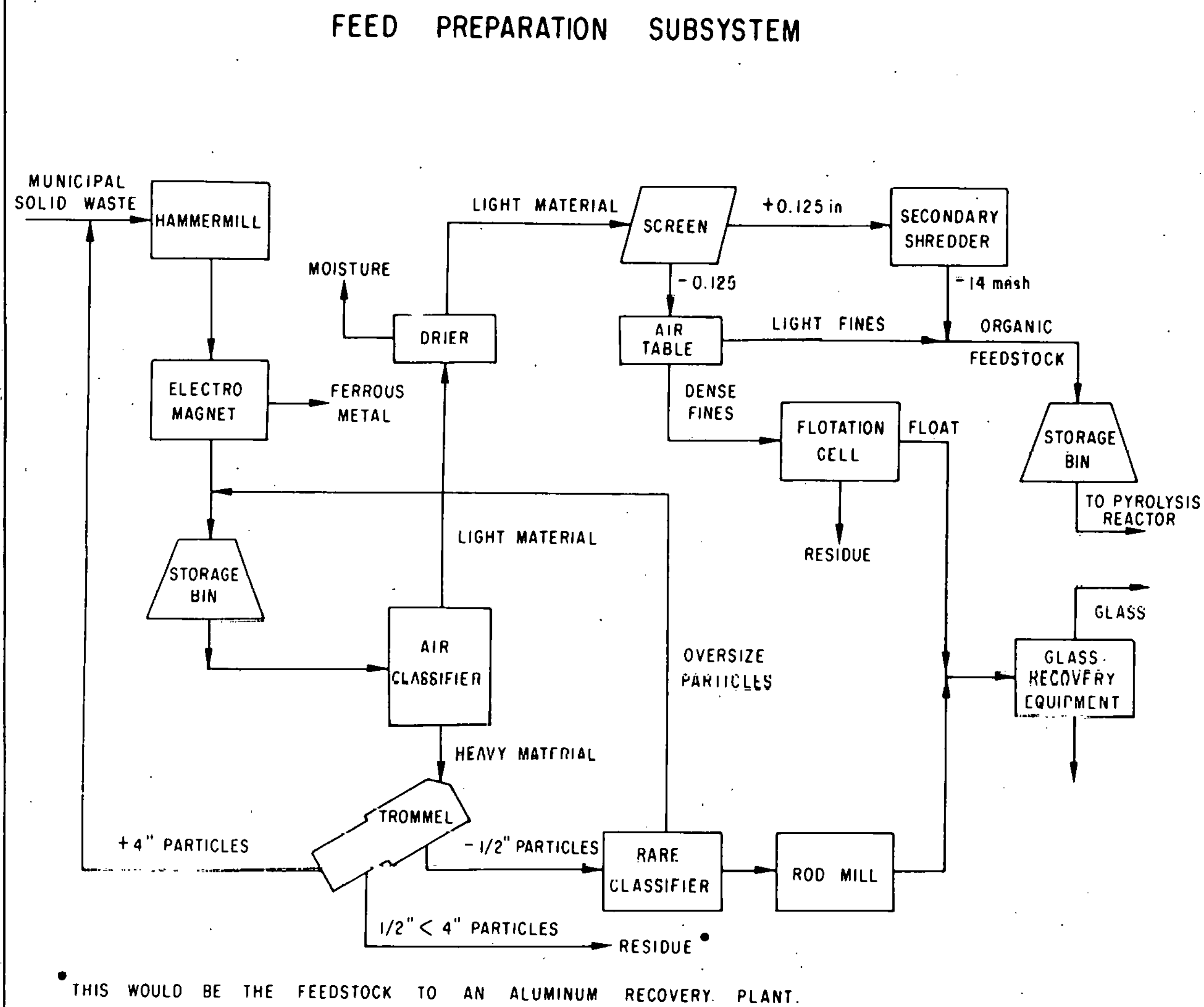

Fig. 2.1 Feed Preparation Subsystem Which Produces Fine Particles of Moisture-Free Organic Material

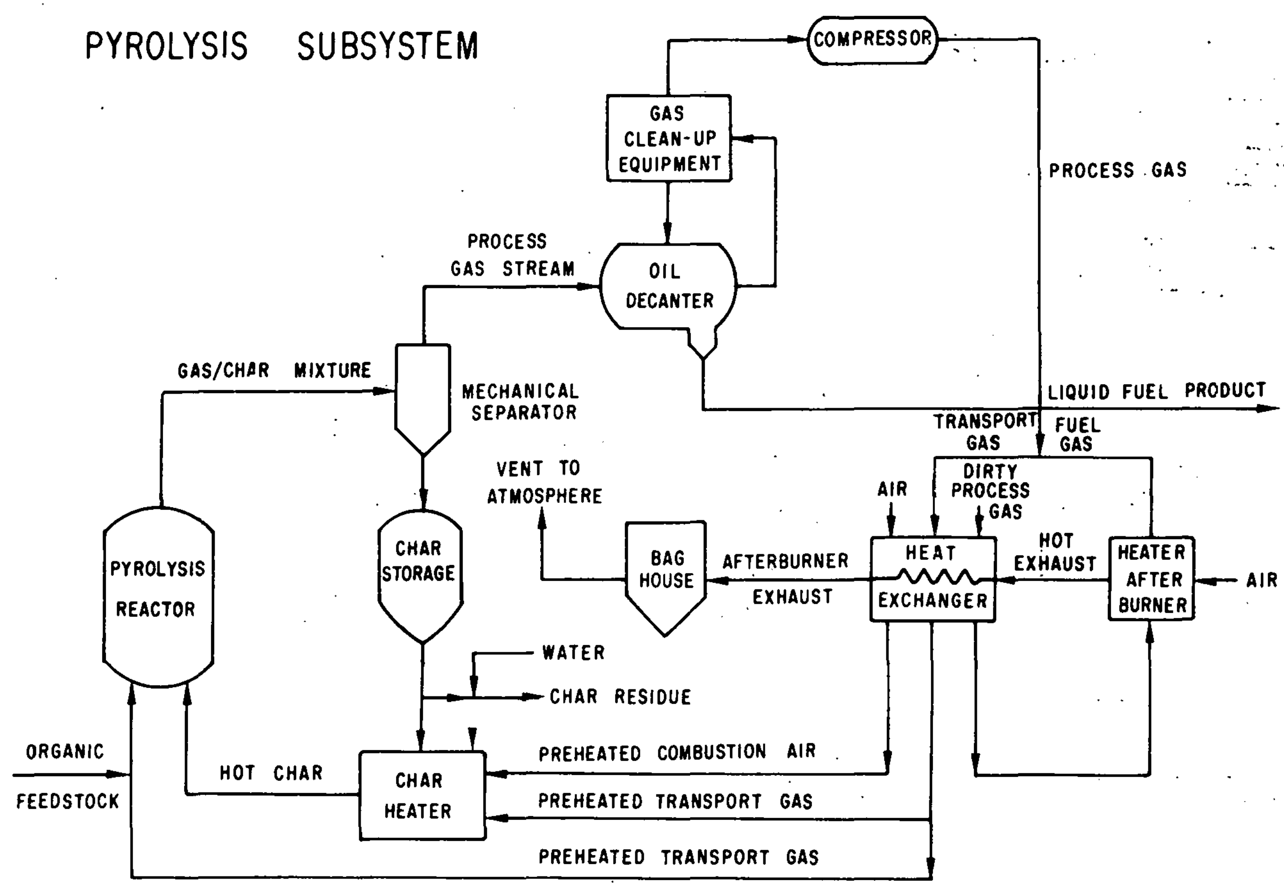

Fig. 2.2 Pyrolysis Subsystem

are added for each pound of organic material. The gas and char mixture leaves the reactor at a temperature of about 950°F. The char is separated from the gas and stored for reuse. Excess char will become landfill; however, Occidental is looking at possible alternative markets for this material. The gas from the separator is cooled quickly to 175°F in an oil decanter. Cooling is performed by spraying a mixture of liquid fuel produced by the plant and No. 2 fuel oil. About 36 gallons of liquid fuel will be recovered from each ton of mixed solid waste. A portion of the gas produced is not condensed but is used within the plant. Tables 2.1 and 2.2 give the design composition of the waste assumed for the San Diego pilot plant and the assumed amounts of materials recovered.

Table 2.1 Composition of Municipal Solid Waste*

Component	Percent	Tons/day at plant
Organics	52	104
Metals		
(a) Ferrous	12	24
(b) Aluminum	1	2
Glass	7	14
Other inorganics	2	4
Miscellaneous solids	1	2
Moisture	25	50
Total	100	200

*Based on data from pilot testing conducted at Vancouver, Washington, 1972-73.

2.2 PRODUCT CHARACTERISTICS

As stated earlier, the Occidental process is mainly directed at producing a liquid fuel. As presently conceived, char and gas is used as a part of the process and do not represent saleable products. Table 2.3 compares the characteristics of the pyrolysis fuel with No. 6 fuel oil. Each gallon of pyrolytic oil contains about 76 percent of the heat energy available and No. 6 oil (about 4.1 million Btu of energy per ton of solid waste).

Table 2.2 Estimated Amounts of Materials Recovered [Input = 200 tons/day municipal solid waste (150 tons dry weight).]

Outputs	Percent, wet weight	Tons/day
Products (dry weight)		
Ferrous metals	12	23.7
Glass	5	10.4
Oil	17	33.8 (172 barrels)
Residue to landfill (dry weight)		
Solid residuals	16	31.5
Waste char	5	11.1
Waste gases†	20	39.5
Moisture	25	50.0
Total	100	200.0

†This includes the combustible gas that is used as a fuel in in the afterburner and moisture that forms in the pyrolysis reactor.

Table 2.3 Typical Properties of Liquid Fuel From Solid Waste and No. 6 Fuel Oil*

	Liquid fuel product	No. 6 fuel oil
Physical properties(dry basis):		
Heating value (Btu/lb)	10,500	18,000
Specific gravity	1.30	0.98
Density (lb/gal)	10.85	8.18
Volumetric heating value (Btu/gal)	113,910	148,840
Chemical analysis (dry basis, % by weight):		
Carbon	57.5	85.7
Hydrogen	7.6	10.5
Sulfur	0.1-0.3	0.5-3.5
Chlorine	0.3	†
Ash	0.2-0.4	0.5
Nitrogen	0.9	2.0
Oxygen	33.4	

*Finney, C.S., and D.E. Garrett. *The Flash Pyrolysis of Solid Wastes*, Presented at Annual Meeting, American Institute of Chemical Engineers, Philadelphia p. 18b (Nov. 11, 1973).

†Not available.

2.3 PLANT CAPACITIES

The original Garrett pilot plant had a capacity of four tons per day and was constructed and operated in Vancouver, Washington in 1971. The current pilot plant in San Diego has a capacity of 200 tons per day, but the literature does not indicate any other proposed projects. Detailed information on the 4 tons/day plant may be of interest to the ICES program, but these data are not available.

2.4 ECONOMICS

Actual operating costs of the San Diego Plant were not available at the time this report was written, so the following reported cost data were estimated by Occidental. Capital costs (as of June, 1974) for the San Diego pilot plant are given in Table 2.4. On a per-ton-of-capacity basis, this represents a unit cost of $32,000 per ton of daily capacity which is much higher than that for water-wall incinerators.

Table 2.5 gives the annual operating costs for the San Diego pilot plant. Using the estimated amounts of products recovered and their estimated values (Table 2.6), the net cost of the process can be calculated. This amount is estimated to be $841,000 per year or $13.42 per ton (operation 85% of design, 7 days/week, 24 hr/day, 200 tons/day). Occidental anticipates that larger units would have lower unit costs, but has not estimated costs for smaller units.

Occidental has estimated that the costs for a 1000 ton per day plant (second quarter 1975 costs) would be $25,200,000, or a cost of $25,200 per ton. Operating costs are estimated to be $15.70 per ton, and with credits for revenue, the net operating cost would be $11.49 per ton.

2.5 STATE OF PROCESS DEVELOPMENT

Although the process has been piloted, the demonstration plant has not been operated. Consequently, operational problems have not been identified. Thus, the process does not appear to have ICES application before 1980.

Table 2.4 Breakdown of Capital Costs Estimated for 200 Ton/Day Pyrolysis Plant

Item		June 1974 estimates
Design		$ 777,000
Site development costs		679,000
Construction		3,716,000
Receiving and preparation (through air classifier and trommel)		
Equipment	596,000	
Installation	885,000	
Organic feed preparation		
Equipment	317,000	
Installation	306,000	
Pyrolysis and fuel recovery		
Equipment	254,000	
Installation	398,000	
Glass recovery		
Equipment	113,000	
Installation	262,000	
General and utility (product storage, afterburner, package boiler, spare parts)		
Equipment	312,000	
Installation	273,000	
Inflation, overhead, and contractor's profit		1,172,000
Total		$6,344,000

Table 2.5 Operating and Maintenance Cost

Operating costs	
Electric power	$ 127,000
Other utilities	39,000
Labor (20 positions)	361,000
Maintenance	317,000
Land rent	34,000
Residual transfer and disposal	38,000
Total operating costs	916,000
Capital costs	
Amortization of $6,344,000 (20 years at 6%)	+ 553,000
Total annual cost	$1,469,000

Table 2.6 Estimated Revenues

Ferrous metal (7,874 tons at $47/ton)	$370,000
Glass (4,033 tons at $6.40/ton)	26,000
Liquid fuel (53,644 barrels at $4/bbl)	232,000
Total	$628,000

The weights for the products as shown in the material balance are dry weights. In actual operations these materials will contain certain amounts of moisture. Product values are based on the wet weight of the respective materials. Ferrous is 6.64 percent moisture; glass is 20 percent moisture; the fuel is 14.2 percent moisture.

2.6 ENERGY AND MATERIAL BALANCES

Figure 2.3 shows the material balance for the San Diego plant. Tables 2.1 and 2.2 give the design composition of the waste to be processed in the plant. The material balance shown in Fig. 2.3 is based on dry weight, i.e., 200 tons/day, as delivered and corresponds to 150 tons/day dry weight.

Energy requirements of the Occidental process are 140 kWh of electricity. Assuming the heating value of the liquid fuel produced is 113,910 Btu/gal, and that it takes 10,000 Btu to produce 1 kWh, the net energy yield and the energy efficiency of the process can be calculated. These calculations are given in Table 2.7.

2.7 MISCELLANEOUS INFORMATION

Because of difficulties in obtaining a site and various permits, construction of the pilot plant was not started until February, 1976 and is scheduled for completion early in 1977. As a result, the original capital cost for construction of $6,344,000 has increased to $11,300,000 (about $56,000 per ton-day). Some factors leading to this increase are:

1. inflation;
2. change in plant site and design limitation caused by the new site;
3. additional odor-control equipment required;
4. addition of aluminum recovery facilities; and
5. additional redundancy and site landscaping.

Because of site limitations and local meteorological conditions, production of nitrogen oxides by the pyrolysis plant may require periodic shutdown of the facility for several days per year. Moreover, operating costs are expected to be high because the plant capacity (200 tons/day) is not considered by Occidental to be of commercial scale.

2.8 RATING OF THE DATA BASE

Although the Occidental process has been described in some detail in the literature, some changes, still untested, have been made in the process design. The rating of the data base should be improved when the San Diego plant is in operation. Economics appear to be questionable at this time.

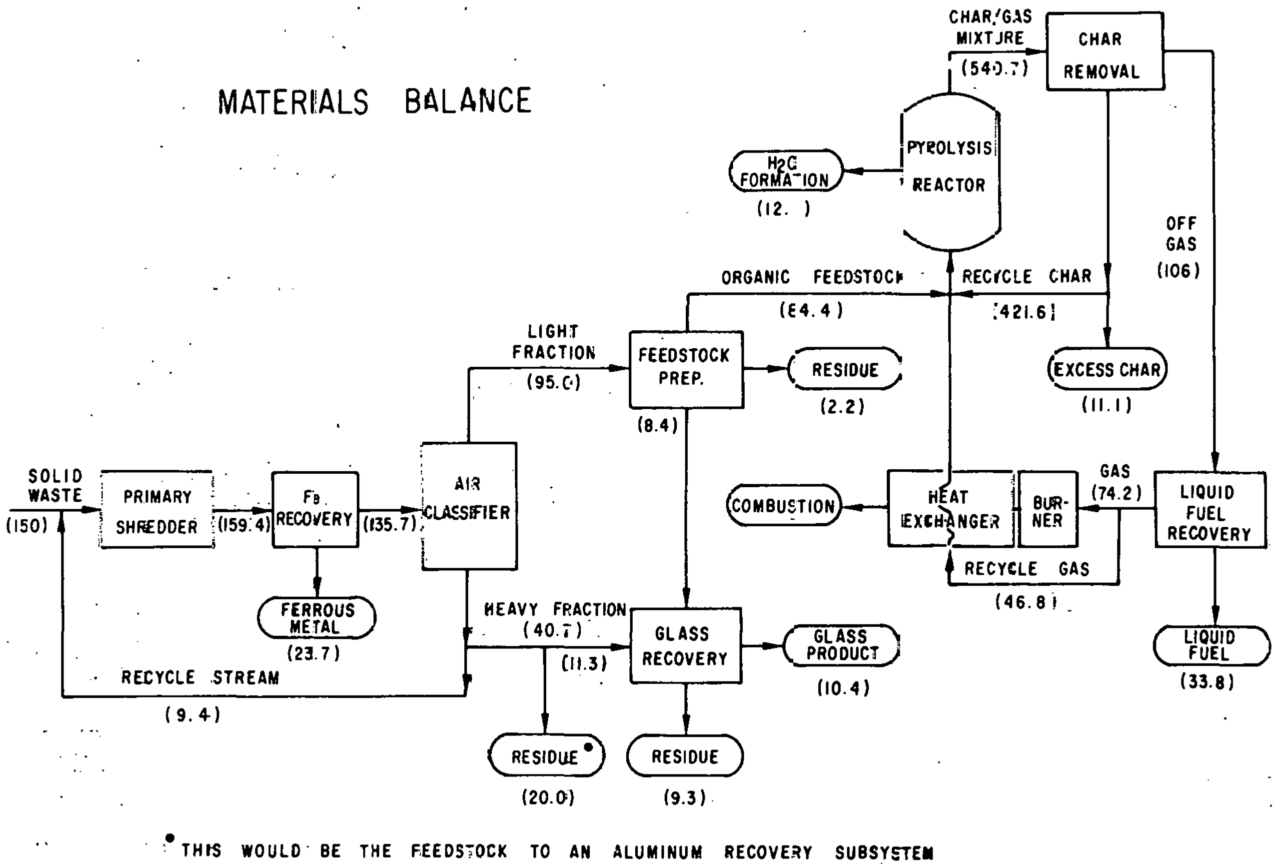

Fig. 2.3 Materials Balance Based on a Dry Input of 150 Tons/Day of Municipal Solid Waste (200 tons/day including moisture).

Table 2.7 Energy Balances for Occidental System

$$\underline{\text{Yield}} = \frac{\text{Energy out (liquid fuel)} - \text{Energy in (electricity)}}{\text{Total energy in solid waste}}$$

$$= \frac{(36 \text{ gal} \times 113{,}910 \text{ Btu}) - (140 \text{ kWh} \times 10{,}000 \text{ Btu})}{1 \text{ ton} \times 10{,}000{,}000}$$

$$= \frac{4{,}101{,}000 - 1{,}400{,}000}{10{,}400{,}000}$$

$$= \frac{2{,}701{,}000}{10{,}000{,}000} = 0.27$$

$$= 27\%$$

$$\underline{\text{Efficiency}} = \frac{\text{Energy out (liquid fuel)}}{\text{Energy in (solid waste, electricity)}}$$

$$= \frac{36 \text{ gal} \times 113{,}910 \text{ Btu}}{(1 \text{ ton} \times 10{,}000{,}000 \text{ Btu}) + (140 \text{ kWh} \times 10{,}000 \text{ Btu})}$$

$$= \frac{4{,}101{,}000}{10{,}000{,}000 + 1{,}400{,}000}$$

$$= \frac{4{,}101{,}000}{11{,}400{,}000} = 0.36$$

$$= 36\%$$

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3 ROTARY KILN - MONSANTO "LANDGARD" PROCESS

3.1 PROCESS DESCRIPTION

The Rotary Kiln "Landgard" pyrolysis process is designed to pyrolyze municipal solid waste, produce a gaseous product, and then burn it in an auxiliary boiler to produce steam for sale to a power plant or industrial user. Recovery of ferrous metals and glassy materials from the pyrolysis residue is proposed. Glassy material may be used as aggregate in bituminous concrete paving of streets ("glassphalt"). The char is being studied as a possible additive in wastewater treatment or as a soil conditioner.

Currently the Landgard process is being tested in a 1000 ton per day demonstration plant in Baltimore, Maryland. Figure 3.1 shows the Baltimore plant flowsheet. Solid waste is received and shredded during a ten-hour daily shift. The balance of the plant will operate 24 hours per day, seven days a week. A storage capacity of 1000 tons has been provided in the waste reception area, and 2000 tons of storage follows the shredder to ensure continuous operation of the pyrolysis plant.

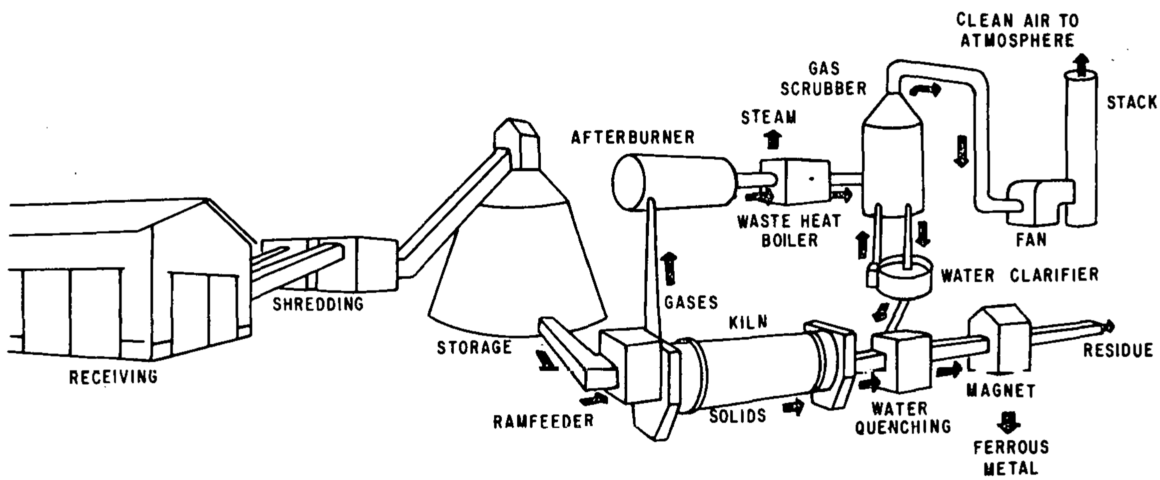

Fig. 3.1 Flow Diagram Depicting Processing at the Baltimore Plant

The shredded solid waste enters the pyrolytic reactor - a refractory lined, horizontal, rotary kiln which is 19 feet in diameter and 100 feet long. The kiln rotates at a speed of two rpm. The refractory lining serves: (1) to keep the heat of reaction in the kiln, and (2) to prevent corrosion of the metal kiln shell. Solid waste in the kiln is combusted using 40% of the theoretical air required for complete combustion and 7.1 gal/ton of No. 2 fuel oil to provide the required energy. In this design, the auxiliary fuel burner is located at the discharge end of the kiln and the pyrolytic gases exit from the feed end. Gas temperatures are held below 1200°F and the residue is kept below 2000°F to prevent refractory damage and to facilitate further separation of the residue.

The 1200°F gases then are directed to an afterburner where they are burned in the presence of additional air. The pyrolysis gases are expected to have a heating value of about 120 Btu per dry standard cubic foot. The gas stream exiting the afterburner is directed to two waste-heat boilers which generate 200,000 lb of steam per hour.

As originally designed, waste gases from the waste-heat boilers pass through a water scrubber. The gases exiting the scrubber are saturated with moisture and are passed through a dehumidifier where gases are cooled and water is removed for recycle back into the scrubber. The cooled off-gas is then mixed with heated air, to suppress formation of a steam plume, and discharged to the atmosphere.

Before entering the scrubber, the recycled dehumidifier water is treated with flocculents in a thickener to remove solids. The overflow goes to the scrubber, and the underflow stream (containing the settled solids) is directed to the residue quench tank. Makeup water requirements in the closed-loop scrubber are low.

The plant is designed to ensure continuous operation by allowing the afterburner gases to enter the scrubber system directly in case the boilers are out of service.

Hot residue from the kiln is discharged into a water-filled quench tank. A conveyor dewaters the wet residue and transfers it to a flotation separator. The light material (char) floats off and is thickened and filtered. The liquid effluent goes back into the plant's closed water loop, and the char will be disposed of as landfill until a market is developed. The heavy residue that settles out is passed through a magnetic separator to remove ferrous metals, and the remaining glassy aggregate will be used by the city for street paving.

3.2 PRODUCT CHARACTERISTICS

As described above, the Baltimore Landgard system produces gas (which is burned onsite for steam production), carbon char, ferrous metal, and a glassy aggregate. Characteristics of these products are given in Tables 3.1 through 3.4.

Table 3.1 Composition of Pyrolysis Gas

	Percent by volume, dry basis
Nitrogen	69.3
Carbon dioxide	11.4
Carbon monoxide	6.6
Hydrogen	6.6
Methane	2.8
Ethylene	1.7
Oxygen	1.6

Table 3.2 Quality of Ferrous Metal Recovered from Pyrolysis Residue

Bulk density	35 pounds per cubic foot
Iron	98.85% by weight
Contaminants	1.15% by weight

Chemical analysis

Component	Percent	Component	Percent
Iron	98.850	Antimony	.020*
Tin	.153	Sulfur	.016
Carbon	.150	Phosphorus	.015
Copper	.150	Cobalt	.010*
Nickel	.140	Molybdenum	.010*
Lead	.088	Titanium	.010*
Manganese	.048	Vanadium	.010*
Silicon	.045	Aluminum	.001*
Chromium	.035	Other	.249

*Less than percent shown.

Table 3.3 Analysis of Carbon Char Residue

Bulk density	20-50 pounds per cubic foot
Moisture content	50% by weight
Heating value, dry basis	7,000 Btu per pound

Analysis, dry basis

Component	Percent
Carbon	50.0
Ash and glass	45.8
Volatiles	4.0
Sulfur	0.2

Analysis of water-extractable fraction

Component	Percent or parts per million (ppm)
Sodium	over 30%
Calcium	0.1-1.0%
Copper	0.03-0.3%
Magnesium	0.03-0.3%
Potassium	0.03-0.3%
Boron	0.01-0.1%
Strontium	0.001-0.1%
Iron	0.001%*
Molybdenum	0.001%*
Silicon	0.001%*
Phosphorus	22 ppm*
Chromium	10 ppm*
Lead	10 ppm*
Tin	10 ppm*
Vanadium	5 ppm*
Zinc	5 ppm*
Aluminum	1 ppm*
Cadmium	1 ppm*
Manganese	1 ppm*
Silver	1 ppm*
Titanium	1 ppm*

*Less than figure shown

Table 3.4 Analysis of Glassy Aggregate Recovered from Pyrolysis Residue

Bulk density	150 pounds per cubic foot
Component	**Percent**
Glass	65
Rock and miscellaneous	28
Ferrous metal	3
Nonferrous metal	2
Carbon	2

3.3 PLANT CAPACITIES

Following laboratory studies on pyrolysis, a 35 ton per day pilot plant was built at the St. Louis County, Missouri landfill. The Baltimore plant has a capacity of 1000 tons per day. Monsanto may have designed plants having other capacities, but they are not documented. Currently, there is insufficient information available to determine if the Landgard system could be used in small systems. More detailed information will be required before consideration for use in ICES.

3.4 ECONOMICS

Although the Baltimore plant has been operational since 1973, there is still considerable question concerning its economics. Table 3.5 lists cost estimates as of January, 1973 and February, 1974. The capital costs are now estimated at $25,950,000 (see later section on operating problems). Operating revenues are currently estimated at $30.75 per ton. It has been stated that the system will be "economically competitive with most other disposal and recovery alternatives" in Baltimore.

3.5 STATE OF PROCESS DEVELOPMENT

Further operation and evaluation will be initiated during the period January, 1977 to December, 1977. Currently, the plant is undergoing replacement of the refractories in the rotary kiln and other extensive mechanical modifications. An electrostatic precipitator also has been added to the off-gas system.

Table 3.5 Economic Estimates for the Baltimore Plant
($ per throughput ton)

Costs and revenues	January 1973	February 1974
Amortization*	$4.34	$5.55
Operating costs		
Fuel	.89	2.20
Electricity	1.06	1.50
Manpower	1.02	1.10
Water and chemicals	.31	.30
Maintenance	1.84	1.90
Miscellaneous	.42	.40
Char removal	.18	.20
Total	$5.72	$7.60
Total expenses	$10.06	$13.15
Revenues		
Steam†	$3.89	$11.18
Iron	.44	1.55
Glassy aggregate	.34	.40
Total revenues	$4.67	$13.13
Net operating cost	$5.39	$ .02

*Approximate plant cost: in January 1973, $16 million; in February 1974, $20 million.

†Price is keyed to fuel oil price, which was $3.70 per barrel in January 1973, and $10.63 per barrel in February 1974.

3.6 ENERGY AND MATERIAL BALANCES

As with any energy system, the energy balance sheet is important in determining overall system efficiency and effectiveness. A solid waste disposal system can be either energy-consumptive, neutral, or energy-producing, depending on its design and technology. In choosing pyrolysis as a technology, a net energy gain was expected.

The inputs and outputs of energy and materials were calculated using the following assumptions:

1. Electrical power required to process one ton of waste can be determined by using quoted electrical equipment ratings and estimating how long each piece of equipment would have to operate to process one ton of waste, and then converting to Btu, assuming 30 percent conversion efficiency from fossil fuel.
2. No. 2 fuel oil needed to pyrolyze the waste is fed at a rate of 7.1 gal/ton.
3. The waste has a heat value of 4600 Btu/lb.
4. The two bulldozers use 16 gal of fuel per hour.
5. Other internal combustion engine vehicles (crane, loader, etc.) use 10 gal/day.

Based on the above assumptions, the energy and material balances (shown in Fig. 3.2) can be calculated.

3.7 MISCELLANEOUS INFORMATION

Monsanto is responsible for the complete design, construction and startup of the plant, all at a fixed price. The "turn-key" contract calls for Monsanto to turn over to Baltimore a completely operational facility. Additionally, the contract provides for up to $4 million in performance penalties if the plant fails any of the following requirements:

1. air emissions that meet existing federal, state, and local air pollution regulations;

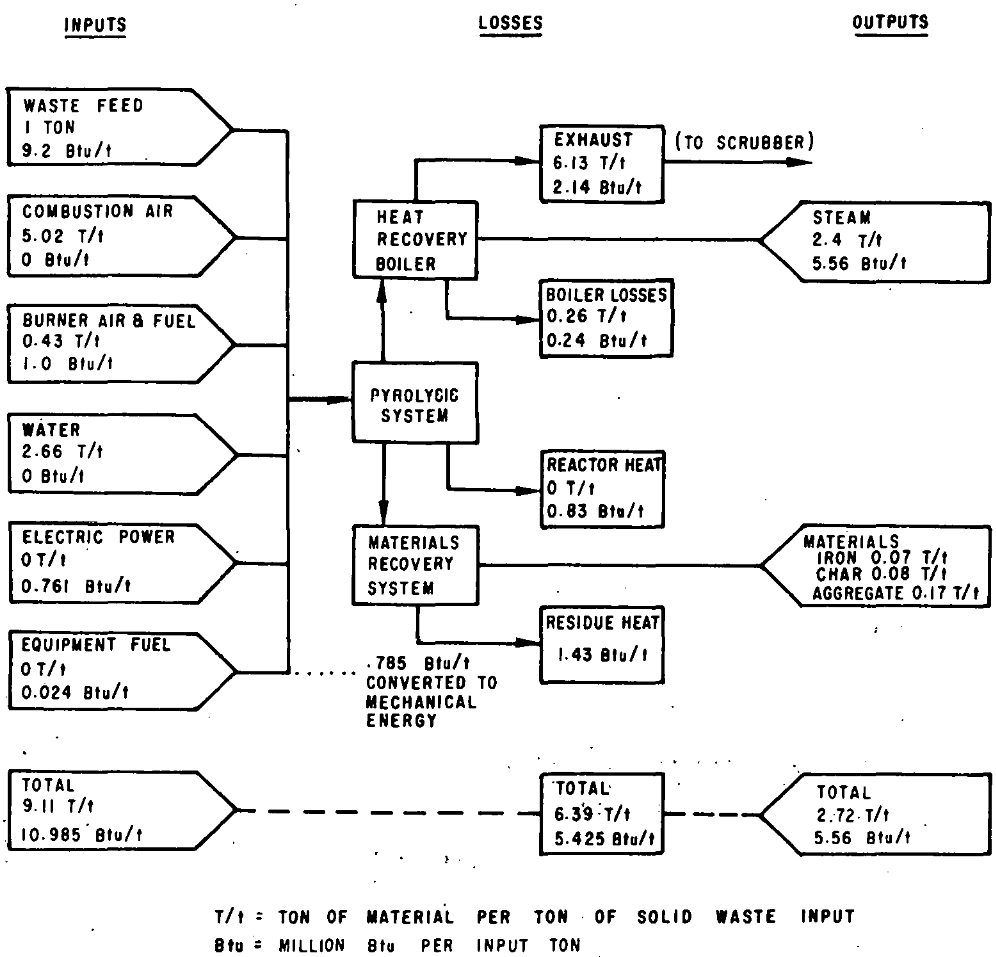

Fig. 3.2 Energy and Material Balances for the Monsanto "Landgard" Pyrolysis Process

2. plant capacity that will average a minimum of 85% of design capacity for an identified 60-day period; and
3. putrescible content of residue less than 0.2%.

After testing in 1975, it was found that the system throughput was not able to process the 51,000 tons required for a 60-day period, and that emission standards (less than 0.03 grains/dry standard cubic foot) could not be met.

Monsanto, the system designer, attributes the high emission levels in the demonstration plant to the presence of a greater number of submicron particles than had been produced in the pilot plant. In scaling up from 35 to 1000 tons/day, key design and operating parameters (equipment size, temperatures, residence time of solid waste in kiln, etc.) were increased in certain proportions. The difference in performance between the demonstration plant and the pilot plant appears to have been caused by incorrect scaling of some parameters. Many of the mechanical problems that are limiting the system throughput are also a result of scale-up difficulties. This situation illustrates the risk inherent in scaling up technology from pilot to commercial scale.

A supplemental agreement between the City of Baltimore and Monsanto was signed on December 31, 1975. Funds for the work outlined in this agreement were $4 million contributed by Monsanto (equivalent in amount to the original performance guarantee) plus an increase in the EPA grant of $1 million. This work included mechanical modification required to improve the reliability of the system and enable the plant to meet the design performance. This phase also covered testing, evaluation, and specification of the air-pollution-control devices required to bring the plant into compliance with applicable standards.

3.8 RATING OF THE DATA BASE

Because of scale-up difficulties, information reported on Landgard economics and amount of products produced will have to await further testing.

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4. VERTICAL SHAFT FURNACE - PUROX "PURE OXYGEN" PROCESS

4.1 PROCESS DESCRIPTION

The Purox "pure oxygen" pyrolysis process (Union Carbide Corporation) is designed to produce a fuel gas having a heating value of about 300 Btu/standard ft^3. The key features are the use of a vertical shaft furnace and pure oxygen. Some advantages of using pure oxygen include the reduced volume of fuel gas produced, its increased fuel value (less nitrogen impurity), and a smaller requirement for offgas treatment equipment.

The main feature of the process is the vertical shaft furnace as shown in Fig. 4.1 in which the refuse is dried and pyrolyzed, and metals and

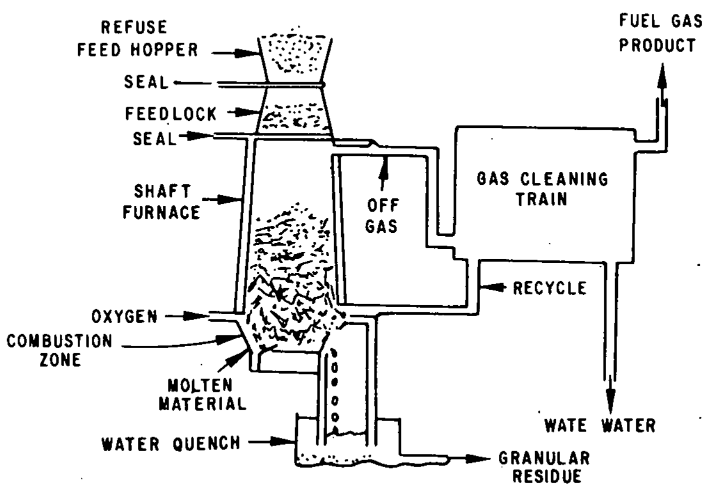

Fig. 4.1 The Key Element of the Union Carbide Process is a Vertical Shaft Furnace.

glass are melted. Figure 4.2 is a schematic of what is occurring in the shaft furnace. In the upper portion of the furnace, the drying zone, gases from the lower portions of the furnace dry the incoming municipal solid waste. The middle zone of the furnace is the area where the dried waste is pyrolyzed. In the lower zone, oxygen is injected, and primary combustion and melting occurs. According to the process patent, from 0.15 to 0.28 ton of O_2 is required per ton of refuse (nominally 0.2 ton of O_2/ton of refuse). Oxygen

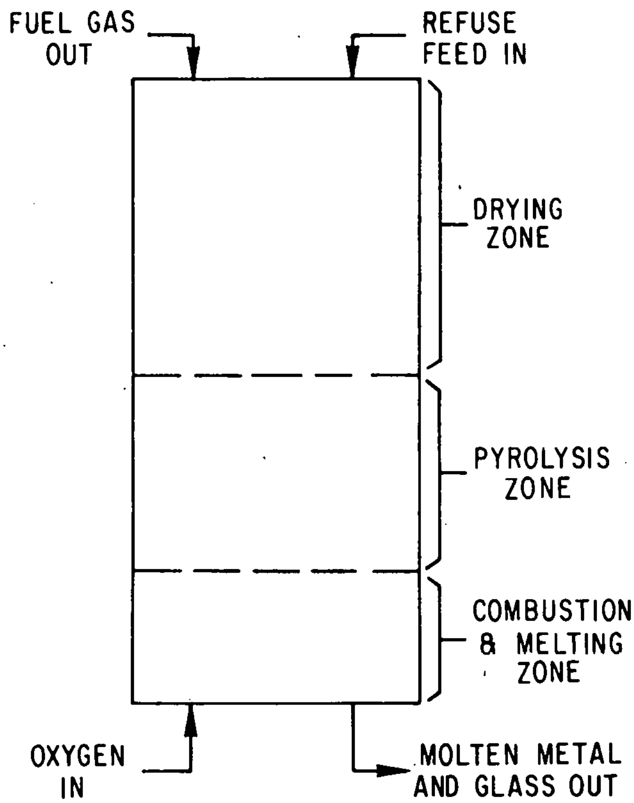

Fig. 4.2 Schematic Diagram of Shaft Furnace

injected into the bottom of the furnace reacts with the char from the upper zone, and the resulting combustion is at a high enough temperature to melt any incombustible fraction of the waste. The molten material, drained continuously into a water quench tank, forms a hard granular material. The hot gases from the combustion zone rise through the descending solid waste and provide heat to pyrolyze the waste. No external heat source is required. Gases leaving the pyrolysis zone are cooled as they come into contact with newly added waste. Gases exit the unit at about 200°F. The gas contains water vapor, some oil mist, and fly ash. These components are handled by a gas-cleaning train consisting of an electrostatic precipitator, an acid absorption column, and a condenser. Organics, removed from the gas, can be recycled back to the furnace for further cracking.

The fuel gas produced is reported to be a clean burning fuel comparable in characteristics (but with lower Btu value) to natural gas. It is essentially free of nitrogen oxides and sulfur compounds, and it burns at about the same temperature as natural gas. The limitation on the offsite use of the gas is the extra cost of compressing it for storage and pipelining. Consequently for economic reasons, the market for such gas should not be more than 1 or 2 miles from the pyrolysis facility.

Gas from this process can be recovered for offsite use because use of oxygen instead of air precludes dilution of the fuel gas product by the 79% nitrogen in the air. However, this process requires a constant oxygen supply that can be relatively expensive for small plants. Table 4.1 compares the Purox system with conventional incineration.

Table 4.1 Comparison of Purox System with Conventional Incinerator

	Purox System	Conventional Incinerator
Oxidant (tons/ton refuse)		
Oxygen	0.2	-
Air	-	7.1
Furnace volume		
CF/daily ton	2-4	20
Furnace gas		
Tons/ton refuse	1	8
CFM/daily ton	30	620
Temperature, °F	200	1700
Fly ash in clean gas		
lb/ton refuse	0.2	2
Residue - % of original volume	3	10

4.2 PRODUCT CHARACTERISTICS

According to the Union Carbide patent application, the composition of the fuel gas should be similar to that shown in Table 4.2. It is reported that for a municipal solid waste having a heating value of 9×10^6 Btu/ton, the total heating value of the gas produced in a full scale plant would be from 5 to 7 million Btu/ton of refuse processed, depending on whether oils

Table 4.2 Offgas Composition

Component	Gas Sample Analysis (Volume percent) Sample #1	Sample #2	Sample #3
CO	53.2	46.6	44.3
CO_2	14.8	21.8	18.0
CH_4	3.1	2.9	3.0
H_2	26.4	26.8	31.1
N_2	0.6	0.8	0.3
C_2H_2	0.9	0.3	1.3
C_2H_4	0.8	0.6	1.7
C_2H_6	0.1	0.2	0.3
Higher Heating Value Btu/CF@70°F	309	277	317

were recycled. No char is produced, and it is anticipated that any oils will be recycled back to the pyrolysis furnace for further cracking; however, Union Carbide leaves the end use of the oil as "optional." Analysis of the Tarrytown, N. Y. plant slag, using New York City refuse, is given in Table 4.3.

Table 4.3 Analysis of Granular Residence

FeO	8.3 wt%
Fe_2O_3	1.4
MnO	0.6
SiO_2	53.0
CaO	11.5
Al_2O_3	7.7
TiO_2	0.1

4.3 PLANT CAPACITIES

The original Tarrytown pilot plant had a capacity of 5 tons/day. Union Carbide has built and is currently operating a 200 ton/day plant at its South Charleston, West Virginia facility. To date, nothing is reported in the literature on further projects or customers. However, in 1976, Union Carbide entered into negotiations with the City of Seattle, Washington to install a Purox unit as a part of a proposed solid-waste-to-methanol or-ammonia project.

4.4 ECONOMICS

At the current stage of development, economics for a full-scale Purox system are speculative. However, based on currently available information, the net cost of disposal for this process is projected to be about $4.50 per ton for a 1000-ton/day plant. The basis for this projection is a capital cost of $14 million, exclusive of land or site-specific design costs. The plant would have three 350-ton/day modules served by one oxygen plant. Annual amortization and operating costs would amount to about $3 million. Revenues from the sale of gas at 75 cents per million Btu (and a gas yield of 7 million Btu per ton of solid waste) would be about $1.6 million. Plant throughput on the basis of 85% availability would be 310,000 ton/yr.

4.5 STATE OF PROCESS DEVELOPMENT

The Purox Process has been tested in both a 5-and a 200-ton/day pilot plant. Very little data on operation appear in the literature, and the process does not appear to have ICES application before 1980.

4.6 ENERGY AND MATERIAL BALANCES

Union Carbide Corporation has reported some information on energy and material balances. Electrical consumption for a 1000-ton/day plant is estimated to be 5000 kW (120 kWh/ton of solid waste processed). Fuel is required only for startup. Figure 4.3 gives the material balances for Purox (on a per-ton-of-solid-waste basis). Table 4.4 gives the energy yield and plant energy efficiency.

4.7 MISCELLANEOUS INFORMATION

Although the original Purox flowsheet did not include size reduction of the incoming solid waste, Union Carbide has initiated studies to evaluate the effect of shredding on the Purox Process.

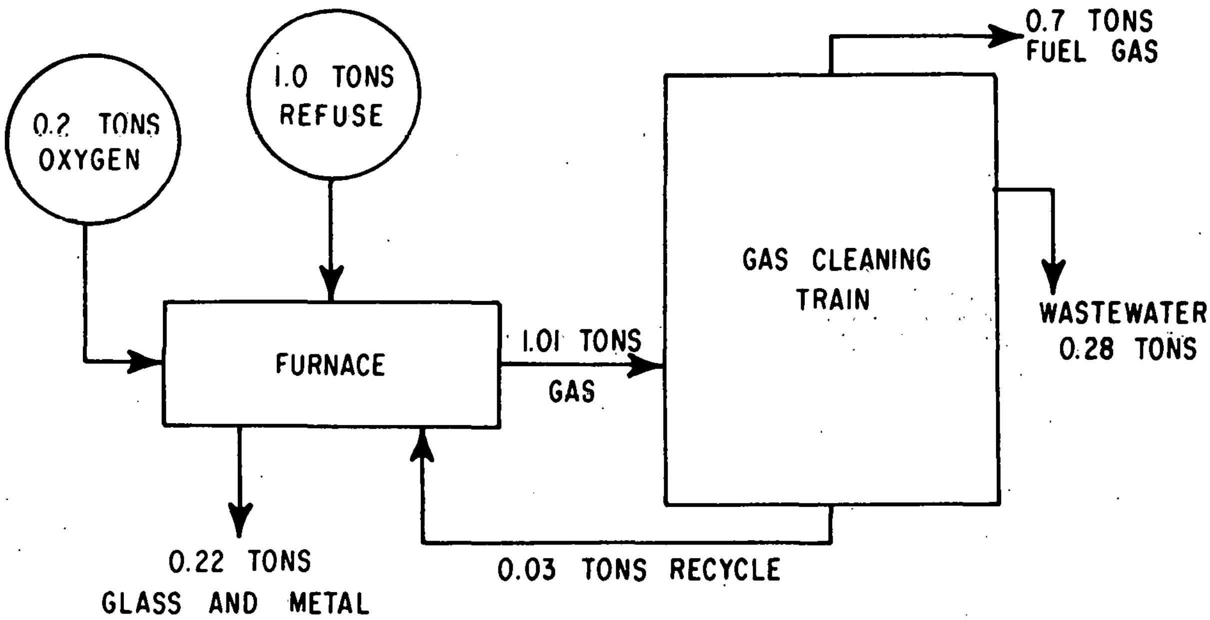

Fig. 4.3 Material Balance - Inputs and Products of Purox System

Table 4.4 Energy Balances

$$\text{Yield} = \frac{\text{Energy out(gas) - electricity in}}{\text{Total energy in waste}}$$

$$= \frac{7{,}000{,}000{,}000 \text{ Btu/ton} - 120 \text{ kWh/ton} \times 10{,}000 \text{ Btu/kWh}}{9{,}000{,}000 \text{ Btu/ton}}$$

$$= \frac{5{,}800{,}000}{9{,}000{,}000}$$

$$= 0.64 \text{ or } 64\%$$

$$\text{Efficiency} = \frac{\text{Energy out (gas)}}{\text{Energy in (solid waste, electricity)}}$$

$$= \frac{7{,}000{,}000 \text{ Btu/ton}}{9{,}000{,}000 \text{ Btu/ton} + 120 \text{ kWh/ton} \times 10{,}000 \text{ Btu/kWh}}$$

$$= \frac{7{,}000{,}000}{10{,}200{,}000}$$

$$= 0.69 \text{ or } 69\%$$

4.8 RATING OF THE DATA BASE

Because all of the money invested in Purox development is from corporate funds, currently available data are somewhat limited. More is expected to be released when pilot plant testing is completed and commercialization commences. However, the data released to date appear to reflect accurately the Purox concept.

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5. VERTICAL SHAFT FURNACE - HAMILTON STANDARD "REFU-CYCLER" PROCESS

5.1 PROCESS DESCRIPTION

The Hamilton Standard Refu-Cycler Process (Fig. 5.1) uses a pyrolysis system designed for single-step, nonpolluting refuse disposal and energy recovery. The system consumes "as-received" municipal trash and generates gaseous fuel at approximately 70% efficiency. A sterile inert solid residue that can be used as a construction material or as landfill also is generated. The 130 to 150 Btu/scf product gas can be used to reduce primary fuel consumption in ATMES. At 1977 prices for energy and waste disposal, the system is projected to generate a net savings in sizes greater than approximately 12 tons/day capacity.

The components that make up the Refu-Cycler can be classified into seven categories: (1) refuse loading, (2) the reactor, (3) product gas processing, (4) solid residue processing, (5) water processing, (6) combustion air processing, and (7) system control.

As shown in Fig. 5.1, refuse is dumped directly from packer trucks to a tipping floor at grade level. The plant operator uses a hydraulic lifting arm to transfer the refuse from the tipping floor to a hopper located atop a commercial hydraulic trash compactor which is used as the reactor loading ram. Depending on the application, other methods of refuse transfer can be used.

Trash from the hopper is compacted and forced into the reactor through an S-shaped duct. The compacted refuse in the duct and the ram face stopped in the forward position form a gas seal preventing the raw product gas in the reactor from entering the loading ram area. Operation of the loading ram is controlled by the reactor's ultrasonic level sensors which cycle the loading ram, as required, to maintain the proper trash level. If bridging should occur in the hopper and prevent trash from being introduced while the loading ram is cycling, an excess cycle alarm will sound. The operator can then reposition trash within the trash holding bin.

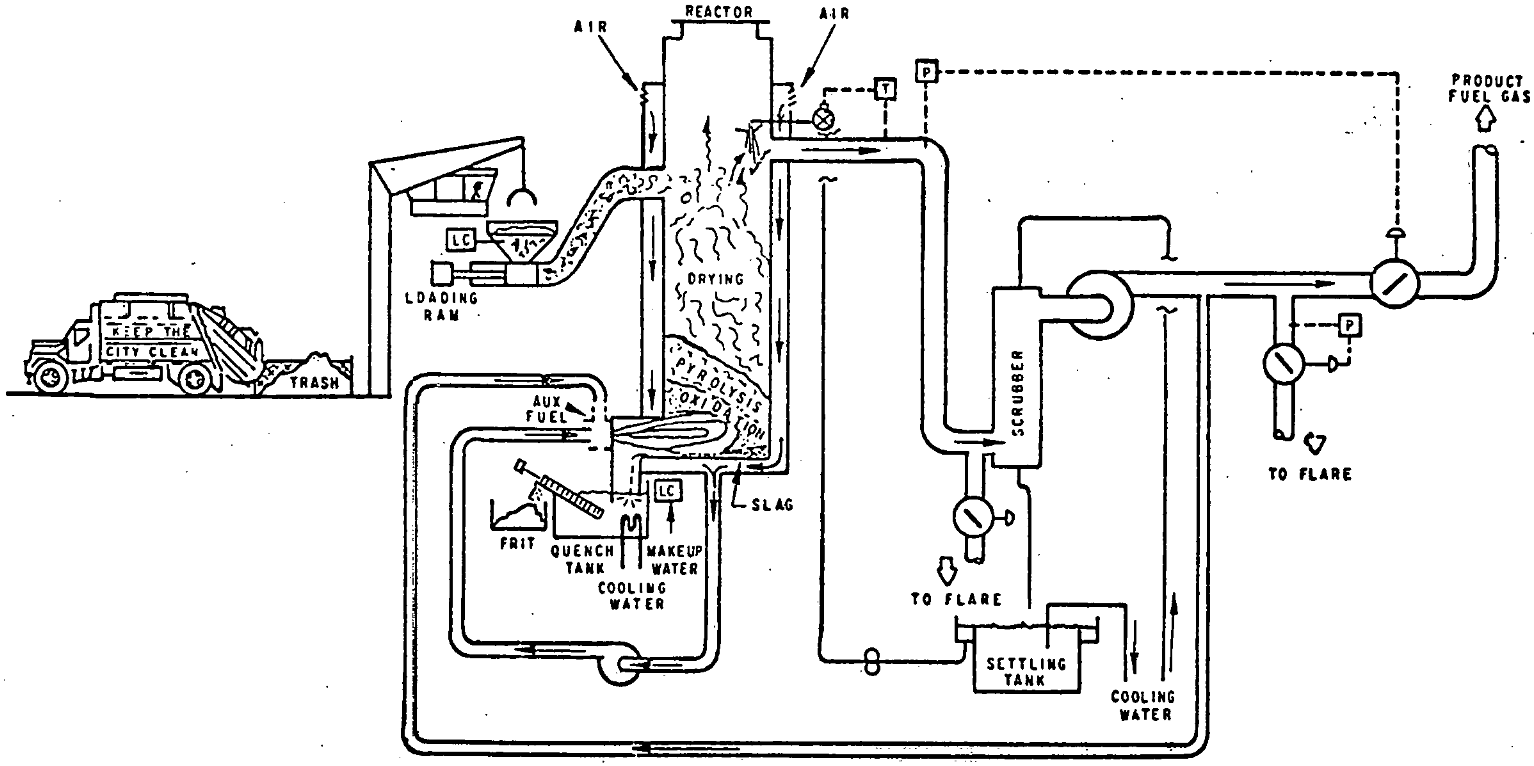


Fig. 5.1 Refu-Cycler System Schematic

The Refu-Cycler uses a vertical shaft, partial air oxidation, slagging pyrolysis reactor that is constructed as a double-steel-walled, air-cooled vertical cylinder with fire brick and refractory insulation in the high-temperature areas. Within the reactor are four discrete zones where different processes occur. These zones are the drying zone, the pyrolysis zone, the oxidation zone, and the slagging zone. (For description of the zones, see Section 4.1.)

Pressure is controlled to 2 or 3 in. of water above atmospheric at the reactor outlet resulting in pressures as high as 10 in. of water at the slag tap area. The top of the reactor consists of a full diameter weighted relief panel that protects the reactor from overpressure.

The first step in the product gas processing occurs in the reactor with the water spray cooling of the outlet gases for temperature control ($\sim$200°C). The effect of low gas velocities (<2 ft/sec) and the fine water spray excludes virtually all particulate carryover from the reactor. High-and-low-temperature alarms and a temperature indicator provide continuous monitoring of gas cooling performance.

When the product gases leave the reactor, they are scrubbed of condensibles, compressed, and discharged through a back-pressure control valve. System back pressure is maintained slightly positive to exclude air from the product gas stream. Gas enters the scrubber at 200°F (with a dew point of approximately 170°F) and leaves at 90°F to 100°F and 100% relative humidity. During periods of no demand, the product gases are diverted to a flare tube for disposal. Should a component failure occur in the Refu-Cycler system, the product gases are shunted directly from the reactor to the flare tube.

During the primary mode, the flare burner and blower are not operated. However, by means of a bleed valve, the flare tube is continuously purged by the oxidation air blower. This continuous purge removes auxiliary fuel or pyrolysis gases that might leak into the flare tube while the burner is off. Moreover, the base of the flare tube has air openings to allow air to enter while the flare burner is operating and to allow heavier gases to escape from the flare tube if a leak should develop when the burner is not operating.

The solid residue from the processed waste is discharged from the reactor as a molten slag that is immediately quenched in water as it falls from the slag tap hole into the bottom of the reactor. When the molten slag contacts the water, it solidifies and fractures into a fine gravelly substrate (frit) which is removed from the quench tank by a screw-type conveyor and deposited into the frit container.

The water in the quench tank is cooled continuously by submerged cooling panels that absorb the heat from frit quenching. A supply of cooling water to the panels is required, and some makeup water is necessary to compensate for the vaporization that results from the quenching process.

The oxidation air burner supplies heated air, as required, to the reactor to maintain the proper rate of pyrolysis. This burner, capable of burning either an auxiliary fuel or pyrolysis gas in excess air preheated in the reactor shell, is used for rate control of the pyrolysis process and for startup and shutdown.

During startup, auxiliary fuel is used. When steady-state conditions are reached, the burner is switched over to burn approximately 15% of the product gas for oxidation air heating.

The oxidation air blower that supplies air to the oxidation air burner also supplies purge air flow to the flare tube and serves as a backup air supply in the event of a flare tube blower failure.

Because trash loading is a part-time operation and critical safety functions are automated, the operator may be able to perform other functions, such as trash collection, from area pickup points. However, he should be on call to respond to noncritical alarm situations, e.g., loading ram excess cycling, or trash bin low level.

The Refu-Cycler is designed to process refuse as delivered in common packer trucks. In general, anything that can be fed through the compactor of a packer truck will be within the acceptable size range for the Refu-Cycler.

The physical refuse size limitation of the Refu-Cycler results from the dimensions of the opening between the hopper and the loading ram chute.

This opening is sized to be compatible with the packer truck load characteristic size and to limit the dimensions of any single object to less than the internal diameter of the reactor. This size relationship minimizes the potential for bridging (hang-up) within the reactor and the feed chute.

The anticipated energy recovery efficiency, based on a lower heating value for relatively dry industrial and commercial refuse with a high percentage of combustibles, is 72 -- 75%. Increasing the inerts and the moisture content to a residual-type trash and adding sewage sludge to bring the moisture content to 50%, will reduce the recovery efficiency only slightly to a value above 70%. The effect of moisture on efficiency is minimized by the cooling water spray in the top of the reactor. Sufficient moisture is required at the top of the reactor for cooling the product gas. When dry trash is processed, water must be added to achieve the necessary cooling. However, when the trash moisture content is increased to 50% in the input mix, there is sufficient moisture in the trash itself to cool below the 200°F outlet gas temperature.

Some ferrous metal is required in the refuse to flux the slag at the base of the reactor. Normal refuse variations include adequate quantities. However, if the refuse mix does not contain sufficient metal during some temporary period, frit can be recycled to the reactor with the trash.

5.2 PRODUCT CHARACTERISTICS

The product fuel gas generated by the Refu-Cycler system is in the 130 to 150 Btu/scf range and is delivered at approximately 5 psig, 100°F and with a dew point of about 80 to 90°F. Tables 5.1 and 5.2 list the gas composition and properties, respectively. Both are for an average municipal waste with 25% inerts, 25% water and an HHV of 4400 Btu/lb.

The primary fuel constituents of this gas are carbon monoxide and hydrogen. As such, the gas has very clean and stable burning characteristics with performance only slightly below that of natural gas for most applications. The only major disadvantage of the pyrolysis gas, compared with natural gas, LP gas, and other common fuels, is its low Btu/ft^3 content leading to an

Table 5.1 Typical Product Gas Composition

Dry Gas Composition	%	Dry Gas Composition	%
CO	14.9	NH_3	0.3
CO_2	13.7	N	57.16
H_2	9.0	O_2	0.4
CH_4	2.7	H_2S	0.01
C_2H_2	0.9	HCL	0.03
C_2H_4	0.9		

Molecular Wt: 27.5 lb/mol
Water Content: 0.037 lb H_2O/lb dry gas
Tars and Oils: 0.014 lb, tar and oil/lb dry gas

Table 5.2 Typical Properties

Temperature	100°F
Pressure	5 psig
Heating Value	132 Btu/scf fuel gas, (LHV) 144 Bru/scf fuel gas, (HHV)

inherent high cost of storage and transportation. This disadvantage restricts the practical applications to close-by utilization as it is produced. For most integrated or mixed-energy systems, however, this restriction presents no disadvantage.

The Refu-Cycler fuel gas is especially applicable as a supplement for the reduction of primary fuel consumption. This fuel gas can be used in boilers, ovens, gas turbines, fuel cells, and both spark- and compression-ignition internal combustion engines. Finally, because the gas is synthetic, by adjusting the H_2 and CO ratio, methanol can be produced to provide a storable fuel.

The only residue from the Refu-Cycler is the slag in the form of frit. There is no waste tar or char, and no wastewater if an evaporative cooling tower is used. The frit is a glassy, black granular, material that can be sold for roadway construction or as a decorative material for landscape gardening. It may be remelted and molded into any shape for sale as an attractive construction material, or it may simply be used for landfill at a convenient location. Because the material is biologically inert, earth cover is unnecessary.

5.3 PLANT CAPACITIES

The Refu-Cycler can be constructed in a wide range of sizes and still perform its refuse disposal and product-gas generation functions. The economies of scale make the larger plant sizes more economically attractive. The smallest reactor that can effectively treat municipal refuse without shredding or other preprocessing handles approximately eight tons of 4400-Btu/lb of municipal refuse per day. Below this size, the reactor inside diameter becomes too small for uniform trash distribution, and large objects in the trash will allow channeling of hot gases through the bed. The largest reactor that can be built in the vertical cylinder configuration would handle a range of 70 -- 100 tons/day. Above this range, to maintain the low bed loadings that prevent particulate carryover, the reactor inside diameter becomes so large that uniform distribution of the incoming trash cannot be achieved, and channeling can occur.

Within this span of sizes, virtually any specific size can be effectively produced. For sizes above the 70-to-100-ton/day capacity, multiple reactors can be used to achieve virtually any total capacity, and downstream processing equipment, such as blowers and scrubbers, can be common to several reactors and thereby allow some capital equipment savings. A given reactor's capacity is a function of the type of trash to be consumed. The higher the Btu-content of the trash, the lower the rated capacity.

Hamilton Standard has made detailed designs of six-, ten-, and twenty-ton/day plants, and is in the final stage of construction and checkout of a 10-ton/day pilot plant. These size ratings are based on industrial refuse; hence their capacities would be higher when municipal refuse is consumed. Accurate measurements of pilot plant performance will prove the effective bed loading and related plant trash consumption rates for the selected reactor size and configuration.

5.4 ECONOMICS

The economics of the Refu-Cycler show a positive net annual savings for all units greater than approximately 21 tons/day (of 6000-Btu/lb trash). Depending on the situation, the economics may be positive even for smaller installations.

For purposes of this study, the following assumptions are made:

- Fuel Cost - $2.25/million Btu
- Unit Conversion Efficiency = 70%
- Lower Heating Value of Input Trash - 6000 Btu/lb
- Startup/Shutdown Fuel Requirements - 1.4 million Btu/cycle for each ton/day capacity
- Conventional Waste Disposal Costs - $10/ton
- Operating Cycle - 5 days/week, 24 hr/day, 52 weeks/year
- Local Cost of Electricity = $0.03/kWh
- Debt amortization = 10 years @ 10% interest

Using these assumptions and Hamilton Standard's estimates for capital cost, maintenance cost, and operator requirements, the economic data in Fig. 5.2 were generated. Depending on a given situation, fuel costs, trash

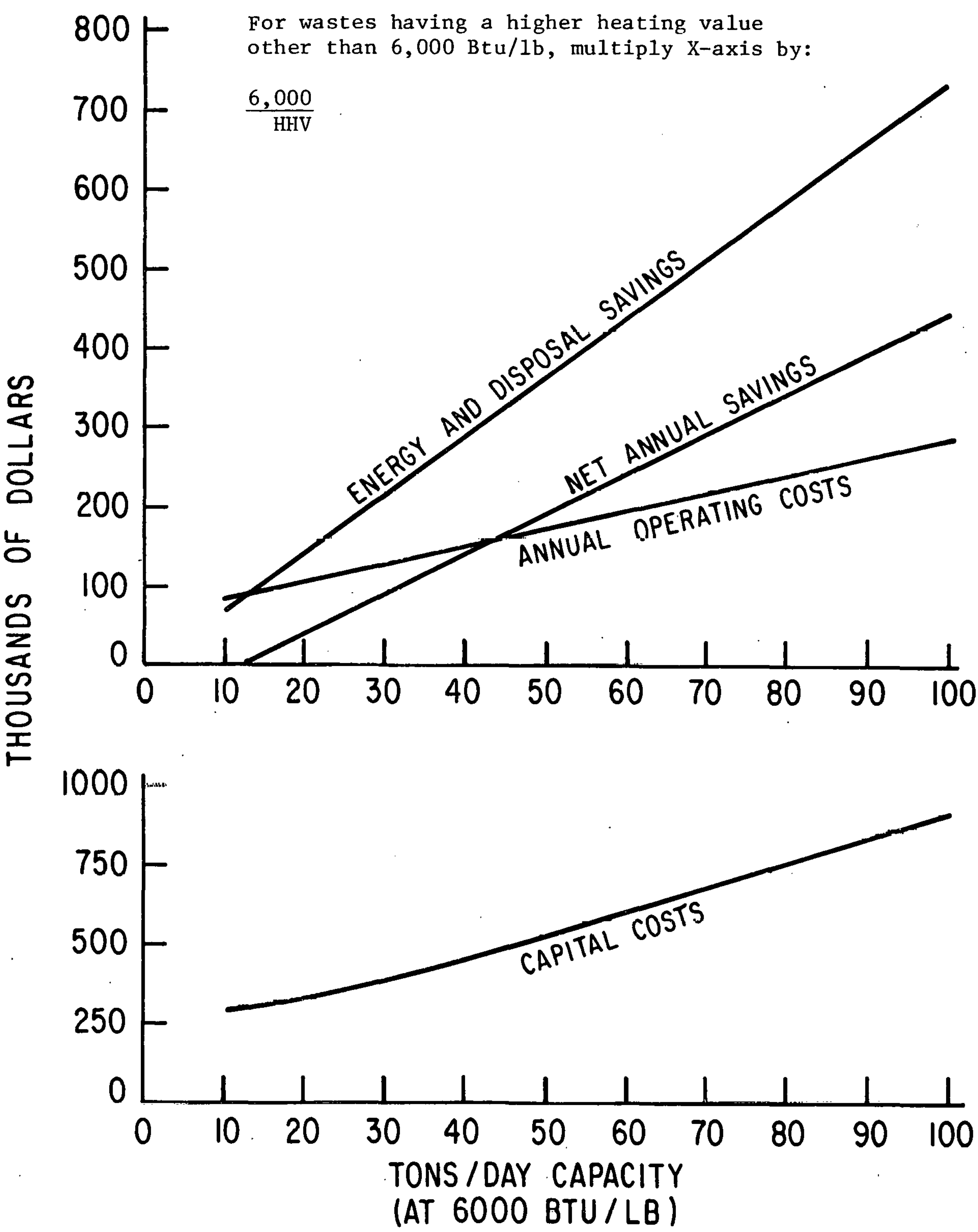


Fig. 5.2 Refu-Cycler Economic Data

heating value, waste disposal costs, and operating cycle can vary and thus adjust the economics. Not included are site preparation costs, depreciation, or tax considerations because these factors show a wide range of variability for different types of application.

The variables that have the greatest impact on net savings are fuel costs and waste disposal. Fuel costs in the U.S. in 1977 range from $0.75 up to $2.75 per million Btu. However, by 1986, projections have shown this range narrowing and the cost increasing to $3.75 -- $4.10. Thus, the pyrolysis fuel output will become even more valuable as the economics change and as fuel becomes more scarce. Waste disposal costs in 1976 ranged from $2 to $3 per ton for landfill and up to $25 per ton and higher in the highly populated areas. In future years, higher costs for disposal will become more common as government regulations become more strict and land becomes scarcer. To demonstrate the impact of higher cost, if fuel costs of $3 per million Btu and waste disposal costs of $15 per ton are assumed, the net savings on a 10-ton/day unit becomes $23,500 per year instead of a deficit of $5300. Therefore, the data contained herein, while representative only of an average installation, are extremely general. Any given application must be investigated in greater detail to establish economic viability.

System capital costs can be approximated by:

$$C_c = 250 + \left(\frac{6000}{HHV}\right) \left(\frac{S - 10}{100}\right) 625, \qquad \text{(Eq. 5.1)}$$

where:

C_c = Capital cost in thousands of dollars,
S = System capacity, in tons/day.

System annual operating costs can be approximated by:

$$C_o = 90 + \left(\frac{6000}{HHV}\right) \left(\frac{S - 10}{HHV}\right) 190, \qquad \text{(Eq. 5.2)}$$

where:

C_o = Annual operating cost in thousands of dollars, and
S = System capacity in tons/day.

5.5 STATE OF PROCESS DEVELOPMENT

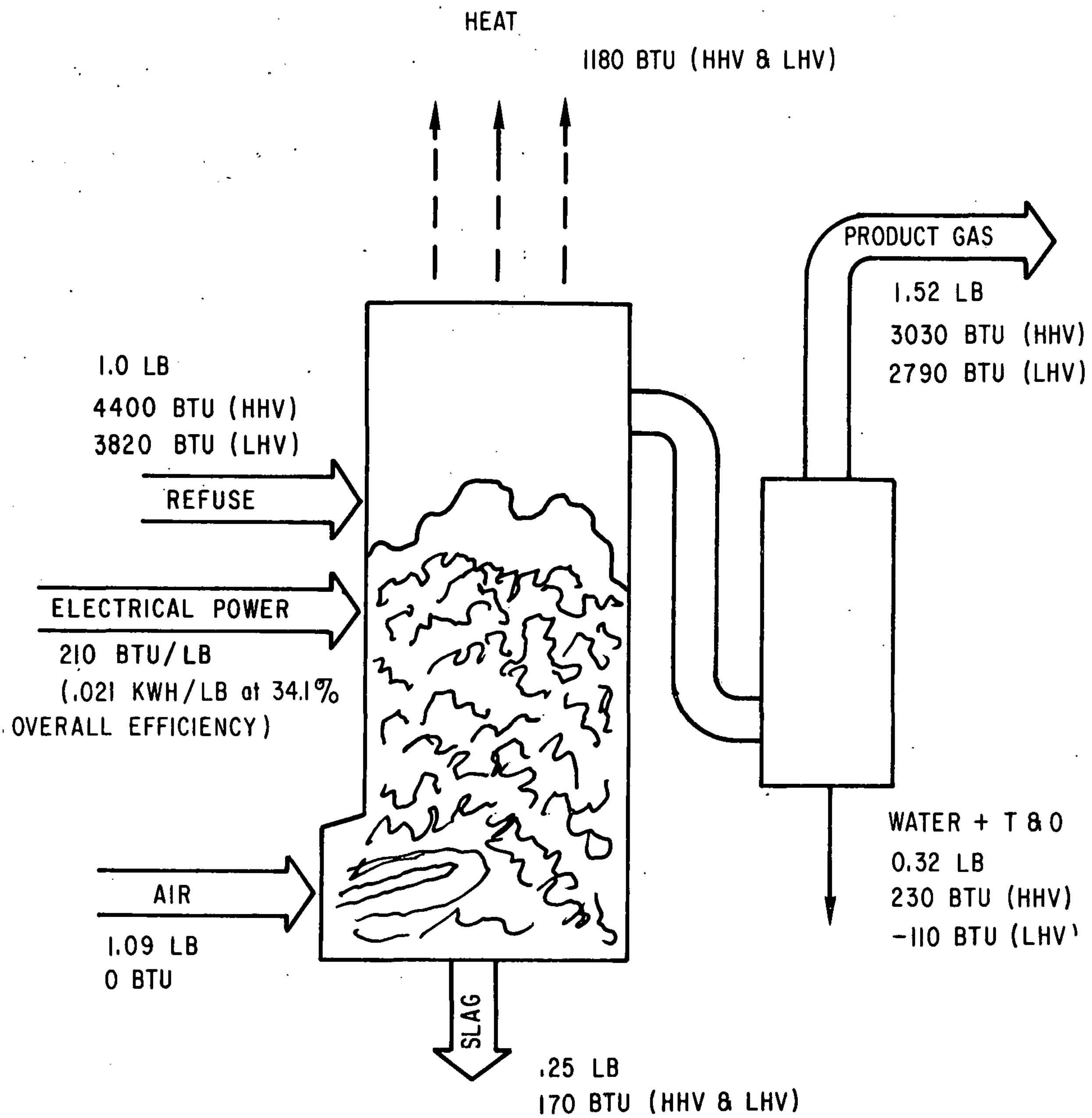
The Refu-Cycler has evolved from development testing, evaluation, and design studies which began in 1968. Hamilton Standard's design effort resulted from a 1974 company-funded, industry-wide study of pyrolysis of waste. Based on this study, Hamilton Standard selected the vertical shaft, partial air oxidation, slagging pyrolysis design as the most practical and efficient technique for refuse conversion to usable energy. This concept has been proved in the initial development work conducted by Urban Research and Development Corporation (URDC).

Initial experimental work by URDC utilized a process that approached "pure" pyrolysis, i.e., most of the heat required to dry and pyrolyze the refuse was supplied through the walls of a retort within the reactor.

Some conclusions drawn from past historical development by URDC in NASA studies by Hamilton Standard, the encouraging results of the Andco-Torrax partial air oxidation pilot plant operation in New York State, and their subsequent sales efforts in the European market, have led Hamilton Standard to invest in a pyrolysis waste disposal plant of its own design. The pilot plant configuration is as described in Sec. 5.1 with the inclusion of an evaporative cooling tower to handle the cooling requirements and to dispose of generated water. The plant is rated at 10 tons of industrial trash per day (at 6000 Btu/lb) but could handle 14 tons/day of 4400 Btu/lb municipal trash. The plant is being built on company property at Windsor Locks, Connecticut and will deliver the product gas approximately 400 ft to the plant boiler facilities where it will be burned as a portion of the base load to reduce fuel oil consumption. The unit is to become operational in early 1977.

5.6 ENERGY AND MATERIAL BALANCES

Figure 5.3 shows typical mass and energy balance for the Refu-Cycler direct-fired, oxidation air system. The values show both higher and lower heating values per pound of refuse input. Note that approximately one pound of air is required per pound of refuse. The effluent water includes some dissolved tars and oils, and the heat rejection includes both cooling and direct losses to the environment.



BASED ON MUNICIPAL REFUSE

25% Inerts

25% H_2O

50% Combustibles

RECOVERY EFFICIENCY

HHV 69%
LHV 73%

NET EFFICIENCY

HHV 64%
LHV 67%

Fig. 5.3 Refu-Cycler Mass and Energy Balance

Performance will vary somewhat with system configuration and size. In general, however, the energy recovery efficiency based on the LHV will exceed 70%.

Auxiliary services required by the Refu-Cycler shown schematically in Fig. 5.1 are auxiliary fuel, makeup water, and electrical power.

Auxiliary fuel is required for startup of the reactor and startup and shutdown of the product gas flare tube. During normal operation, auxiliary fuel is not used.

Makeup water is required at the quench tank and at the evaporative cooling tower, if used. The amount required is small because the basic pyrolysis process generates water. Where cooling is other than evaporative, a discharge stream -- rather than a makeup water supply -- is required for the generated water.

Electrical power is used for the loading ram hydraulic pump, blowers, water pumps, compressors, and the instrumentation and control equipment. The required input to the performance algorithm is:

$\dot{m}$ = refuse input flowrate (ton/day),

X_i = fraction of inerts in waste, and

X_w = fraction of water in waste.

The output algorithm then becomes:

$X_b = 1 - X_i - X_w$ (fraction combustibles),

$\dot{HHV}_{in} = 17.6 \times 10^6 X_b \dot{m}$ (energy input, HHV basis, Btu/day),

$V/m = 96,600 X_b^{1.2}$ (fuel gas volume per ton waste, scf/ton),

$\dot{V}fg = (\dot{m}) \times (V/\dot{m})$ (fuel gas volume output, scf/day),

$HHV_{out} = 124 X_b^{-0.15} \dot{m}^{0.01}$ (fuel gas higher heating value, Btu/scf fuel gas),

$$\dot{HHV}_{out} = (\dot{V}fg) \times HHV) \text{ (energy output HHV basis, Btu/day),}$$

$$N_R = 100\frac{\dot{HHV}_{out}}{HHV_{in}} \text{ (recovery efficiency).}$$

5.7 MISCELLANEOUS INFORMATION

A desirable feature of any energy recovery system is the ability to respond to off-design or partial-load demands. A fixed product gas production rate, for example, would waste energy at low demand rates, and alternate energy sources would be required to meet high demands. The Refu-Cycler has been designed with "throttle-ability" in mind to allow adjustment of product gas flowrate to meet cyclic energy demands.

The pilot plant burner and oxidation air flow controls allow flow rate variations of 25% to 150% of nominal flow; however, because of reactor process limitations, a reasonable expectation of range would be 50% to 150% of design flow. Process rate is controlled primarily by the amount of air injected into the oxidation zone of the reactor for oxidation of char. A secondary control variable is the ratio of product gas recycled to the oxidation air burner, and thus the temperature of the excess air combustion products. Product gas flowrate is measured to provide a feedback control point.

The minimum capacity is set by the ability to maintain reliable slag flow. If the oxidation air flow or temperature is too low, the slag will not flow properly. The maximum capacity of this type of reactor is set by particulate carryover caused by excessively high velocities at the top of the bed. The Refu-Cycler is designed with such low loadings that even at 150% of design flow, top end velocities should not exceed 3 ft/sec, and carryover should not be a problem. Experimentation with the pilot plant will verify the "throttle-ability" range of the Refu-Cycler.

The Refu-Cycler is designed for continuous-duty operation to achieve maximum operating efficiency, minimum plant size, and minimum use of fuel for startup/shutdown cycles. Noncontinuous operation is possible, but not as desirable. The requirement for partial operator attention while the unit is operating adds three-shift and weekend operator expense to continuous operation. For this reason, it may be desirable to operate the Refu-Cycler on a part-time basis. The auxiliary fuel expense and equipment inefficiency of daily startup and shutdown make any daily duty cycle unattractive. It is expected to take 6 hr for a combined startup/shutdown cycle, leaving only 2 hr for operation in an 8-hr shift and 10 hr for operation in a 16-hr shift.

A weekly operation cycle of 24 hr/day, 5 days/week offers an attractive compromise because only 6 hr/week are required for startup/shutdown, and weekend operator expenses are eliminated. Moreover, the 2-day regular shutdown period allows time to replace components that are approaching maximum useful life before random equipment failure shuts down the plant at unscheduled times.

Reactor scaling is done at constant bed loading and bed-length-to-diameter ratio. Heat losses, therefore, remain essentially constant, and the effect of plant size on performance is relatively minor for systems that do not attempt to recover sensible heat.

Residence time increases for larger size reactors. Because bed loading is constant, bed velocity also is constant. The flow path length, however, is proportional to diameter, so that residence time is proportional to diameter or the square root of total refuse volume flows. This increased residence time has only a minor effect on the thermochemical characteristics of the gasifier.

From the standpoint of physical size alone, larger-size gasifiers obviously can handle a wider variety of wastes than can smaller ones. In general, the size limit for any particular system will be set by ram feeder size limitations, so that anything that can get into the feeder will be satisfactory for the gasifier. Even a reactor as small as 1.7 ton/day has accepted ordinary municipal refuse with a minimum of selection and removal of oversized material. Differences in the composition of the combustible portion of municipal refuse can be expected to be negligible. However, there can be large differences in the proportion of water and inerts.

The composition of the inert fraction of municipal refuse can vary significantly, and the effect of the variability is felt most in the smaller systems. For example, because beverage containers make up a significant proportion of the inert fraction, local variations in the relative mix of glass, steel, and aluminum containers can be sizable. Local recycling efforts also may have a noticeable effect. Earlier development work on composition effects indicates that the properties of the slag are insensitive to composition variations within the range that would be expected for ordinary municipal wastes. The only constituent that does produce a significant effect is the iron content and then only when the proportion of iron drops below that which would normally be expected. When the iron content drops below approximately 11% of the inert fraction, slag viscosity increases. Although this increase makes a system more susceptible to slag freeze-up problems, it certainly does not make tapping impossible.

5.8 RATING OF THE DATA BASE

The predicted performance of the Refu-Cycler is based on data taken during earlier development testing at URDC. These data were evaluated, adjusted for size and other effects, and used in the preparation of a mathematical model. As a verification, the model was used to predict published performance data of other operational installations; the results agree closely. Therefore, the model should predict the Refu-Cycler performance reasonably well. Nevertheless a certain amount of development work will be required on the pilot plant because some aspects of that system have not yet been tested.

Cost estimates for the Refu-Cycler are based on recent equipment purchases for the pilot plant. As a result, they are accurate for near-term installations, but become questionable for long-range estimates. This is the result of the inability to predict accurately inflation of capital, and operating and fuel costs. It is evident that the Refu-Cycler always will be applicable to reduce primary fuel consumption, but that the predicted break-even points for future systems may vary.

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