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Data Summary of Municipal Solid Waste Management Alternatives

Volume VI: Appendix D—Pyrolysis and Gasification of MSW

*SRI International
Menlo Park, California*



National Renewable Energy Laboratory
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This report, *Data Summary of Municipal Solid Waste Management Alternatives*, comprises 12 separately bound volumes. Volume I contains the report text. Volume II contains supporting exhibits. Volumes III through X are appendices, each addressing a specific MSW management technology. Volumes XI and XII contain project bibliographies. The document control page at the back of this volume contains contacts for obtaining copies of the other volumes.

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APPENDIX D PYROLYSIS AND GASIFICATION OF MSW

D.1 INTRODUCTION/OVERVIEW

This Appendix summarizes information available in the open literature describing the technology and operating experience of pyrolysis technology as applied to the management of municipal solid waste (MSW). The literature search, which emphasized the time frame of greatest activity in MSW pyrolysis (i.e., the mid-1960s to the mid-1980s), focused on the scale of application, material feedstock, technical limitations and economic considerations. Smaller scale facilities, either laboratory/research scale (< 1 TPD) or process development/pilot scale plants (1-20 TPD) for municipal waste and related materials (agricultural, forest residues, industrial wastes, etc.), are mentioned in the literature (275, 495). However, such data are sparse, dated, and often have limited applicability to MSW in general, and for design scale-up in particular. Therefore, greatest emphasis was placed on identifying demonstration scale (20-150 TPD) and commercial scale (> 150 TPD) studies which could be expected to provide economic, environmental, and energy data that can be scaled with possibly less risk.

While the promise of pyrolysis of MSW lies in its ability to transform municipal waste into gaseous and liquid chemicals and fuel products, the major limitation is the unproven technical and economic feasibility of a large scale facility.

D.1.1 Background

Pyrolysis is most simply defined as a chemical change brought about by the addition of heat in the absence of oxygen. In the context of energy recovery from solid fuels, it encompasses all thermal degradation processes without combustion, proceeding either in the absence of oxygen (pure pyrolysis) or under partial oxidation (275). The end products of pyrolysis include a solid char, a liquid tar and a gas, all of which are potentially marketable forms of energy (453, 573). One of the major reasons for interest in pyrolysis in the United States stems from our dependence on liquid fuels, or, in general, on fuels that are storable, economically transportable, and that can readily substitute for conventional fuels. Pyrolysis is one of the few technologies that offers the potential for the production of "high density" alternative fuels.

D.1.1.1 United States

The impetus to apply pyrolytic technologies to municipal waste feedstocks grew out of concern for the mounting MSW problem, including diminishing landfill space and groundwater contamination and environmental problems associated with early MSW incineration efforts. Further, with the belief in the early 1970s that cheap and abundant energy was a thing of the past, alternatives to traditional sources of energy had to be explored (60). The emphasis on environmental protection was, therefore, extended to energy recovery. Among the possible alternatives for achieving energy recovery from MSW, pyrolysis offered the potential for volume reduction and improved control of emissions.

Recognition of environmental concerns and energy needs led to the enactment of environmental legislation, formation of the EPA and, later, DOE. Initial passage in the United States of the 1965 Solid Waste Disposal Act was followed by the 1970 Clean Air Act and 1976 Resource Conservation and Recovery Act and their Amendments. These Acts mandated and enabled the federal government (EPA and its predecessor agencies) to support research and demonstrations to develop and apply new and improved technologies for recovering materials and energy from solid wastes (466). This mandate was closely coupled with the DOE's charge to investigate the utilization of wastes as sources of energy.

The three pyrolysis projects/processes selected by the EPA for large-scale demonstration during the early 1970s were: 1) the Monsanto Landgard Process; 2) the Andco-Torrax Process; and 3) the Occidental Petroleum Liquefaction Process. The Purox process was developed in parallel by Union Carbide Corporation with corporate funds (275).

D.1.1.2 Japan

Similar to the United States, legislation and regulatory agencies have evolved in other countries, most notably in Japan and Europe. For many of the same reasons they were pursued in the United States, Japan built pilot, demonstration and commercial scale pyrolysis plants during the late 1960s, 1970s and early 1980s. Pyrolysis appears especially attractive for managing Japanese MSW from the standpoints of heavy metals contamination and HCl emissions from plastics contained in the waste (275, 108).

In Japan, heavy metal contamination of groundwater from conventional incinerator ash is of great concern. In pyrolysis, most of the harmful by-products of thermal degradation report to the char, which, in most Japanese plants is slagged, leaving the ash as a completely vitrified, obsidian-like sand (10). With little additional treatment, this material becomes virtually inert and can serve as a construction material.

Some Japanese cities experience high (approximately 20 percent) concentrations of a variety of plastics in the household waste stream. When conventionally incinerated, such plastics cause corrosion of the boiler and HCl emissions from the stack. This problem has been significantly reduced using lime and/or other alkali constituents in a dual fluidized bed gasification system (287). According to a 1988 report, Japan's Funabashi City is the site of one of only a few commercial scale pyrolysis systems in the world. In addition, it is the first and only fluidized-bed pyrolyzer using MSW (108, 799). As of 1988, this Tsukishima Kikai Co. system, which began operations in 1981, had been operating largely uninterrupted since 1983 (108).

D.1.1.3 Europe

When the United States and Japanese initiatives were undertaken in the early 1970s, Western Europe was largely committed to conventional mass burn systems for managing MSW and complying with the prevailing air pollution codes (822). Commercial and small-scale efforts have been undertaken as discussed in Sections D.2.3 and D.2.6, respectively.

D.1.2 Status of MSW Pyrolysis Facilities Worldwide

Although several pyrolysis systems have been built, most have been small-scale laboratory experiments or demonstration/research plants. Table D-1 lists the pyrolysis systems built, tested and operated, excluding laboratory pilot experiments smaller than 4 TPD (799). While most of these projects were built with at least partial government assistance, limited data in the literature suggests that there may be only four commercial scale facilities operating worldwide as of 1988. These include: the 450 TPD Tsukishima Kikai system in Funabashi City, Japan; the 400 TPD Andco-Torrax system in Creteil, France; the 150 TPD Union Carbide (Purox II) system in Chichibu City, Japan; and a 35,000 TPY commercial scale, indirectly heated drum-type pyrolyzer system in Burgau, Germany (552, 723). Although not part of the survey results presented in Table D-1 (799), the limited information in the literature on the Burgau facility is summarized in Section D.2.3.

TABLE D-1. WORLDWIDE MSW PYROLYSIS SYSTEMS¹
FACILITY DESCRIPTION AND STATUS AS OF 1988 (799)

Location	Capacity tpd	Process Developer	Startup/ Closure	Reactor Product	Reactor Type	Oper. Conditions	Remarks
Tonawanda, N.Y. S. Charleston, W.V.	5 200	Union Carbide (Purox)	Pilot/CL Pilot 74/CL (3 Yr.)	Med Btu Gas	Vert-shaft fixed-bed	Slagging temp.	Pre-Processed MSW
Chichibu City, Japan	2x75	Union Carbide	1981/OP	300-390	updraft	(2000°C)	
Tobata, Japan Tokyo, Japan Kamaishi, Japan Ibaragi, Japan	20 40 2x50 3x150	Nippon Steel.	Pilot/CL Pilot/CL /CL /CL	Med Btu Gas	Vert-shaft fixed-bed updraft	Slagging temp. (2000°C)	Size-Reduced MSW
OrchardPark, N.Y. Luedellange, Lux. Grasse, France Frankfurt, W. Ger. Crétell, France Hamamatsu, Japan Orlando, Florida	75 200(DR120) 170 200 2x200 87 100	Andco-Torrax	Pilot 71/77 1976/CL 1977/1979 78/81(13 Mo) 1979/OP /CL 82/83	Low Btu Gas 180 Btu/SCF	Vert-shaft fixed-bed updraft	Slagging temp. (2000°C)	Un-Processed MSW
Iwanuma, Japan Funabashi, Japan	40 3x150	Tsukishima Kikai (Pyrox)	Pilot 73/75 1981/OP	High Btu Gas	Vert-shaft 2-fluidized beds	1500°F	Size-Reduced MSW
Yokohama, Japan Yokohama, Japan	5 30	AIST - Ebara	Pilot 75/78 Pilot(2)78/84	High Btu Gas	Vert-shaft 2-fluidized beds	1500°F	Pre-Processed MSW (Plastics)
Upland, CA Elmwood Park, NJ	6 50	Waste Distillation Technology (Lantz Converter)	Pilot Pilot 82/84 (2 Yr.)	NA NA	Hor. Rotating Retort	1000°F+	Pre-Processed MSW
St. Louis, MO Baltimore, MD	35 1000	Monsanto (Landgard) Tech. Unavailable	Pilot 69/71 75/77	Low Btu Gas	Rotary Kiln	1800°F	Sized-Reduced MSW
La Verne, CA El Cajon, CA	4 200	Occidental (Flash Pyrolysis) Tech. Unavailable	Pilot 77/79	Low Btu Gas, fuel oil	Vert-shaft entrained bed	900°F	Pre-processed MSW (organics)

NOTES:

- /CL = Closed, if closure date is known it is provided instead
 /OP = Operational
 DR = Derated
 Pilot = Pilot Plant operated intermittantly for testing only
 (1) Laboratory experiment smaller than 4 tons per day are not included
 (2) One portion of a 100 TPD paper, compost and combustion plant

In the United States, two 200 TPD demonstration facilities, one in South Charleston, West Virginia, and one in El Cajon (near San Diego), California, have been shut down (271). The South Charleston pilot plant operated for three years producing medium Btu gas in a vertical shaft, fixed bed Union Carbide (Purox) system. The pilot plant near San Diego operated for two years producing both low Btu gas and high heating value liquid fuel in an entrained bed flash pyrolysis unit developed by Occidental Research Corporation. Two commercial facilities have been shut down and dismantled. These are the 1000 TPD rotary kiln pyrolysis system in Baltimore, Maryland, developed by Monsanto/Landgard, and a 100 TPD Andco-Torax system at Disney World in Florida. Problems typically centered on poor control of product quality, materials corrosion and erosion, and materials plugging (275, 343).

D.2 TECHNOLOGY DESCRIPTION

D.2.1 Overall Process Description

D.2.1.1 Reactions

Pyrolysis may be defined as an endothermic or thermally induced, destructive distillation of a solid fuel that produces a combination of non-combustible gases, water vapor, large molecule ("oil") vapors and char. High temperature processes, greater than 760 degrees C, are primarily used to produce gaseous products such as hydrogen, methane, carbon monoxide and carbon dioxide. Lower temperature processes, operating in the 454 to 740 degrees C range, primarily produce liquid products such as oils, acetic acid, acetone and methanol. With all pyrolysis processes, a carbonaceous residue or char is produced (271).

In order to control the types and quality of the products in pyrolysis reactions, oxidizing agents (air, oxygen or water) or reducing agents (hydrogen or carbon monoxide) may be used (271). Most pyrolysis processes make use of oxidation, or partial oxidation, of some of the products of pyrolysis in order to generate the heat necessary to drive the endothermic reactions. The addition of air to effect partial oxidation produces a fuel gas that is diluted by nitrogen and has a lower heating value. Thus, the yields and qualities of the products are degraded by the presence of inerts in the reactants which simply flow through the reactor with no useful change in character. These "parasitic" components, which may include nitrogen and ash, must be heated to the pyrolysis temperature by use of the fuel products, but play no useful role in the products' attributes.

Often the term pyrolysis connotes a process whose objective is liquid oil production, while gasification optimizes the production of a fuel gas. In reality, gasification is a subset of pyrolysis. In pyrolysis and gasification processes, the non-condensable gases and oil vapors produced typically display a heating value that can vary from low quality gas (85-150 Btu/SCF, often called low Btu gas, or LBG) to a medium quality gas (250-350 Btu/SCF) to a high Btu gas (greater than 500 Btu/SCF). The oils are highly oxygenated tars, very viscous, often unstable, corrosive (acidic), and extremely difficult to handle. Their heating values are roughly half that of a conventional crude petroleum oil. The char characteristics can also vary considerably with respect to volatiles, ash, fixed carbon, and calorific value.

In gasification, the characteristics of the three general products of pyrolysis (gases, vapors and char) are shifted within limits to favor the production of the non-condensable gas. The gasification process often makes use of high temperatures to crack the large oil molecules into non-condensable gases, and to convert carbon in the char and water vapor into small-molecule non-condensable gases. In gasification, the yield and quality of the gas is at the expense of the yields of the oil and char, and at the expense of the quality of the char.

In the pyrolysis of MSW or refuse-derived fuel (RDF), the high ash and moisture levels make the production of high quality char or gas difficult. Therefore, some degree of oxygen enrichment is needed to alleviate the parasitic burden of the nitrogen. The quality of the char is also a strong function of the quality of the feedstock. Large quantities of chemicals and residues, including sulfur, metals, glass, and ash in the char may cause it to become contaminated and unusable (271).

D.2.1.2 Process (271, 799)

Pyrolysis systems accepting solid fuel typically intend to produce a gaseous fuel and a char for sale to an energy customer. Following processing or presorting, a relatively homogeneous solid waste feedstock is fed into the pyrolytic converter or reactor, and heat is supplied externally or through the exothermic process to drive the reactions. The pyrolytic gases are drawn off the reactor, collected, quenched, and stored or combusted in a nearby combustion chamber.

The composition and yield of the pyrolysis products can be optimized by controlling feedstock composition and properties, as well as time, pressure, temperature, and presence of catalysts. As indicated by the more recent pyrolysis systems listed in Table D-1, the waste (RDF) should be shredded

and screened to produce a high quality pre-processed material. Since the char tends to bind up inert contaminants, the majority of the glass, sand, grit and metals in the feed must be removed to maintain char quality.

Some systems are designed to use a portion of the gases or oils produced to sustain the pyrolytic reaction, while others use auxiliary fuels such as natural gas, coke or coal. Pyrolytic gases or liquids and chars are collected and used either directly or processed further to produce higher quality fuel products.

Pyrolysis products have been proposed for use as fuel for power plants or industrial facilities, as well as burning these products on-site to produce steam. Other approaches include burning the pyrolysis products in a gas turbine or an internal combustion engine to produce electric power. Also, pyrolytic gases may be transformed into useful chemical products such as methanol, ethanol, benzene or ammonia.

In view of the difficulty in precisely controlling the pyrolysis reactions, the marketing of gaseous and solid pyrolysis products has not proven successful. Therefore, all of the previous operating and presently existing solid waste pyrolysis facilities utilize system products on-site for energy production of steam and/or electricity.

D.2.2 Technology Types/Operational Characteristics

Many different types of reactors have been employed in the pyrolytic conversion of MSW as noted in Table D-1. These include such vertical-shaft reactors as fixed bed, fluidized bed and entrained bed varieties, and the rotary kiln approach (275). Selection has been a function of the feedstock preparation, product characteristics desired, and operating conditions required to achieve the stated reactions. For example, vertical-shaft, fixed bed updraft reactors operate at slagging temperatures of 2000 degrees C, generally producing low to medium Btu gas. Vertical-shaft, dual fluidized bed reactors typically operate in the 1500 degrees F range producing a high Btu gas.

This section briefly describes the basic reactor types; Section D.2.3 discusses actual commercial-scale systems which were designed utilizing these technologies. It is important to emphasize that actual experience with MSW pyrolysis on a large scale is not well reported in the open literature, to the extent that it exists at all. In some instances, plants presumed operating may be under private contract which tends to explain the unavailability of data in the public domain. In any event, this Appendix reports

available technical, economic, environmental, and energy information that may prove useful in evaluating the suitability of pyrolysis as a means of managing municipal solid waste while simultaneously producing valuable products.

D.2.2.1 Vertical-Shaft Reactors

Although several types of reactors have been used in the pyrolytic conversion of MSW, approximately 70 percent of the "cumulative" MSW pyrolysis system design capacity for systems operating worldwide anytime between 1969 and 1988, utilized vertical-shaft reactors (799). Fixed bed designs accounted for 50 percent, followed by dual fluidized bed systems, and entrained beds as a distant last (see Table D-1).

D.2.2.1.1 Fixed Bed, Updraft Reactor. In the fixed bed pyrolytic reactor, MSW feedstock enters from the top or side, falling onto a grate which contains the material. Normally operated in an incomplete combustion mode, air or oxygen is injected to achieve a countercurrent flow (updraft design), parallel flow (downdraft), or perpendicular flow (crossflow) with respect to the solids flow (275).

Perhaps the most simple pyrolysis design is the partially oxidative, air-blown, updraft, fixed bed gasifier. This technology makes an oily, low quality, low Btu gas when fired with RDF. Although better suited to the charging of higher quality feedstocks, when applied to MSW this technology should be used in a close-coupled combustor to avoid fouling (275). Also, owing to the low heating value of the product gas, a supplemental fuel supply is usually required in the combustor or the RDF feedstock must be supplemented with higher quality biomass (559).

D.2.2.1.2 Fixed Bed, Downdraft Reactor (275). In partially oxidative, air-blown, downdraft, fixed bed gasifiers, oxygen is injected downward through a series of nozzles located around the circumference of the reactor. The low Btu product gas passes through an incandescent bed of char at very high temperature before exiting the reactor. This tends to crack the oil vapors, producing smaller molecule, noncondensable gases. Further, as the gas passes through the hot char bed, ash and particulate matter are filtered out.

In both the downdraft and crossdraft designs, slag removal has been a problem on a continuous or short-cycle basis without substantial gas losses. Downdraft and crossdraft reactors have not been used in firing MSW on a large scale.

D.2.2.2 Fluidized Bed Reactor (275)

Unlike the fixed bed reactors which exhibit nonuniform temperatures throughout the bed, fluidized bed reactors are designed to minimize temperature variations through constant agitation of the bed materials. Fluidizing gas is typically introduced at the bottom of the reactor at such a velocity so as to achieve entrainment of the solids, which are literally blown out of the top of the reactor, captured in a cyclone and returned to the bed. Heat transfer is achieved by the circulation and uniform mixing of hot particles, such as sand, catalyst, char, or ash, that comprise the bed.

D.2.2.3 Entrained Bed Reactor (275)

Like fluidized bed pyrolytic reactors, entrained bed reactors have excellent heat transfer, the ability to use catalysts effectively, and a gas throughput capacity greater than other reactor types. However, both technologies are more complicated than fixed bed reactors relating primarily to the energy and wear associated with moving the solids. The available fluidizing gases include air, oxygen, steam, and recycled pyrolysis gas.

D.2.2.4 Other Reactor Types

Other reactor types include the vertical-shaft stirred bed (or multiple hearth) reactor, several horizontal-shaft reactors, as well as solution (thermolysis), rotary kiln and cyclone designs. No information in the open literature was found to support the use of these other reactors in the firing of MSW.

D.2.3 Recent, Large-Scale MSW Pyrolysis Systems

As described earlier in Section D.1, there appear to be only a handful of large-scale systems operating worldwide as of 1988 (799). The status of these systems today is not easily determined from the published literature. Whereas the status of these systems appears to be known as of 1988, the information available in the literature typically dates back to technical references from the early 1980s. The limited amount and quality of published information is consistent with the downturn in research activity into the design and implementation of MSW pyrolysis systems. Further, it is possible that development efforts have proceeded but have not been published in the literature because the developer may also be the owner and operator of the system.

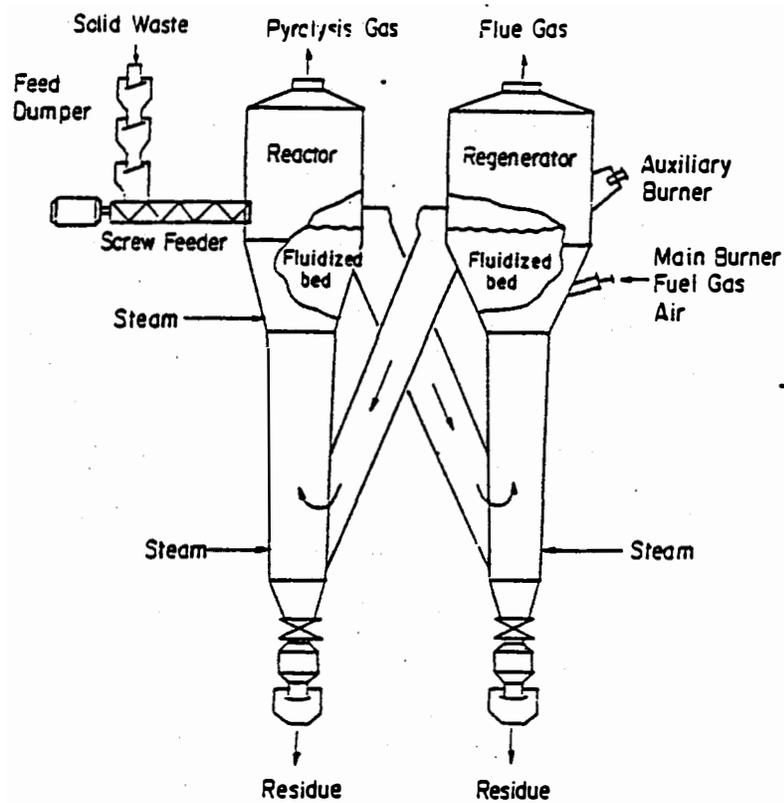
D.2.3.1 Tsukishima Kikai Co., Ltd., Pyrolytic Process

The Tsukishima Kikai system in Funabashi City, Japan is the first full-scale, dual fluidized bed gasification system accepting MSW (108). Earlier research and laboratory investigation by Tsukishima Kikai centered on single and, in particular, circulating-solid dual bed systems. A 40 TPD demonstration plant in Iwanuma, Japan, funded by the Ministry of International Trade and Industry, preceded the Funabashi City facility which was completed in 1981 (275). Even though support has been gaining for fluidized bed gasification systems in general (799), as of 1988, no other large-scale, fluidized bed pyrolysis system has been placed into commercial operation.

The Funabashi plant was designed to process 450 TPD of mixed municipal solid waste (MMSW) with limited emissions of multi-media pollutants and recovery of high quality pyrolysis gas to be burned on site to produce steam and electricity. The reasons cited for selection of this technology (108) over conventional waste-to-energy systems include the ability to: process plastic waste along with MMSW without the emissions and corrosion attendant with lower temperature, conventional operation; minimize pollution due to lower volume of the gas (and lower gas velocities) and effectively bind the heavy metals with the char; offer closed-loop treatment of wastewater; produce a high-Btu gas; and minimize organic matter in the char.

The principal of operation of the dual fluidized bed reactor is illustrated in Figure D-1 (108). Both reactor and regenerator are filled with sand, which is fluidized by the action of superheated steam introduced at the bottom of each reactor. As the fluidizing medium is constantly circulated between the reactors, solid waste is fed into the reactor where, upon mixing with the hot sand, it is pyrolyzed. Pyrolysis gas and oil-tar vapor are removed at the top with the steam. Char overflows with the sand into the regenerator where, in the presence of air, it burns, and gaseous emissions exit the regenerator. The circulating sand is cooled in the reactor by the drying and pyrolysis and reheated in the regenerator by the combustion of char and fuel gas.

While relatively little information is available about plant modifications undertaken between 1981 and 1983, it appears to have operated nearer to 75 percent of design capacity during the mid-to-late 1980s (799). The plant has three 150 TPD trains for the pyrolysis reactors. The eight major unit processes depicted in Figure D-2 are (108):



**Figure D-1. Tsukishima Kikal Dual Fluidized Bed Reactor
Funabashi City, Japan (108)**

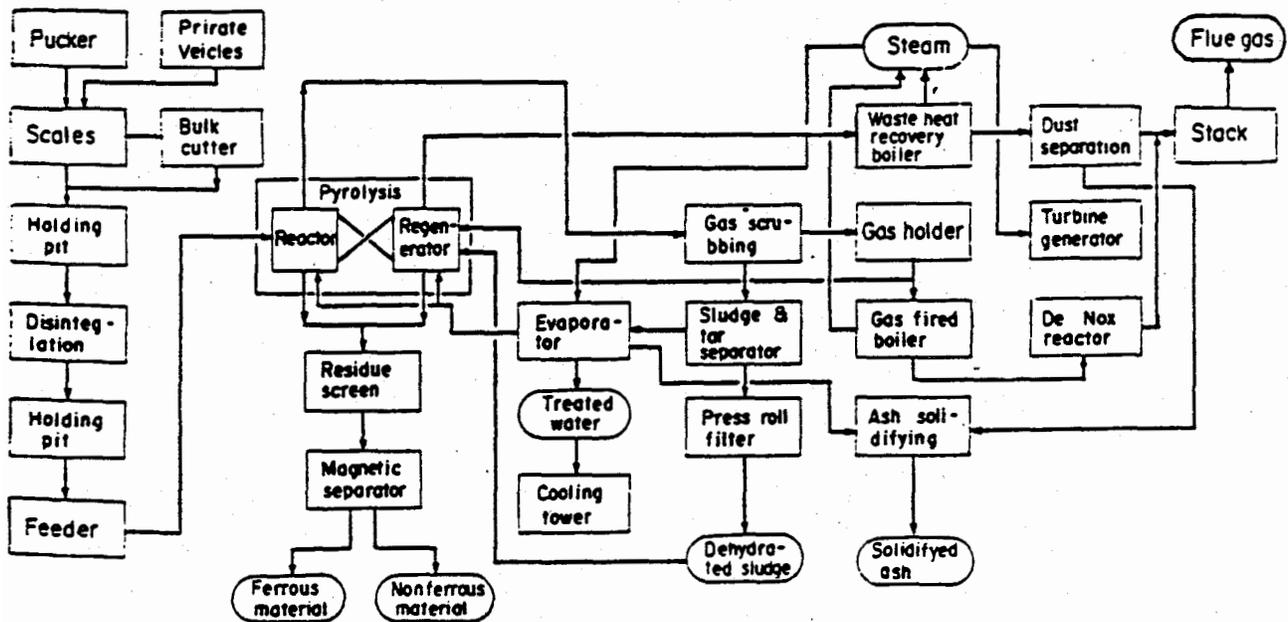


Figure D-2. Tsukishima Kikal Pyrolysis System
Flow Diagram, Funabashi City, Japan (108)

- o Solid waste size reduction
- o Pyrolysis reactor
- o Residue treating unit
- o Wastewater treatment
- o Flue gas treatment
- o Ash handling
- o Energy recovery

At least from early operating accounts (108, 275), the reactors accept unseparated waste, which is atypical of circulating-solid fluidized bed systems. After receipt of raw MSW in the pit, the material is size reduced with vertical hammermills to approximately 4 inches and placed in interim storage. As needed, RDF is conveyed to a lock-hopper/screw feed system that feeds the fluidized bed pyrolytic system. At 700 to 800 degrees C and 1000 mm H₂O pressure, pyrolysis proceeds in a residence time of approximately 30 minutes. The sand from the bed is reheated in approximately 40 minutes in the regenerator where char and pyrolysis gas are incinerated.

The non-combustible materials are drawn off, cooled, and separated into regenerator feed material and ferrous and non-ferrous metals. The pyrolysis gas produced is scrubbed, cooled, and passed through a wet electrostatic precipitator to remove fine particles, oil mist, and tar. Scrubber wastewater is reprocessed to produce: a filter cake, which is incinerated in the regenerator; a sludge and an oil-free wastewater, which are evaporated; a vapor, resulting from condensate from the first evaporator, which is treated by activated carbon before use as make-up water; and a condensed liquid, which, when mixed with a chemical agent, helps stabilize fly ash for landfill.

The hot flue gases from the regenerator pass through a cyclone for particulate removal, a waste heat recovery boiler, then through a double cyclone and electrostatic precipitator for final gas clean-up. Recovery of heat energy as steam from the regenerator flue gas is accomplished by a waste heat recovery boiler. Pyrolysis gas serves as supplementary fuel for both the regenerator and the gas-fired boiler. A catalytic de-NO_x reactor controls oxides of nitrogen from the gas-fired boiler.

Operational experience is generally limited to an account of the first 5 months of operation in 1983 (108). During shakedown in the 1981 to 1983 timeframe, operational problems that developed with gas handling and wastewater treatment were resolved through design modifications. Early bridging due to

the presence of tramp metal in the feed stream was virtually eliminated when the solid waste collection method removed most metals separately from MSW. Periodic cleaning of the heat transfer units installed in the gas handling and water treatment process was required due to scaling.

A materials balance for the Funabashi dual fluidized bed pyrolysis reactor is shown in Figure D-3 (108).

Table D-2 shows a typical product gas analysis from early operation (108). This relatively high heating value crude gas was used directly as feed for the regenerators and the gas-fired boiler.

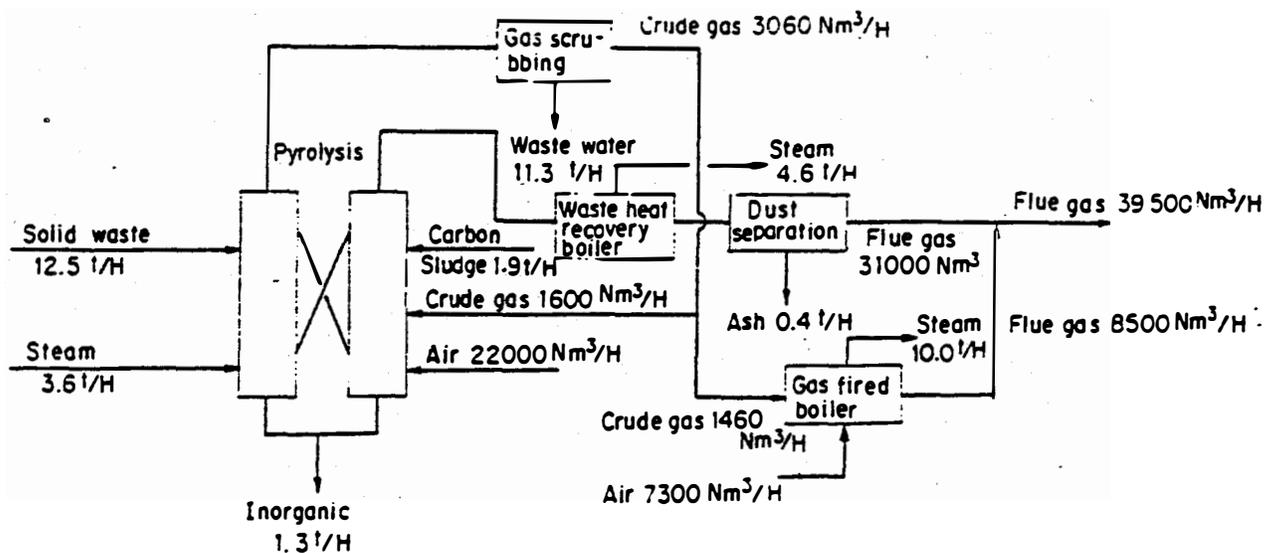


Figure D-3. Tsukishima Kikal Pyrolysis System Materials Balance
Funabashi City, Japan (108)

TABLE D-2. PRODUCT GAS ANALYSIS, TSUKISHIMA KIKAI (108)

<u>COMPONENT</u>	<u>% BY VOLUME</u>
Hydrogen	15.32
Oxygen	0.17
Nitrogen	2.41
Carbon Dioxide	16.72
Carbon Monoxide	31.34
Methane	17.04
Ethane	2.33
Ethylene	9.79
Propane	0.11
Propylene	3.09
Other	1.68

	100.00

H₂S 800 - 2200 ppm

Hydrochloric gas 200 - 1200 ppm

Dry base calorific value: 630 Btu/ft³

D.2.3.2 Union Carbide Incomplete Combustion Process

As stated earlier, Union Carbide developed the Purox (TM) system in the 1970s with corporate funding specifically to handle municipal feedstocks. The design employed an oxygen fed (highly enriched), vertical-shaft updraft reactor operating under partial combustion conditions (349). Pilot plant testing in Tonawanda, New York and South Charleston, West Virginia highlighted the need to improve process economics before proceeding with further development in the U.S. (275). This technology has been widely reported in the literature (828 - 839). An interpretation of the Purox flow sheet is provided as Figure D-4 (based largely on information presented in reference 275).

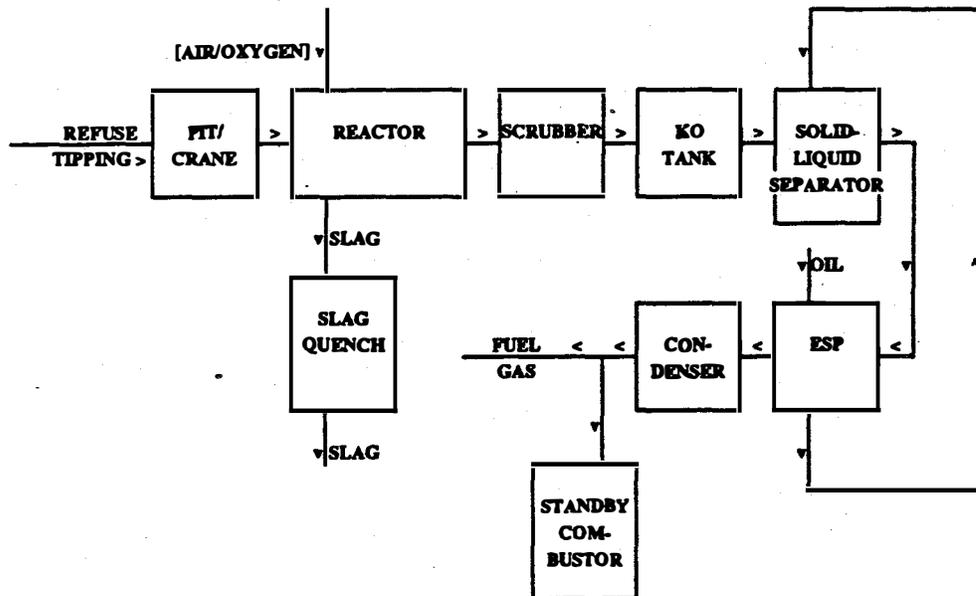


Figure D-4. Union Carbide Purox Pyrolysis Process
(modified from 275)

Union Carbide also developed the Purox system for licensing, which resulted in the design and installation of a municipal waste processing facility in Chichibu City, Japan. This vertical-shaft reactor and ram feeding system are licensed by Union Carbide, while Showa Denko K.K. designed and developed the remaining system components (275). The literature suggests that the Chichibu City plant uses the Purox II process (i.e., 60 psi reactor pressure). As indicated in Table D-1, this facility, operating as of 1988, has two 75 TPD trains that can produce up to 390 Btu/SCF of gas (60) based on a throughput of 70 Mg/day. A vertical shaft oxygen-blown reactor using essentially pure oxygen gasifies and slags the ash, making it into an obsidian-like glass that is hard and stable (10). The Union Carbide technology was selected because heavy metals carry-over is minimized, causing the metals to be discharged in the slag.

The Chichibu City plant has no waste heat recovery due to governmental restrictions (275). Therefore, the inclusion of a generator for producing electricity as shown on the process flow diagram in Figure D-5 is questioned. (It should be noted that this figure was derived from reference 275).

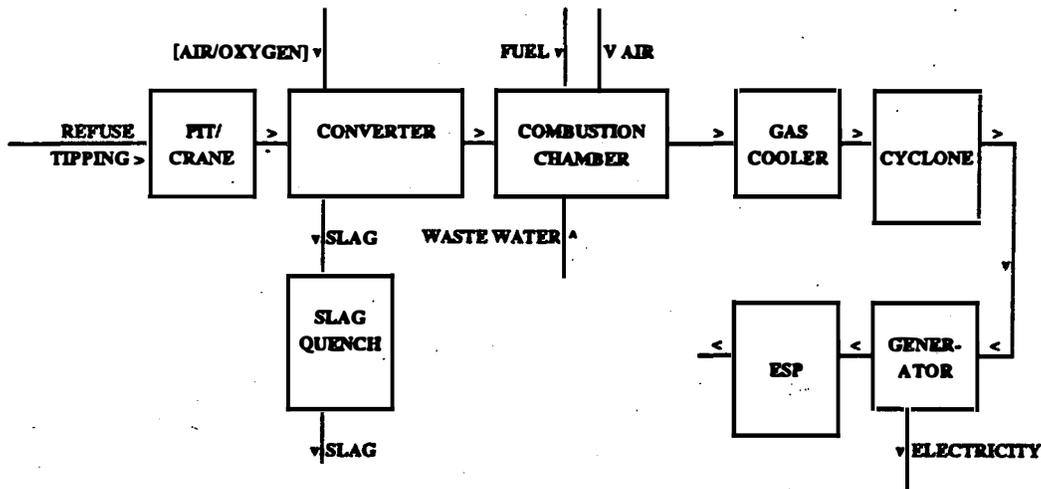


Figure D-5. Showa Denko/Purox Pyrolysis Plant
Chichibu City, Japan (modified from 275)

D.2.3.3 Andco-Torrax Incomplete-Combustion Process

The major distinction between the Andco-Torrax and other incomplete-combustion systems is that preheated air, not oxygen or oxygen-rich air, is fed to the reactor (275). The preheated air is produced in regenerative towers, while gas is produced in the vertical-shaft reactor with a quality of 150 Btu/SCF (10). Furthermore, it is the only one of the systems reviewed that was designed to accept unprocessed MSW as feed. An interpretation of the basic Andco-Torrax process flow diagram is shown in Figure D-6 (275).

A 75 TPD demonstration plant started operations in Orchard Park, New York, in 1971. The unit was dismantled after shutdown in 1977 (275). Commercial operations ranging in size from 87 to 400 TPD were subsequently located in Luedellange, Luxembourg; Grasse, France; Frankfurt, West Germany; Creteil, France; Hamamatsu, Japan; and Orlando, Florida. Operational problems such as reactor plugging, high energy consumption, and explosions were remedied in some cases through design modifications (833). Some facilities, such as the Disney project near Orlando, Florida and the facility in Hamamatsu, Japan were intended to evaluate the safe disposal of nuclear wastes as well as MSW (830 and 832). Of the six commercial facilities operating between 1976 and 1982, only the Creteil France facility appears to be still operating (799, 822). No further information has been located in the literature on this facility.

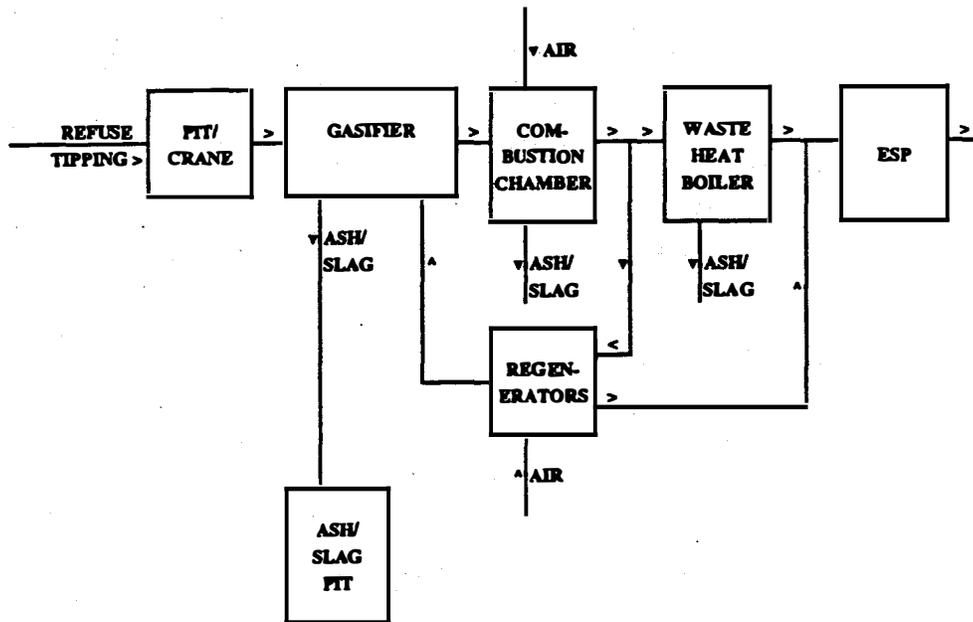


Figure D-6. Andco-Torrax Pyrolysis Process
(modified from 275)

D.2.3.4 Indirectly Heated Drum-Type Pyrolyzer

The first large-scale pyrolysis plant for waste disposal in the Federal Republic of Germany has been in commercial operations in Burgau since 1985 (552, 723). Located in the state of Bavaria, northwest of Munich, this facility receives 35,000 TPY of MSW after paper, glass, aluminum cans and household batteries have been removed (723). Shredded MSW is fed into an indirectly heated rotary drum kiln and pyrolyzed. Resulting gases are burned with oxygen in a secondary chamber which provides heat for the kiln or passed through a heat exchanger to produce steam and electricity. The facility is publicly owned and operated based on fees paid by citizens as a function of the volume of MSW they generate.

D.2.3.5 Studsvik Fluidized Bed Gasifier

A Studsvik (Swedish) 200 TPD capacity, fluidized bed gasification (FBG) system is reported to be under construction in Greve, Italy (362). Pelletized RDF, previously prepared for landfilling, will be gasified to produce electricity for the local utility, and fuel gas and stabilized ash for use by a local cement plant. Developers claim that it will be the first application in Europe of fluidized-bed gasification of RDF. The overall plant process flow is depicted in Figure D-7.

The RDF, whose properties are stated in Table D-3, will be metered from the odor controlled pit/silo storage module to two circulating FBGs each rated at 4.2 TPH (362). The average output from each gasifier will be 4,100 SCFM; the maximum capacity is 20 percent higher. The typical gas composition is shown in Table D-4 (362). Except for a small stream of fuel gas output to be used in the cement kiln as a substitute for natural gas, the output from each gasifier will be used to fire a steam boiler. This steam will power a Rankine cycle condensing turbine rated at 6.7 MWe which can accommodate the total output of 80,000 pounds/hour of steam from both boilers (362).

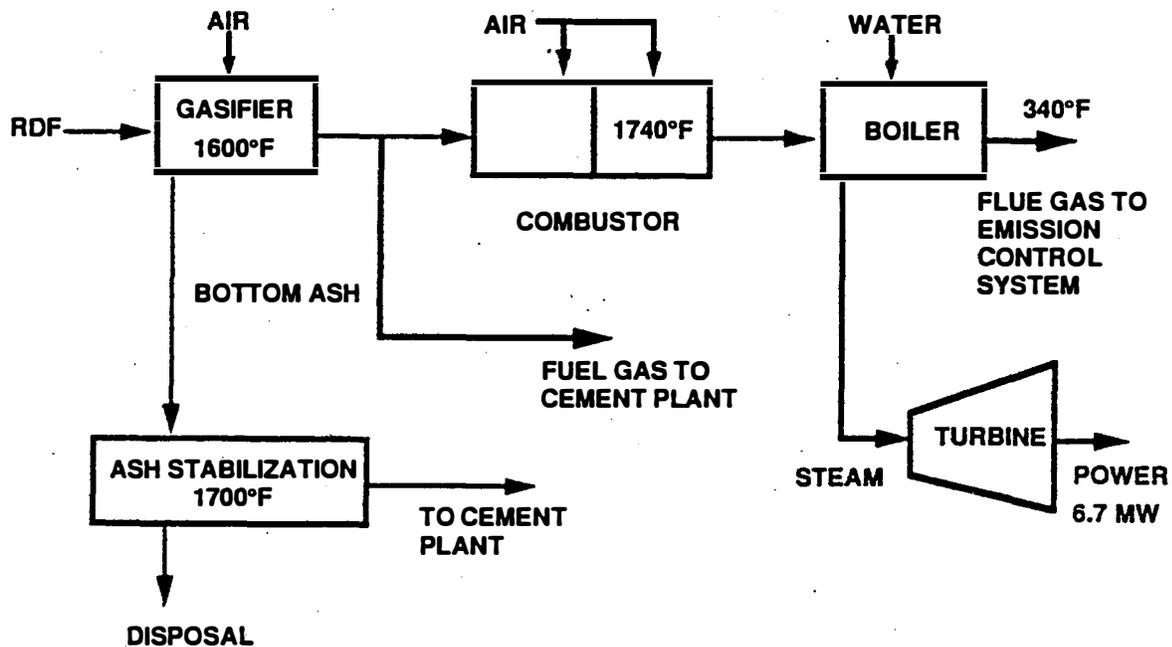


Figure D-7. Studsvik Pyrolysis Plant, Greve, Italy (362)

**TABLE D-3. RDF CHARACTERISTICS
GREVE, ITALY (362)**

Type	Pellets
Size	1/2 inch x 1-6 inches (12 mm x 25-150 mm)
Bulk Density	32 to 44 lb/cu ft (500-700 kg/cu m)
Calorific Value	7,400 Btu/lb (4,100 kcal/kg)
Moisture	4 - 10 percent
Ash	15 percent
Sulfur	0.4 percent
Chlorine	0.6 percent

**TABLE D-4. CHARACTERISTICS OF FUEL GAS FROM GASIFIER
GREVE, ITALY (362)**

Composition (by volume, in percent):

H ₂	5 - 20
CO	5 - 30
CO ₂	5 - 15
CH ₄	3 - 5
C ₂ H ₆	1 - 3
Calorific Value	175 Btu/scf (1,550 kcal/nm ³)

The pollution control train is shown in Figure D-8 (362). It consists of the Teller dry scrubbing technology to remove acid gases, particulates, dioxins/furans and heavy metals. This system includes three stages - a quench reactor (dry scrubber), a dry venturi, and a fabric filter pulse jet system.

Ash stabilization, depicted in Figure D-9, will be accomplished via vitrification at 1650 degrees F in the rotary kiln, followed by a brief residence time in a separate post-combustion chamber. Exhaust gas is cooled in a quench tower and then mixed with dry hydrated lime before disposal in a stabilized state (362).

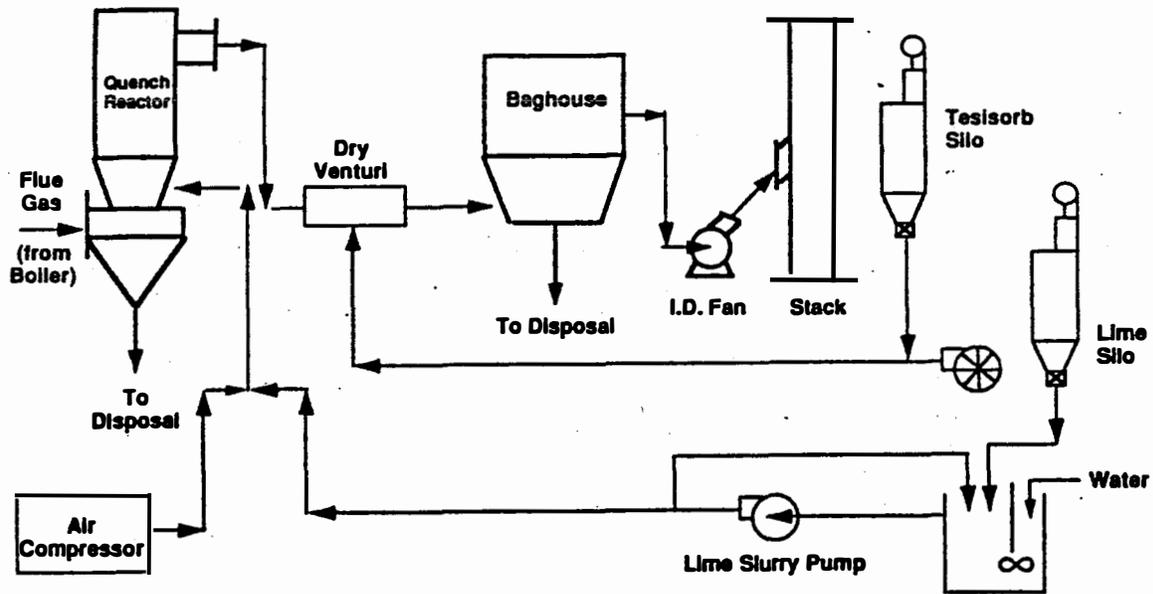


Figure D-8. Emission Control System for Pyrolysis Reactor
Greve, Italy (362)

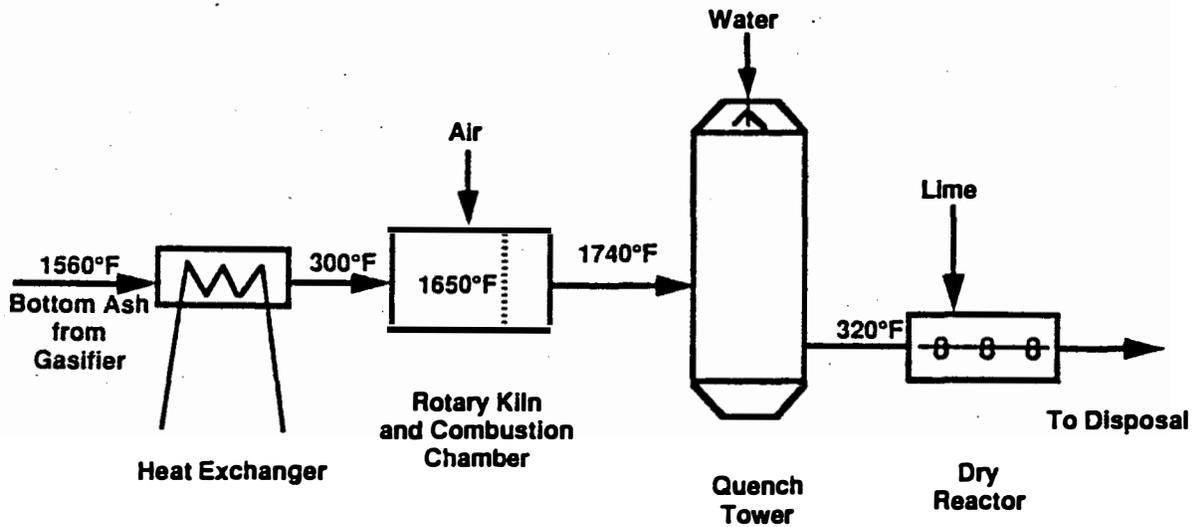


Figure D-9. Bottom Ash Stabilization System for Pyrolysis Reactor
Greve, Italy (362)

D.2.4 Earlier Large-Scale MSW Pyrolysis Systems

Although not now operating, many pilot and larger scale MSW pyrolysis systems listed in Table D-1 contributed to the experience base for this technology. Some, however, would contend that in retrospect it would have made more sense to focus these efforts on a single project, taken carefully through phases to full-scale commercialization (480). In any event, these facilities represent important milestones and are briefly described here in terms of their design, operation, and basis for failure, to the extent such information exists.

D.2.4.1 Nippon Steel Incomplete-Combustion Process

Nippon Steel's involvement in the development of high-temperature, slagging-type, updraft incomplete-combustion processes for MSW has included the operation of a 20 TPD pilot plant in Tobata and a 40 TPD demonstration facility in Tokyo (275). This work led to a 450 TPD commercial installation in Ibaragi City, with start-up in 1980, followed by a 100 TPD facility in Kamaishi.

The Ibaragi installation was designed as an oxygen enriched process combined with preheated air (10) in order to help eliminate "parasitic" nitrogen from the pyrolysis process flow. Feedstock preparation involves the size reduction of oversize bulky waste. The pyrolysis reactor is crane-fed through a top-mounted lock-hopper. Coke is added as a fuel supplement at a rate of 90 Kg/Mg of feed, and limestone is added as a flux at a rate of 90 Kg/Mg of feed to ensure that ash can be withdrawn as a completely vitrified slag (287). Particulate and gaseous products of combustion are collected using electrostatic precipitators (ESPs) and scrubbers. The molten slag can be used as a roadbase, but the particulate matter collected in the ESP is encased in concrete prior to landfilling in order to prevent heavy-metal leaching (275).

While no performance data was found in the literature on the Ibaragi facility, Figure D-10, which has been interpreted from the literature (275), depicts the basic process concept for the facility. All of the Nippon Steel pyrolysis facilities are believed to be closed (799).

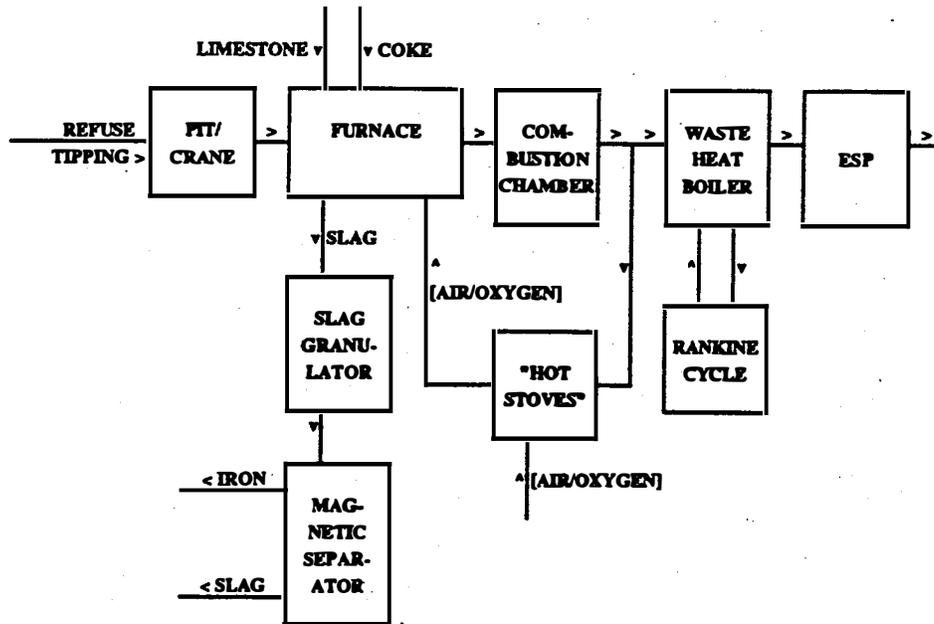


Figure D-10. Nippon Steel Pyrolysis Process
Ibaragi, Japan (modified from 275)

D.2.4.2 Monsanto Incomplete-Combustion Process

Developed by Monsanto Enviro-Chem Systems and pilot tested in St. Louis at a 35 TPD plant, the "Landgard" process was selected by the City of Baltimore and approved under a demonstration grant by the U.S. EPA in 1972 (479). The construction of the 1000 TPD plant began in 1973 supported by the City, the EPA, and the Maryland Environmental Service. The environmental benefits claimed for this system (479) included a substantial reduction in particulate emissions due to precleaning of the flue gas by flyash slugging in the secondary combustion chamber-gas purifier, and reduction in heavy metals due to pyrolytic reactions in the kiln primary chamber-reactor.

The basic concept for the Landgard system was to pyrolyze the organic fraction of MSW in a reducing atmosphere in a rotary kiln, the gaseous products from which would be burned in waste heat boilers to produce steam for sale. Shredded MSW was fed into a 100-foot long rotary kiln reactor rotating at 2 rpm (275). With heat provided by the burning refuse supplemented with oil firing, temperatures reached 1800 degrees F in the chamber where these hot combustion gases moved countercurrent to the MSW.

It was intended that a secondary combustion chamber would combust the pyrolytic gas with temperatures of up to 2800 degrees F, causing entrained flyash from the kiln to be trapped as liquefied slag (479). Off gases were cleaned with a wet scrubber; solids from the kiln were separated in a quench-flotation step (275).

Many problems occurred during plant start-up in 1975 through 1977, including failure to meet air emission standards and failure of refractory materials (836, 842 - 846). Further, the theoretical energy and materials balance for the waste, auxiliary fuel and power inputs and losses could never be verified at capacity for a sufficiently long period of time (479). After several modifications without success, Monsanto withdrew from the project and the City converted the facility to a mass burn plant (832). The Landgard technology is no longer being offered (799).

D.2.4.3 Occidental Direct-Liquefaction Pyrolytic Process

Garrett Research & Development Company (a part of Occidental Petroleum Company) developed a flash pyrolysis process for the conversion of size-reduced and air-classified RDF (194). The objective was to separate out the inorganic components such as metals and glass, and convert the organic portions via flash or low residence time pyrolysis to a fuel oil suitable for use in utility boilers. Following successful testing on a 4 TPD pilot plant in La Verne, California, a 181 TPD plant was designed and constructed in El Cajon, California to demonstrate the process. Funding was provided by both the U.S. EPA and San Diego County. While the plant received and processed MSW at the design rate, recovering glass, ferrous metal and aluminum, the pyrolysis section of the plant failed to demonstrate reliable production of pyrolytic oil from MSW during the course of the contract (194).

In this process, RDF fluff was pneumatically introduced to the reactor where hot ash particles from the char burner mixed with the fluff thereby providing the necessary process heat. Within a very short residence time at 510 degrees C and without combustion, oil, gas, water and char were produced (194). The gas leaving the reactor was passed through a cyclone to separate ash and char which then passed to a char burner. Here the char was combusted with air to produce process heat, leaving a residue high in ash, which was recycled back to the pyrolysis reactor, with periodic ash bleed off. The gas from the cyclone was treated with oil sprays followed by oil collection and separation (275). The gas product was used as a process fuel; all process off-gas was filtered in a fabric filter collector prior to the stack (194).

D.2.4.4 AIST-Ebara Corporation Pyrolytic Process (275)

With funding from Japan's Agency of Industrial Science and Technology (AIST), the Ebara Corporation developed a process which specially prepared raw MSW by pulverizing and screening in a rotary drum, followed by air classification, ferrous removal, and shredding (275). As indicated in Figure D-11 (828), raw MSW was fed axially along a rotary drum. Scrapers rotating at different speeds against screens within the drum, effectively "pulverized" the refuse. Food wastes, solids and glass were removed and composted; paper was purified in a pulping system; and metals were removed from the remaining materials before pyrolysis. The RDF was then introduced to a dual fluidized bed pyrolyzer/regenerator with recirculating solids, not unlike that utilized in the Tsukishima Kikai system. However, there are some differences with respect to feedstock preparation, feeding systems, fluidizing gas and its distribution, temperature and residence times (275).

A 5 TPD pilot plant which operated between 1975 and 1978 was replaced by a 30 TPD pyrolytic subsystem operated as part of a 100 TPD pyrolytic compost and combustion plant in Yokohama (799). Operational performance data on the 30 TPD Yokohama facility which operated from 1978 through 1984 (see Table D-1) was not provided in the literature reviewed.

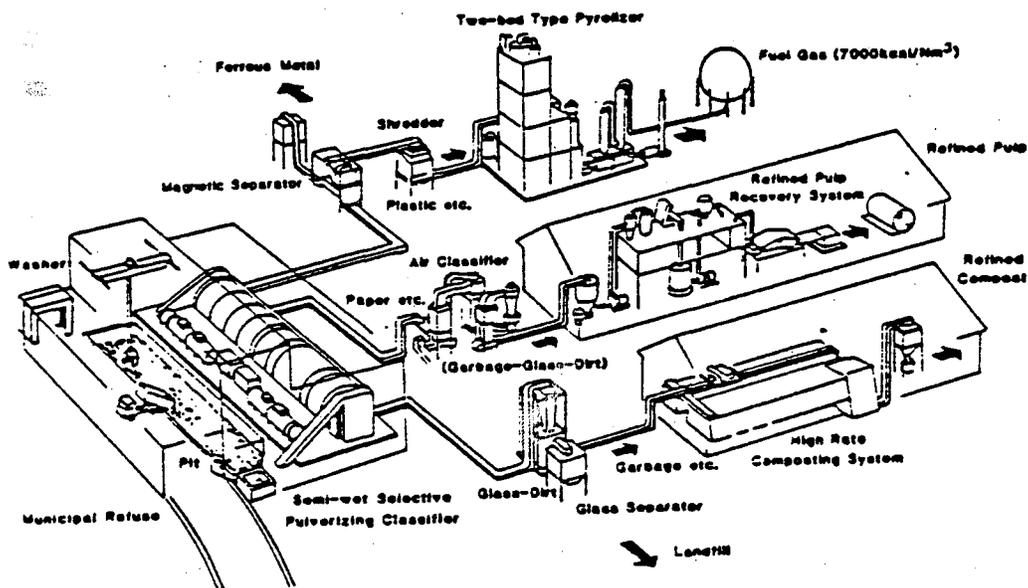


Figure D-11. AIST-Ebara Pyrolytic Process (828)

D.2.5 Small-Scale MSW Pyrolysis Systems Experience in the U.S.

While there were several small-scale pyrolysis projects undertaken in the United States in the 1980s and earlier, using various biomass feedstocks, few utilized municipal solid waste (275). Selected examples of the more promising experiments are mentioned below.

D.2.5.1 Fast Pyrolysis (SERI Vortex Reactor)

Fast (flash) pyrolysis technologies have begun to be developed to optimize the oil yield from biomass. An early effort in the large scale application of fast pyrolysis at the Occidental Research Corporation's facility at El Cajon, California proved disappointing (194). Considerable progress has been made in the conversion of biomass to pyrolytic oils using solid convective heat transfer techniques developed at DOE's Solar Energy Research Institute (SERI) National Laboratory in Golden, Colorado using the vortex reactor design (618).

Recently, the vortex reactor design has been successfully adapted to the pyrolysis of RDF (464). Relatively "clean" feed material (absent non magnetic tramp material) is entrained tangentially into the reactor at approximately 1200 ft/sec. Centrifugal forces constrain the feed particles to impact the inside surface of the hot vortex tube, which causes the "flash" heat transfer known as fast pyrolysis. An axial outlet removes vapors, carrier gas, and some attrited solids, while partially pyrolyzed feed and other particles are removed tangentially for subsequent recycle into the reactor. Additional research is needed to evaluate the physical and chemical qualities of the tars and oils produced from the standpoint of their efficient collection, storage, and use.

D.2.5.2 Fast Pyrolysis (Pyrolysis Mill)

Also under SERI sponsorship, a novel "pyrolysis mill" has been developed to achieve fast pyrolysis while avoiding temperatures over approximately 600 degrees C which tend to crack the vapors produced (619). The objective in this approach is to effect rapid heat transfer by pressure contact of the feed materials with a hot solid. Feed enters the process between two heated "millstones" near the center of the reactor and follow a spiral path to the outer edge where ash is collected; vapors are collected in a series of traps. Currently at the laboratory scale, no data are yet available on the fast pyrolysis of RDF using this approach.

D.2.5.3 Argonne's Bench-Scale Research (466)

During the mid-1980s, DOE's Argonne National Laboratory carried out laboratory experiments to study the effect of pyrolyzing various RDF feedstock components to determine the chemical and physical properties of the products (50, 453, 466). Experiments with their bench-scale reactor attested to the complex chemical mechanisms governing the potential for converting MSW into high quality chars and tars with heating values similar to conventional fossil fuels. The high heating value chars produced with RDF were thought to have potential for use in hydrogasification. Experiments with aluminum and plastics were not conclusive in determining the quality of pyrolytic products derived from a more heterogeneous mixture approaching that of as-received MSW. Additional work was planned or underway in developing a fundamental process information -data base, understanding of reaction chemistry and pyrolysis, and product characterization and optimization.

D.2.6 Small-Scale Pyrolysis Experience In Europe

While European experience in the pyrolysis of solid waste followed that of the United States and Japan, a number of companies and research institutes in Europe have undertaken R&D efforts and/or introduced foreign technology. A 1986 account of this activity (822) is summarized in Table D-5. Selected highlights with respect to pyrolyzing MSW are provided below.

Early developments in applying vertical shaft pyrolysis technologies in Denmark (circa 1967) and later in Germany suffered from small capacity and refractory problems, low rate of heat transfer, and a char that produced a substantial wastewater problem (822). Limitations of the vertical shaft pyrolysis reactor were recognized by Warren Spring Laboratory in England where a cross-flow pyrolysis reactor was developed. Foster Wheeler conducted additional successful experiments on refuse, forest wastes and tires.

The BKMI (or PYROCAL) process, developed by one of the Deutsche Babcock companies, featured the firing of shredded refuse, molded into a plug and introduced along with limestone into an indirectly heated rotary drum pyrolyzer. While the carbonized residue was discharged into a Martin residue quenching tub, the pyrolysis gas passed to a combustor equipped with a heat exchanger. Problems noted included incomplete elimination of gaseous pollutants, high moisture content and unpredictable quality of the char, and low overall thermal efficiency of the process.

**TABLE D-5. EUROPEAN EXPERIENCE IN THE PYROLYSIS
AND GASIFICATION OF SOLID WASTES (822)**

Name of process	Plant location	Size of the plant (t day ⁻¹)	Operating temperature (°C)	Period of activity	Comments
<i>(a) Vertical shaft processes</i>					
Destrugas	Kolding (DK)	n.a.	1000	1967	First tests at a former gas factory development in refractory retort pyrolysis tests and waste water purification by Techn. Univ. of Berlin
	Kalundborg (Dk)	5	1050	1970	
	Berlin-Ruhleben incinerator plant (D)	0.5	900	1977-79	
Sodeteg	Grand Quevilly (F)	12	n.a.	1973	Soon halted because of difficulties in handling the refuse
Warren Spring Laboratory	Stevenage (Eng.)		400-600	1975	Reactor with induction heating of steel balls cross-flow reactor
Foster Wheeler Power Products	Hartlepool (Eng.)	1	800	1976	Cross-flow reactor (WSL-license)
Tyrolysis	n.a.	168	800	1984	Being commissioned
<i>(b) Rotary kiln processes</i>					
Pyrocal (BKMI)	Münich (D)	12	400-500	1977-78	Test plant with partial oxidation of tar laden gas
	Günzburg (D)	2 x 72	400	1983	Direct combustion of the gas addition of limestone to the feed
DKAM	Plaidt (near Koblenz, D)	24	400	1982	Production of a smokeless solid fuel from various wastes
Kiener	Goldshöfe (D)	small batch plants	450	1974	Rotary kiln with internal heating tubes, heated by the exhaust gases of an engine, powered by pyrolysis gas
	Goldshöfe	7		1976	
	Goldshöfe	72		1977-78	
	Goldshöfe	72		1982-	
Odapyr (Dr. C. Otto & Co.)	Aalen	2 x 72		1985-86	
	Plaidt (D)	24	650-700	1982	cfr DKAM
Rotopyr (MVU)	Bochum (D)	144	650-700	1984 (start-up)	High temperature pyrolysis, mainly of industrial wastes
		5	700	1978-80	as above
		36-48		1986 (planned)	
<i>(c) Fluidized bed processes</i>					
Deutsche Reifen Pyrolyse GmbH (D.R.P.)	Univ. of Hamburg (D)	0.024, 0.24 and 2.4	500-850	1973-	Indirectly heated
	Ebenhausen (D)	24	650-750	1982 (constr.) 1984 (start-up)	Fluid bed pyrolysis for tyres
<i>(d) Small batch units</i>					
Eisenmann KB, Böblingen [10]	Rietheim (D)	5	450 (F) 700 (S)	1983	Combination of fixed (F) and shaft (S) reactor for plastic wastes
Hildebrand/Strunz GmbH Nuremberg	Various units	up to 8	250-400	1973	Low temperature pyrolysis in externally heated chamber, followed by the combustion of the pyrolysis gas
and various other constructors e.g. PPT, Ramms					

Although not listed in Table D-5, the KWU (Kraftwerk Union Umwelttechnik - Subsidiary of Siemens, AG) design is a pure non-oxidative pyrolysis process that utilizes a heat exchanger to ensure that heat is supplied indirectly without any mixing of products of combustion with pyrolysis products. From the limited process flow information published for this process (582), it appears that it uses indirect heat transfer across tubes axially located in a rotating drum operated at 450 degrees C, followed by partial oxidation at 1000 degrees C to crack the gases produced. This design has been demonstrated in a 3 TPD facility at Goldshofe and a 0.5 TPD unit at Ulm/Wigingen, Germany. The Goldshofe unit has been in operation since 1982 with a demonstrated single-line availability of 88 percent over a 3-month period in 1985. The process block flow diagram presented in Figure D-12 is an interpretation (and logical clarification) of information contained in the literature, hopefully accounting for all of the process flow streams (582).

Also not listed in the table, is a partially oxidative, air blown, updraft fixed bed gasifier design offered by Bioneer (559). As of 1988, a total of nine Bioneer gasification plants were reported to be in operation in Sweden and Finland processing biomass. Experience with RDF appears to be limited to two small-scale testing plants; operating data on RDF was not reported in the literature reviewed (559). This design appears to be most efficient in firing high quality feedstocks, such as dried wood chips. Since pyrolytic gas from MSW feedstock has a lower heating value than most biomass fired, either the reactor will require indirect heating or the MSW will need to be co-fired with higher quality biomass.

The remaining rotary kiln and fluidized bed processes cited in Table D-5 focus more on the firing of industrial wastes. Many of the miscellaneous units operated batch-wise; the flammable products were combusted in an afterburner and served to preheat the unit, the combustion air, or sometimes for external heating purposes (822).

D.3 ECONOMIC DATA

Comparing its economic feasibility with other MSW management technologies is very difficult as long as MSW pyrolysis remains unproven in long-term daily operation. Not only is such an evaluation hampered by past poor performances across many reactor types, but uncertainties linger about the costs of complying with stricter environmental regulations. Also, the markets for pyrolytic products (gas, oil, char, steam or electricity) have not been developed. Further, the quality of pyrolytic products as substitutes for more conventional energy (and chemical) products has also not been proven in sustained operations using MSW as feed.

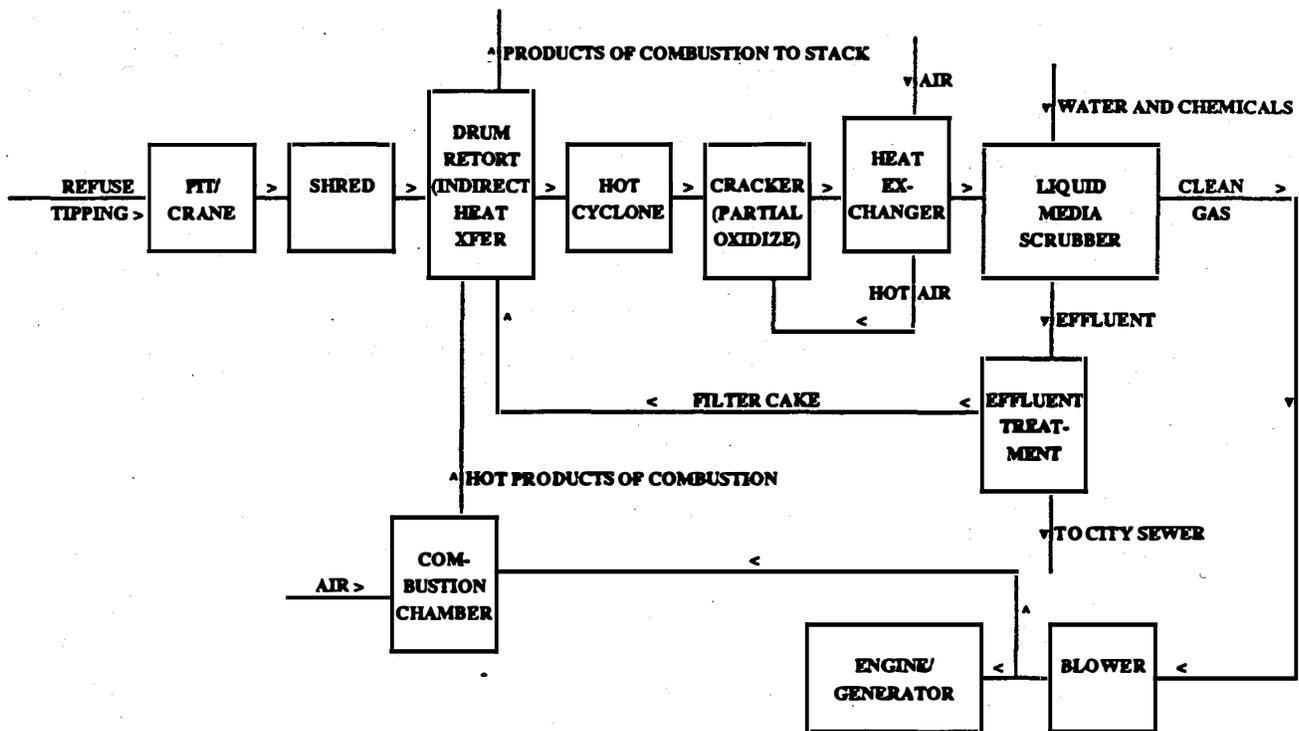


Figure D-12. KWU Pyrolysis Plant, Goldshofe, Germany
(modified from 275)

In view of the above limitations, and the lack of data in the literature, especially for those few (Japanese and European) facilities believed to be currently operating, a rigorous economic analysis of pyrolysis technologies and facilities is not possible. This section does provide cost information, as it appears in the literature, for several of the key facilities described in Section D.2. Table D-6 presents an overview of capital and O&M costs for these facilities, adjusted to 1991 dollars.

The 1979 projected construction cost of the world's largest pure-pyrolysis facility in Funabashi City, Japan was \$35 million, with an operating cost of \$17.85/ton of MSW (849). The fact that this is a privately run operation may explain the lack of readily available process economics information in the literature. Since little information is available regarding extensive plant modifications between 1981 through 1983, the true capital cost including both initial construction cost and all modifications may never be fully known. A more recent account suggests the operating cost of a plant of this design can be expected to be 20 to 50 percent higher than a similar scale stoker-type waste-to-energy unit (287).

**TABLE D-6. SUMMARY OF CAPITAL AND O&M DATA FOR
COMMERCIAL PYROLYSIS SYSTEMS (Developed from 275 and 108)**

PROCESS DEVELOPER	LOCATION	PLANT SIZE (TPD)	DATE	COSTS, AS REPORTED		COSTS, ADJUSTED TO 1991 (1)	
				CAPITAL (\$/TPD)	O & M (\$/T)	CAPITAL (\$/TPD)	O & M (\$/T)
TSUKISHIMA KIKAI	FUNABASHI CITY, JAPAN	450	1979	77,778	17.85	117,595	26.99
UNION CARBIDE	CHICHIBU CITY, JAPAN	150	-	NA	NA	NA	NA
	CONCEPTUAL PLANT - 2 MODULES	700	1980	44,229	25.79	61,111	35.64
	CONCEPTUAL PLANT - 5 MODULES	1,500	1980	41,600	18.71	57,479	25.85
	CONCEPTUAL PLANT - 7 MODULES	2,100	1980	41,057	17.92	56,729	24.77
ANDCO-TORRAX	CRETEIL, FRANCE	400	-	NA	NA	NA	NA
	CONCEPTUAL PLANT - 300 TPD	300	1977	49,967	19.91	88,354	35.20
	CONCEPTUAL PLANT - 900 TPD	900	1977	38,822	12.18	68,647	21.53
	CONCEPTUAL PLANT - 1,500 TPD	1,500	1977	34,153	10.07	60,392	17.81
NIPPON STEEL	IBARAGI, JAPAN	450	-	NA	NA	NA	NA
MONSANTO	BALTIMORE, MD	1,000	1973	20,400	7.60	51,092	19.03
OCCIDENTAL	EL CAJON, CA	200	-	NA	NA	NA	NA
	CONCEPTUAL PLANT - "SMALLER"	(2)	1977	28,605 (2)	5,684 (2)	50,581 (2)	10,051 (2)
	CONCEPTUAL PLANT - "LARGER"	(2)	1977	43,085 (2)	8,660 (2)	76,185 (2)	15,313 (2)
AIST-EBARA	YOKOHAMA, JAPAN	30	-	NA	NA	NA	NA

NA = NOT AVAILABLE FROM LITERATURE REVIEWED.
 (1) = ADJUSTED USING CE PLANT COST INDEX; CHEMICAL ENGINEERING MAGAZINE.
 (2) = PLANT SIZE NOT CLEAR; CAPITAL AND O&M COSTS PRESENTED IN \$000.

Process economics in 1980 dollars for Union Carbide's Purox system are shown in Table D-7 (829). A 1987 account of the Chichibu facility, indicated that operating costs at that time were approximately 12000 to 13000 yen/Mg of refuse, which were noted to be 50 percent higher than a similarly sized conventional thermal treatment technology (287).

Cost information for three different sizes of Andco-Torax pyrolysis systems is provided in Table D-8 (841). As mentioned earlier, operating and economic data on the Andco-Torax pyrolysis system in the Creteil, France facility are not readily available.

Process economics information for the Nippon Steel facilities is not available. All of the plants are believed to be closed (799).

The construction cost of the Monsanto Baltimore facility was projected at \$16 million in 1973, consisting of \$6 million each from the City of Baltimore and the U.S. EPA and \$4 million from the Maryland Environmental Service (479). An additional \$4 million was contributed by Monsanto and EPA before the plant was closed by Monsanto in 1977. The estimated operating cost in 1973 was \$7.60/ton, assuming rated capacity (275).

Representative capital cost information as a function of plant size in 1977 dollars is provided in Tables D-9 and D-10 (847) for the Occidental process. Since this project was not proven successful and the technology is no longer being offered, the usefulness of the cost information presented may be quite limited.

Analysis of data from the 30 TPD AIST-Ebara Company's pilot plant in Yokohama from its 1978 to 1984 operating period is not available.

**TABLE D-7. PROJECTED ECONOMICS FOR UNION CARBIDE PROCESS
1980 DOLLARS (829)**

	Plant Size				
	700 ton/d	1500 ton/d		2100 ton/d	
	2 modules	4 modules	5 modules, one spare	6 modules	7 modules, one spare
Capital Cost (\$10 ³)	10,960	54,790	62,400	77,800	86,220
Amortization, at 8 1/2% over 20 yrs (\$10 ³ /yr)	3272	5790	6594	8221	9111
Overhead and Maintenance (\$10 ³ /yr)	4514	6952	7016	9372	9410
Total Cost of Operation (\$10 ³ /yr)	7786	12,742	13,610	17,593	18,521
Utilization Factor	0.30	0.35	0.92	0.35	0.92
Refuse Feed (ton/yr)	204,400	465,400	503,700	651,500	707,500
Product Gas (10 ⁶ std. ft ³ /yr)	3776	8597	9310	12,036	13,060
Product Gas (10 ⁶ 3cu/yr)	1,397,000	3,181,000	3,444,000	4,453,000	4,836,000
Aluminum and Steel Credits (\$10 ³ /h)	946	2147	2243	3003	3251
Drop charge (\$/Mg)	Net Cost. \$/ton				
0	33.46	22.77	22.56	22.39	21.57
5	28.46	17.77	17.56	17.39	16.57
10	23.46	12.77	12.56	12.39	11.57
Drop charge (\$/ton)	Net cost. \$/10 ⁶ 3cu				
0	4.30	3.33	3.30	3.28	3.16
5	4.17	2.60	2.53	2.55	2.42
10	3.44	1.86	1.84	1.82	1.69

**TABLE D-8. PROJECTED ECONOMICS FOR ANDCO-TORRAX PROCESS
1976 DOLLARS (841)**

Item	Plant Size (Mg/d)		
	300	900	1500
Capital Required (\$10 ³)	14,990	34,940	51,230
Cost of Operation (\$10 ³ /yr)			
Amortization	1584	3692	5413
Operation and Maintenance Costs	1493	2740	3778
Total	3077	6432	9191
Steam Production Rate			
(a) in Mg/h	30.77	92.32	153.9
(b) in lb/h	67,300	203,500	339,200
Net Unit Cost to Produce Steam			
(a) in \$/Mg steam			
Drop Charge:			
0	12.68	8.83	7.58
\$ 5.5/Mg	10.45	6.60	5.35
\$11.0/Mg	8.21	4.36	3.11
(b) in \$/10 ³ lb steam			
Drop Charge:			
0	5.75	4.00	3.45
\$ 5/con	4.73	2.98	2.43
\$10/con	3.72	1.97	1.42

Notes:

Amortization is 8-1/2% over 20 years

On yearly basis, use 0.9 utilization factor for steam production rate

**TABLE D-9. PROJECTED CAPITAL COSTS FOR OCCIDENTAL PROCESS
1977 DOLLARS (847)**

Cost Element	Smaller Plant	Larger Plant
Capital Investment (\$10³)		
Land	100	130
Site Preparation	35	46
Design	2160	3030
Construction and Installation	12,700	19,300
Real Equipment	8100	12,400
Other Equipment	615	808
Contingencies (@ 10%)	2371	3571
Startup and Working Capital	2010	3025
Financing and Legal	514	775
Total Capital Investment	28,605	43,085
Annual Capital Cost [20 years, 8-1/2%] (\$10³)	3023	4553
Capital Cost (\$/Mg)	10.13	7.63
Capital Cost (\$/ton)	9.19	6.92

**TABLE D-10. PROJECTED OPERATING AND OTHER COSTS FOR
OCCIDENTAL PROCESS, 1977 DOLLARS (847)**

Economic Factor	Smaller Plant	Larger Plant
Cost Element (\$10 ³)		
Labor	1604	1925
Fuel	10	20
Electricity	832	1664
Water	56	112
Maintenance and Repairs	1826	2750
Parts and Supplies	195	295
Residue Disposal	193	386
Overhead and Mobile-Equipment Operation	444	556
Property Taxes	195	295
Insurance, Fees, and Professional Services	329	657
Total	<u>5024</u>	<u>8660</u>
Operating Cost (\$/Mg)	19.07	14.52
Operating Cost (\$/ton)	17.30	13.17

The following factors were used in developing the operating costs:

Labor (including benefits): \$7.00/h;
 Fuel: \$0.35/gal;
 Electricity: \$0.02/kWh;
 Water: \$0.50/1000 gal;
 Insurance, fees, and professional services: \$1.00/input ton;
 Taxes: 0.75% of plant investment;
 Maintenance and repairs (including labor): 7% of plant investment;
 Parts and supplies: 0.75% of plant investment;
 Resident transportation and disposal charge: \$7.50/ton.

D.4 ENERGY PRODUCTION/REQUIREMENTS

During the 5 months of operation in 1983 reported for the Funabashi City dual fluidized-bed gasification reactor (108), the recovered energy as a percentage of generated power was noted to be small. As shown in Table D-11, the power consumed for pulverizing the feedstock and supplying air for the generator was high. Plans included improving overall energy recovery efficiency by using pyrolysis gas in a 150 hp gas engine.

**TABLE D-11. UTILITY REQUIREMENTS FOR
TSUKISHIMA KIKAI FACILITY, FUNABASHI CITY (108)**

	Per Ton Solid Waste		
	300 TPD	450 TPD	
Electricity	- for the processing	161.85 kW·h	129.31 KW·h
	- for the lighting, air conditioning	66.18 kW·h	44.12 kW·h
		<u>228.03 KW·h</u>	<u>173.43 kW·h</u>
Water	1.2 ton	1.1 ton	
Caustic soda (as 100%)	8.1 kg	8.1 kg	
Active carbon	0.7 kg	0.7 kg	

Material and energy balances for the Union Carbide Purox system are presented in Figures D-13 and D-14 (831). For the Purox II pyrolysis facility located in Chichibu City, Japan, Figures D-15 and D-16 (834) provide material and energy balance details. Performance data on both Japanese and U.S. MSW indicates that Japanese waste has higher plastics and moisture contents than U.S. wastes, which will affect the heating value of the MSW as a fuel (834).

Representative material and energy balances for the Andco-Torrax pyrolysis are presented in Figures D-17 and D-18 (840). From this data, the thermal efficiency has been determined to be approximately 55 percent for each of the three plant sizes shown.

While an energy balance for the initial configuration of the Baltimore plant has been reported (479), it has limited usefulness in light of the plant's operational failure coupled with the fact that the technology is no longer being offered.

Figure D-19 shows the projected energy balance for the Occidental flash pyrolysis process (848).

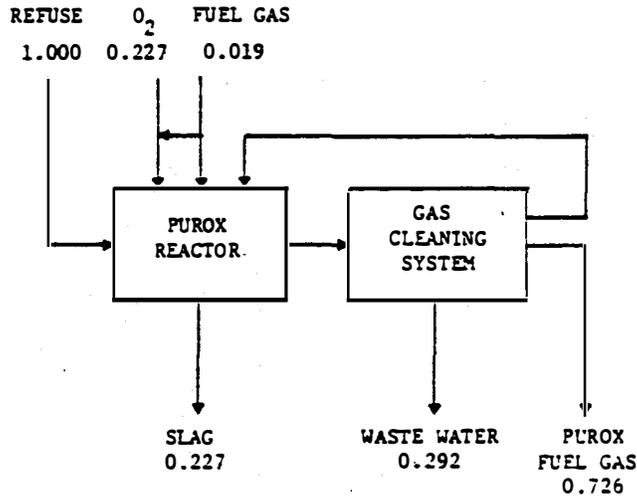


Figure D-13. Typical Material Balance for Union Carbide's Process
 (values are in metric tons) (831)

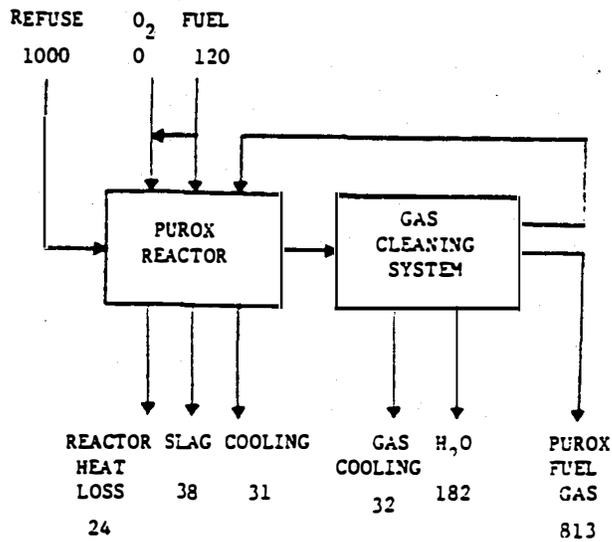


Figure D-14. Typical Energy Balance for Union Carbide's Process
 (values are in kJ) (831)

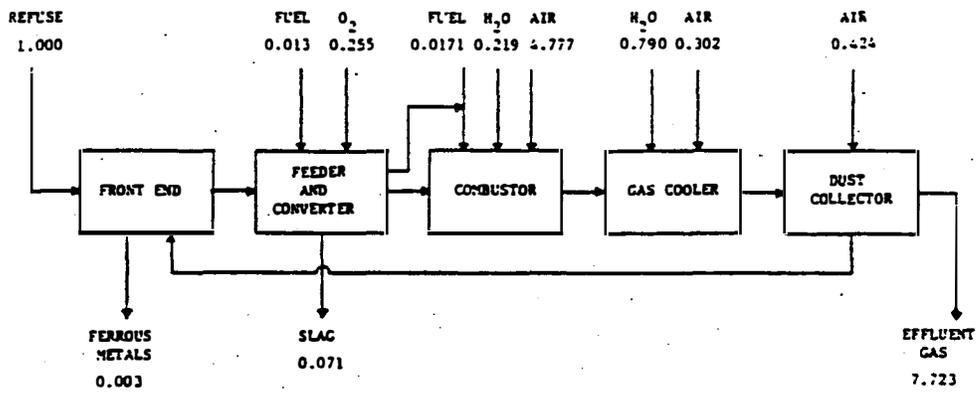


Figure D-15. Typical Material Balance for Chichibu City Facility
(values are in metric tons) (834)

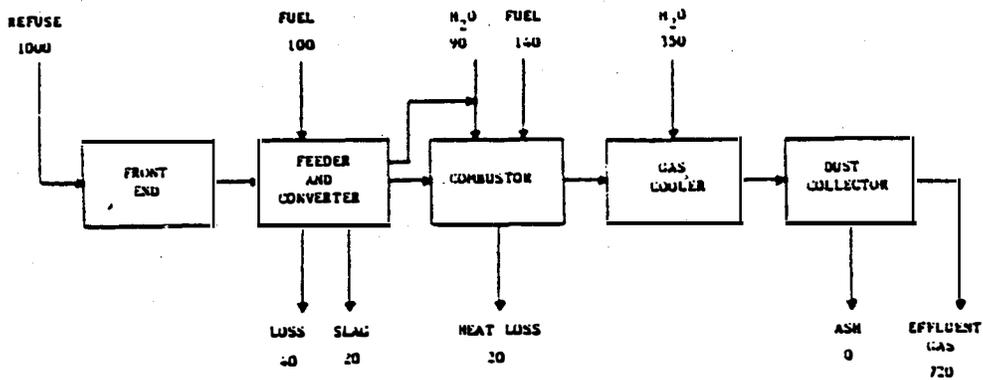


Figure D-16. Typical Energy Balance for Chichibu City Facility
(values are in kJ) (834)

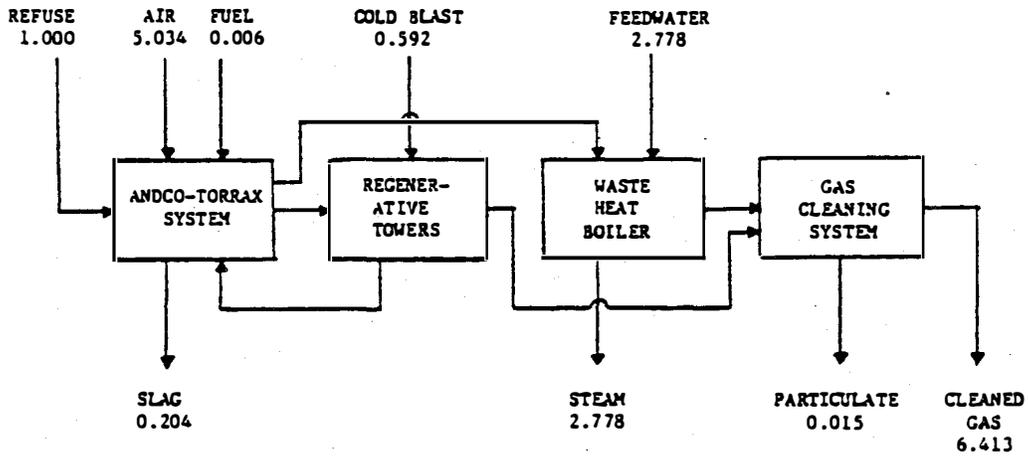


Figure D-17. Typical Material Balance for Andco-Torrax Process
(values are in metric tons) (840)

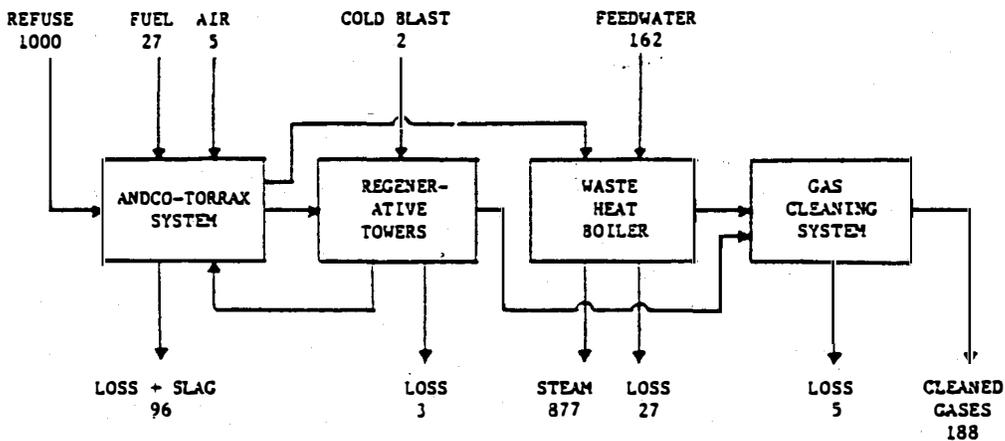
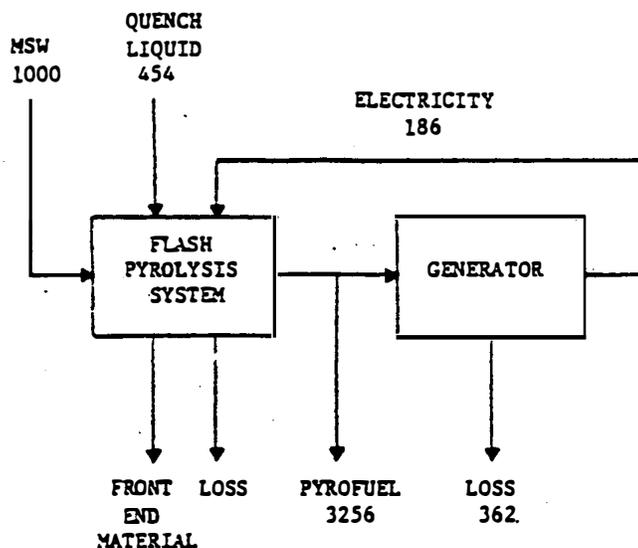


Table D-18. Typical Energy Balance for Andco-Torrax Process
(values are in kJ) (840)



**Figure D-19. Typical Energy Balance for Occidental's Pyrolytic Process
(values are in kJ) (848)**

Data are not available on the energy requirements of the AIST-Ebara pyrolysis process. Energy information regarding the Nippon Steel facilities, all of which are believed to be closed, is not available.

D.5 ENVIRONMENTAL RELEASES/IMPACTS

D.5.1 Overview

Air emissions from pyrolysis plants consist of vent or flare gases and particulate matter. Since pyrolysis systems use little or no combustion air and low velocity gas movement, their air pollution control requirements are expected to be considerably less than conventional systems. One estimate suggests a 50 percent or greater reduction in air emissions requiring treatment compared to other approaches (343). When burning pyrolysis fuels on site, the lower velocities are also likely to entrain fewer particulates. However, if an indirect combustion source is required using less clean fuels, particulate and gaseous emissions will need to be controlled (60).

Water pollution control will be required to handle effluent from a wet scrubber or from a residue quench unit operation, if used. Scrubber effluents are of particular concern in pyrolytic processes since they are likely to contain toxic and ignitable components (275). If the char and inerts are pure enough, a cooling screw conveyor may be able to reduce the char to below ignition temperature thereby enabling the residuals to be handled in a dry state (343). The degree of control required will depend on the quality of the feedstock and its preparation, the pyrolytic process used, and the ability to reliably control operating conditions to produce the products desired.

Heavy metals are not only removed during the gas scrubbing stage, however. A study of sewage sludge pyrolysis indicates that all of the metals, except for mercury, remain in the char provided that temperatures of 600 degrees C are not exceeded (827). Experiments using RDF in a laboratory-scale vortex pyrolytic reactor, whose exit temperatures were maintained at 550 degrees C, appeared to effectively immobilize most of the metals in the char (618). Even at higher temperatures, it appears that most toxics in the MSW feedstock report to the solid products produced in pyrolysis (555).

D.5.2 Environmental Data Associated with Specific Facilities

The exhaust gas from the stack of the Funabashi facility is comprised of both regenerator flue gas and the gas-fired boiler flue gas. Table D-12 shows the results of flue gas tests performed at the plant in 1983 (108). The low NOx concentration is attributed to the catalytic de-NOx reactor installed for the gas-fired boiler exhaust gas.

TABLE D-12. FLUE GAS ANALYSIS
TSUKISHIMA KIKAI FACILITY, FUNABASHI CITY (108)

<u>Component</u>	<u>% by Volume</u>
Carbon dioxide	10.5
Oxygen	8.8
Carbon monoxide	0
Nitrogen	80.7
	100.0
SO _x	17*
NOx	83*
HCl	92*
* parts per million	
<u>Dust consistency: 0.02 - 0.03 g/Nm³</u>	

Tables D-13 through D-16 present, respectively, a representative refuse analysis, reactor gas analysis, comparative stack emissions analysis, and slag-composition results (834) for the Purox II system at Chichibu City. A 1987 account indicates that HCl emissions which had been measured at 1000 ppm, were expected to be reduced to 430 ppm with the addition of alkali (287).

No information appeared in the literature reviewed on the environmental implications of the Andco-Torrax pyrolysis technology.

Emissions testing in 1987 on the Burgau, Germany rotary drum pyrolysis facility revealed concentrations of particulates, SO₂, HCl, HF, CO and dioxins to be within the then applicable national standard (826). The ash generated amounts to 16 to 27 percent by volume (40 to 45 percent by weight).

As stated earlier, the emission control system proposed for the Studsvik FBG system being constructed in Greve, Italy, consists of the Teller dry scrubbing technology to remove acid gases, particulates, dioxins/furans and heavy metals. This system includes three stages - a quench reactor (dry scrubber), a dry venturi, and a fabric filter pulse-jet system. The emission control requirements stated in Table D-17 for particulates, HCl, and heavy metals correspond to removal requirements for these pollutants of 99.95, 97.5, and 85 percent, respectively (362).

The anticipated environmental benefits claimed by designers of the Landgard pyrolysis system constructed in Baltimore included reduced particulate emissions due to precleaning of the flue gas by flyash slagging in the secondary combustion chamber-gas purifier. Emissions of heavy metals were expected to pyrolyze in the char. These benefits were never realized (479).

Table D-18 reports an analysis of the pyrolytic oil produced from Occidental's flash pyrolysis compared to No. 6 fuel oil (848). Pyrolysis oil is shown to be substantially more viscous and corrosive than No. 6 fuel oil, requiring additional refining prior to use in utility boilers (275).

Extensive tests were performed at the KWU domestic refuse pyrolysis demonstration plant near Goldshofe, Germany in 1984 (582). Pollutant constituents contained in the burned clean gas of the KWU plant demonstrated particulate, gaseous and trace metal off-gas compliance with the 1985 national air pollution control code.

TABLE D-13. REFUSE ANALYSIS, CHICHIBU CITY FACILITY
(834)

Sample	Combustibles (wt %)	Ash (wt %)	Moisture (wt %)	LHV ^a (kcal/kg)
A	38.3	6.2	55.5	1390
	28.7	7.3	64.0	910
C	34.3	6.6	59.1	1190
D	44.1	6.0	49.9	1720
E	42.1	4.9	53.0	1580
F	33.1	7.4	59.5	1130
G	32.9	5.9	61.2	1110
H	33.4	4.5	62.1	1130
I	32.9	7.2	59.9	1120
J	27.1	4.4	68.5	810
K	41.4	4.6	54.0	1540
L	25.9	5.9	68.2	760

^aLHV = lower heating value.

TABLE D-14. PYROLYSIS-GAS ANALYSIS, CHICHIBU CITY FACILITY
(834)

	Gas from Chichibu Purox [®] Process	Simulation Test (standard moisture refuse)
Refuse		
LHV (kcal/kg)	1240	1280
Pyrolysis Gas (Vol. %)		
CO	11.3	30.1
CO ₂	43.2	38.9
H ₂	18.5	24.2
CH ₄	22.2	2.5
Other	4.8	4.3
H ₂ O (m ³ N/m ³ N dry gas)	1.2	1.2
LHV (kcal/m ³ N dry gas)	2720	2250

**TABLE D-15. STACK-EFFLUENT-GAS ANALYSIS
CHICHIBU CITY FACILITY (834)**

	Gas from Chichibu Purox [®] Process	Simulation Test (standard moisture refuse)	Standard
NO _x (ppm)	142	108	250
SO _x (ppm)	29	10	1700
HCl (mg/m ³ N)	108	117	700
Particulate matter (g/m ³ N)	0.04	—	0.7

**TABLE D-16. SLAG-COMPOSITION AND LEACHING-TEST RESULTS
CHICHIBU CITY FACILITY (834)**

Test Parameter	Test Results		
Slag-Composition			
Constituent (wt %)	<u>Analysis</u>		
SiO ₂	50.0		
Al ₂ O ₃	9.5		
CaO	9.5		
Na ₂ O	6.3		
FeO	18.8		
Ignition Loss (wt %)	0.2		
Leaching-Test			
Constituent (mg/L)	<u>Analysis</u>	<u>Detection Limit</u>	<u>Standard^b</u>
Hg (total)	ND ^c	0.0005	0.005
Cd	ND	0.005	0.03
Pb	ND	0.03	3
Organic Phosphate	ND	0.01	1
Hexavalent Chromium	ND	0.01	1.5
As	ND	0.01	1.5
Cyanide	ND	0.02	1
PCB	ND	0.0005	0.0003

^bInland landfilling standards.

^cND = Not detected.

**TABLE D-17. PYROLYSIS SYSTEM EMISSION REQUIREMENTS
GREVE, ITALY (362)**

Particulates	0.0023 gr/dscf (5 mg/nm ³)
Heavy Metals	0.0014 gr/dscf (3 mg/nm ³)
Hydrogen Chloride	18 ppmd (30 mg/nm ³)
Mercury	0.1 mg/nm ³

**TABLE D-18. TYPICAL PROPERTIES OF No. 6 FUEL OIL AND
OCCIDENTAL'S PYROLYTIC OIL (848)**

Property	No. 6 Fuel Oil	Pyrolytic Oil
Analysis (wt %)		
C	85.7	57.0
H	10.5	7.7
S	0.7-3.5	0.2
Cl	—	0.3
Ash	0.05	0.5
N	2.0	1.1
O	2.0	33.2
Specific Gravity	0.98	1.30
Energy content		
Btu/lb	18,200	10,600
kJ/kg	42,300	24,600
Btu/gal	148,800	114,900
kJ/L	41,500	32,000
Pour Point		
(°F)	65-85	90 ^b
(°C)	18-29	32 ^b
Flash point		
(°F)	150	133 ^b
(°C)	66	56 ^b
Viscosity		
(SSU ^c at 190°F)	340	1150 ^b
(N·s/m ² at 88°C)	0.064	0.23 ^b
Pumping temperature		
(°F)	115	160 ^b
(°C)	46	71 ^b
Atomization temperature		
(°F)	220	240 ^b
(°C)	105	116 ^b

^bPyrolytic oil containing 14% water (market quality).

^cSSU = Saybolt university viscosity.

D.6 SUMMARY

Although several pyrolysis systems have been designed and constructed in the past two decades, most have been demonstration and laboratory scale systems. The larger-scale demonstration plants in the U.S., employing various reactor types, all experienced technology problems and are no longer operating. There are currently no commercial-scale MSW pyrolysis systems operating in the U.S.

The development of MSW pyrolysis technology in Japan generally paralleled that in the U.S. As of 1988, however, reports in the literature indicate that Japan had two commercial-scale systems: the 450 TPD Tsukishima Kikai system in Funabashi City and the 150 TPD Union Carbide (Purox II) system in Chichibu City. In Europe, a number of companies and research institutions have undertaken R&D or introduced foreign technology, including some commercial scale activity, again as of 1988. These include: the 400 TPD Andco-Torrax system in Cretail, France and a 35,000 TPY commercial-scale, indirectly heated drum pyrolyzer system in Burgau, Germany. Another facility is under construction in Greve, Italy.

The open literature provides fairly limited information on the design, operation and performance of the early pyrolysis systems; even less is generally known about the handful of currently operating systems. The performance data that have been reported is typically dated, taken from limited tests and often represents laboratory-scale experience that is not easily scaled up. Such limitations, especially for those few (Japanese and European) facilities believed to be currently operating, make it difficult to conduct a rigorous technoeconomic analysis of pyrolysis technologies.

Operating problems attendant with the early work in the United States and some projects from other countries have taken many forms, as presented below (275).

- o Charging of feedstock continued to be a source of difficulty relative to plugging of mechanical filters, seal leakage (from both pressure and vacuum lines), etc.
- o Hot solids transfer and tar condensation tended to create plugging and subsequent system shutdown.
- o Materials degradation has occurred from heat exposure and materials fatigue, corrosion (sulfur, chlorides) and erosion from abrasive solids. Unprotected system components as well as refractory lining, walls and transfer lines have all been affected.

- o Catalyst activity in the presence of system impurities has lead to the formation of undesirable emissions.
- o Compression problems have developed, especially for piston-type compression, when pyrolysis systems are processing waste containing aerosols, tars and particulates.

The primary disadvantage of pyrolysis, noted conspicuously by its absence in the literature, is evidence of its ability to achieve performance comparable with conventional thermal conversion systems at similar design levels and competitive system economics. In addition, there is insufficient experience in scaling up from small pilot-scale plants and controlling thermochemical reactions involving highly variable feedstock (799).

Certainly in theory, pyrolysis gas or oil offers the same potential as does coal gasification and liquefaction, i.e., as a substitute for natural gas and oil, which are in wide demand. The major advantage of pyrolysis over other approaches to utilizing MSW is its potential for producing a storable, transportable gaseous or liquid fuel while minimizing environmental problems (275).

Some of the potential advantages of applying pyrolysis to MSW, in addition to the production of pyrolysis gas and oil, are stated below (343).

- o Operation of pyrolysis systems with little or no oxygen implies that the air volumes and velocities (and hence the particulate reentrainment) are much reduced over conventional combustion systems. Therefore, air pollution control requirements are expected to be similarly reduced.
- o Pyrolysis off-gas can be recycled and pyrolysis equipment is expected to require lower energy than conventional combustion. At higher temperatures that produce a molten slag, it is expected that front-end processing equipment may not be needed to separate out unprocessibles and size reduce the MSW feedstock. (It should be noted, however, that, according to Table D-1 in Section D.1, virtually all of the larger scale systems identified worldwide used some type of MSW preparation.)

- o Pyrolysis, in theory, more completely volatilizes combustible material, compared to conventional systems, thereby producing char that is more consistent in form. Pyrolysis also can produce a relatively inert residue, thereby minimizing the adverse environmental interaction, especially as regards groundwater.

- o If proven in scale-up demonstration, the pyrolysis vessel can, in theory, be designed to deliver net electric energy comparable to large-scale conventional waterwall systems, with potentially lower maintenance owing to its relatively simple design.

A recent report of key questions and issues regarding the efficacy of pyrolyzing MSW resulted from an international conference/workshop held in 1989 in Luxembourg (553). While there is some commercial-scale pyrolysis experience reported, there is no reported commercial-scale experience for the conversion of MSW to liquid fuels. How serious will the contamination of liquid fuels be in the presence of halogenated hydrocarbon by-products produced during pyrolysis? Generally, due to the heterogeneous nature of MSW, can pyrolysis products be produced at a consistent level of quality? Is it economical to consider sorting out the inorganic materials as a pretreatment step prior to pyrolysis? Also, are there other disposal options, besides landfilling, for pyrolysis char which contains heavy metals and other inorganic substances? In spite of the relative unpredictability of feedstock quality and resulting operational considerations and variability of product quality, the workshop consensus called for additional "time and effort at working on MSW."

In conclusion, comparison of its technoeconomic feasibility with other MSW management technologies is very difficult as long as MSW pyrolysis remains unproven in long-term daily operation. Not only is such an evaluation hampered by past poor performances across many reactor types, but uncertainties linger about the costs of complying with stricter environmental regulations. Also, the markets for pyrolytic products (viz, gas, oil, char, steam or electricity) have not been developed. Further, the quality of pyrolytic products as substitutes for more conventional energy (and chemical) products has also not been proven in sustained operations using MSW as feed. For these reasons, pyrolysis of MSW has not been actively considered as a proven, or near-term option for the management of MSW.

APPENDIX D. PYROLYSIS AND GASIFICATION OF MSW
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16. Abstract (Limit: 200 words) The overall objective of the study in this report was to gather data on waste management technologies to allow comparison of various alternatives for managing municipal solid waste (MSW). The specific objectives of the study were to: 1. Compile detailed data for existing waste management technologies on costs, environmental releases, energy requirements and production, and coproducts such as recycled materials and compost. 2. Identify missing information necessary to make energy, economic, and environmental comparisons of various MSW management technologies, and define needed research that could enhance the usefulness of the technology. 3. Develop a data base that can be used to identify the technology that best meets specific criteria defined by a user of the data base. Volume I contains the report text. Volume II contains supporting exhibits. Volumes III through X are appendices, each addressing a specific MSW management technology. Volumes XI and XII contain project bibliographies.			
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