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A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
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A project such as this, although it rests in the hands of a research contractor, depends heavily for its success on the cooperation and contributions from firms being evaluated and from other resource persons, agencies, and companies participating. The project team received generous cooperation from the many engineering and business professionals of the over 40 process development firms initially screened and, more particularly, from those seven reported upon in detail. Also, we acknowledge the assistance of the researchers, facility owners, pilot plant technicians, and others that were important in the field trip experiences

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Mr. James Kilgroe	USEPA-AEERL
Dr. Richard Bain	NREL
Mr. Lory Larson	Southern California Edison
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Walter R. Niessen, P.E.	Project Team Leader
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Section 1

EXECUTIVE SUMMARY

A. INTRODUCTION

This report summarizes the state of the art for seven technologies involving gasification, or other innovative thermal processing technologies, for application to municipal solid waste (MSW). The technologies are all at the level of "incipient commercial availability." They have passed through the "idea" stage and through laboratory and bench-scale testing; their prototypes have been demonstrated at an MSW feed rate of at least several tons per hour.

The target audience for this report is the town, city, or regional official responsible for the management of MSW. This individual, with input from engineering, financial, and environmental specialists, is invited to consider these technologies in addition to the well-proven conventional alternatives.

The objective of this analysis was not to determine the "best process." The concept of "best" is valid solely in the context of local values, constraints, and problems. Rather, this work presents the technical, environmental, and economic characteristics of each individual process. After reading the presentation and determining that there is a good match with local needs, an individual or entity can find a point of contact in the report to facilitate follow-up.

B. OVERVIEW

Proper management of solid waste is an important element of municipal sanitation and a major line item in municipal budgets. In years past, waste management created a significant opportunity for thermal processing with energy recovery from MSW. In recent years, several developments have sharply curtailed the market:

- The problem of ensuring a reliable supply
- The low price of energy
- Changing financial mechanisms and capability
- Changing social attitudes

Prospective owners of waste management systems need a reliable supply of MSW to support their capital borrowing; they need firm, long-term contracts for waste disposal. To draw wastes from large areas, it was often necessary to *require* waste collectors to use a proposed waste management facility. However, recent U.S. Supreme Court decisions have restricted the right to direct waste. Unless the Court finding is redressed by act of the Federal Congress, the basic capital-raising mechanism for waste processing facilities will be greatly weakened or lost. Thus the financial risk of project development will be much greater, with a concomitant effect on bonding costs to the communities and counties.

Low energy prices affect thermal processing facilities by reducing the flow of revenue from the sale of electricity or steam. During the 1980s and up to the present, the trend in energy prices has been downward. Consequently, the effective break-even tipping fee for proposed plants has increased, making community acceptance and financing more difficult.

Environmental issues have also affected MSW combustion. Initially, pressure was focused on visible emissions. The Clean Air Act and its Amendments drove the industry away from simple refractory enclosures and toward waterwall boiler designs. This change in direction brought the technical sophistication and systems view of the commercial boiler and combustion industry to the MSW incineration market. In 1977 the pollutant "dioxin" emerged as a new issue. Emissions of acid gases—HCl and SO_2, nitrogen oxides (NO_x), and toxic elements also became of increasing concern. Other interests focused on ash.

Although environmental concerns have not driven thermal processing out of business, they have resulted in significantly higher costs, increased system complexity, and long delays in moving projects through the public review and regulatory approval processes. Interestingly, the situation in Europe is similar to that in the U.S., but the result is different. Recent legislation in Germany, France, and the Netherlands has mandated an end to raw waste landfilling. This legislation will help to further emphasize the role of thermal processing in solid waste management, where waste turned into energy has already assumed a commanding position. However, driven by stringent air emissions limits in some European nations, waste management costs will be very much higher than in the U.S.

Several new or enhanced technologies to thermally process MSW are now well established. One class, which burns waste in the same physical form as it is generated (mass-burn incinerators), is coupled with elaborate back-end air and residue treatment. Another burns wastes alone or with fossil fuels after preprocessing of the waste to a refuse-derived fuel (RDF).

Beyond these well-proven combustion processes, a new technology class has emerged—refuse gasification. During this process, the organic fraction of MSW is heated to drive off a gas with a substantial fuel value. This gas can be cleaned and burned in a gas engine or gas turbine to generate electricity. Emissions data generally show very low rates for dioxins, acid gases, and other problematic pollutants.

The processes studied in detail, identified by the name of the developer, are:

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

Of these seven emerging technologies, two—Energy Products of Idaho and Pedco Incorporated—use full combustion, but in novel contexts. The other five processes—TPS Termiska Processor AB, Proler International Corporation, Thermoselect Inc., Battelle, and ThermoChem Inc.—use gasification methods followed by cleanup and use of the fuel gas. In niche market sectors and in the broader market, the five gasification technologies studied during this project are emerging as "commercially-ready" alternatives.

The penetration of the thermal processing market by advanced technologies is paced by their environmental, economic, and performance acceptability. From an environmental viewpoint, the project team saw the seven technologies as a sound response to the regulatory challenges of the revised New Source

Performance Standards (NSPS) and the Maximum Achievable Control Technology (MACT) rules. The environmental characteristics of the seven processes are summarized in Table 1.1.

In the U.S., economics has always been a critical and probably pacing factor affecting the penetration of thermal processing technology in MSW practice. Tables 1.2a and 1.2b summarize, in metric and English units respectively, the economic data collected and developed in this study. Capital costs of most of these processes are comparable to the $110,000/Mg/d ($100,000/t/d) typical of contemporary mass burn systems. The net operating costs for the gasification technologies, which are equivalent to the break-even tipping fee, are comparable to those for *owner-operated* mass-burn facilities. The revenue stream from selling energy continues to be critical to overall economic acceptability.

Results are less clear concerning "performance acceptability." Most, except for the EPI and Thermoselect processes, require an RDF feed. Historically, most RDF facilities have incurred substantial post-construction rework, capital investment, capacity downrating, etc. Landfills are still required. Many systems in this study have significant development tasks ahead of them. Unfortunately, the catalyst of vigorous market activity to push this development and to foster risk-taking is weak. Further, many systems are quite complex. This complexity presents some problems when seeking acceptance by client communities, by regulatory authorities, and from financial and engineering entities involved in concept selection and project implementation.

C. PROJECT APPROACH

The first task was to prepare a detailed work plan. Then, a two-stage screening process was begun to select the firms for detailed evaluation, the criterion for such evaluation being that they had thermal processes under development worldwide. This screening was followed by process evaluation, facility inspections, and ultimately, by preparation of this summary report. Initially, the project team contacted over 40 firms identified as possible candidates. The data received were analyzed to produce a recommendation for the final seven processes. The selection of the final seven was discussed and confirmed at a meeting with the Project Steering Committee.

The scope of the detailed evaluation effort for the seven selected technologies was broad. Based on a faxed request and answers to a detailed questionnaire, data for the evaluation were obtained from the developers. The evaluation included exploration of technical issues affecting the basic process feasibility, reliability, worker safety, operability, and maintainability. Of importance was the remaining degree of scale-up from the present level of development to commercially useful equipment. Operating experience was also considered critical.

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

Table 1.1 Environmental Comparison of Developing Technologies

Process Name	Thermal Treatment Technology	Air Pollution Control	Water Pollution Control	Residue Treatment or Disposal
EPI, Inc.	Bubbling Fluid Bed Combustor	Lime Spray Dryer Absorber, Fabic Filter, Selective Noncatalytic Reduction, Activated Cabon Injection	None: Dry System.	Landfill
TPS Termiska AB	Circulating Fluid Bed Gasifier with Dolomite Cracker	Scrubbing of Fuel Gas to Remove Particulate Matter, Condensable Organics, and Acid Gasses, NO_x[1]	Cleanup of Scrubber Liquor. Not specified.[2]	Landfill
Proler International	Rotary Reactor Gasifier and Cyclonic Ash Vitrifier	Fabric Filter, Wet Scrubber,NO_x[1]	Cleanup of Scrubber Liquor. Not specified.[2]	Proposed Sale as Vitrified Aggregate; Otherwise landfill.
Thermoselect, Inc.	Raw Waste Gasifier	Acidic and Alkaline Scrubber, H_2S Removal, Activated Coke, NO_x.[1]	pH Adjustment, Metal Precipitation, Filtration, Distillation.	Proposed Sale as Vitrified Aggregate; Otherwise Landfill.
Battelle	Circulating Fluid Bed Gasifier and Combustor	Wet Scrubber, NO_x.[1]	Cleanup of Scrubber Liquor. Not Specified.[2]	Landfill
Pedco Incorporated	Rotary Cascading Bed Combustor	Lime Spray Dryer/Absorber, Fabric Filter, Selective Noncatalytic Reduction, Activated Carbon Injection.	None. Dry System.	Landfill
ThermoChem	Pulse-Heated Circulating Fluid Bed Gasifier	Wet Scrubber, NO_x.[1]	Cleanup of Scrubber Liquor. Not specified.[2]	Landfill

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

Table 1.2a Summary of Statistics for Developing Technologies (per ton quantities relate to raw MSW, metric units)

Process	Product Energy Form	Plant Size Evaluated (Mg/d_{raw})	Capital Cost ($000)	Process Capital ($000)	Proprietary Capital (%)	Capital Cost ($/Mg/d)
EPI Inc.	Steam	780	79,415	28,015	35.3	101,800
TPS Termiska Processor AB	Gas	1600	170,675	58,875	33.3	106,700
Proler International Corp.	Gas	1247	153,625	57,625	37.5	123,200
Thermoselect Inc.	Gas	1440	236,790	192,790	81.4	164,400
Battelle	Gas	849	80,532	12,532	15.6	94,900
Pedco Incorporated	Steam	800	87,067	28,167	32.4	108,800
ThermoChem Inc.	Gas	849	91,733	20,983	22.9	108,800

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

*Gross operating cost/ton raw refuse—total of capital charges, insurance, labor, maintenance, and supplies before energy credits.
†Net operating cost/ton raw refuse—gross operating cost less energy credit.
§Heat rate—factor relating the fuel value in the raw refuse (assumed at 11.6 MJ/kg, 14 MJ/kg as RDF) to the gross or net generation.

Table 1.2b Summary of Statistics for Developing Technologies (per ton quantities relate to raw MSW, English units)

Process	Product Energy Form	Plant Size Evaluated (t/d_{raw})	Capital Cost ($000)	Process Capital ($000)	Proprietary Capital (%)	Capital Cost ($/t/d)
EPI Inc.	Steam	860	79,415	28,015	35.3	92,343
TPS Termiska Processor AB	Gas	1760	170,675	58,875	33.3	96,974
Proler International Corp.	Gas	1370	153,625	57,625	37.5	112,135
Thermoselect Inc.	Gas	1585	236,790	192,790	81.4	149,394
Battelle	Gas	935	80,532	12,532	15.6	86,130
Pedco Incorporated	Steam	880	87,067	28,167	32.4	98,940
ThermoChem Inc.	Gas	935	91,733	20,983	22.9	98,110

Process	Gross Operating Cost ($/t)*	Gross Power (kWh/t)	Net Power (kWh/t)	Net Operating Cost ($/t)†	Gross Heat Rate (Btu/kWh)§	Net Heat Rate (Btu/kWh)§
EPI Inc.	77.46	899	740	47.88	11,117	13,522
TPS Termiska Processor AB	65.31	919	748	35.37	10,879	13,362
Proler International Corp.	90.12	1059	901	54.06	9,445	11,094
Thermoselect Inc.	112.03	895	643	86.29	11,176	15,549
Battelle	71.60	827	720	42.81	12,087	13,896
Pedco Incorporated	85.16	879	717	56.47	11,376	13,938
ThermoChem Inc.	73.60	950	830	40.41	10,529	12,052

*Gross operating cost/ton raw refuse—total of capital charges, insurance, labor, maintenance, and supplies before energy credits.
†Net operating cost/ton raw refuse—gross operating cost less energy credit.
§Heat rate—factor relating the fuel value in the raw refuse (assumed at 5000 Btu/lb, 6050 Btu/lb as RDF) to the gross or net generation.

Business issues revolved around the financial and manpower resources of the firms that could be harnessed to achieve commercial viability. Important factors in the award of disposal contracts are the prospective capital and operating costs of the system. To keep the focus on the thermal processing aspect of the process, standardized costs were developed for the preparation of MSW to RDF and for the conversion of the energy product—the high-pressure steam or a fuel gas—into electricity. The resultant cost information for these technologies is thus an economic picture of a generic plant with standardized feedstock and energy conversion components—a plant that perhaps is not optimal. A serious buyer should contact the developer organizations to give them the opportunity to propose their costs for any specific situation.

D. TECHNOLOGY SUMMARIES

1. Energy Products of Idaho (EPI).

EPI is a limited partnership with headquarters in Coeur d'Alene, Idaho. EPI's basic business is the design and fabrication of fluid bed combustion systems. Although their corporate experience favors the full-combustion mode for their systems, they have pilot plant and commercial plant experience, with three commercial systems, in a "starved-air" gasification mode. Their most proven product, however, is the full-combustion system.

The EPI incineration system uses a bubbling-type fluid bed concept that accepts a prepared 10-cm (4-in.) top size RDF. Within the bed, RDF particles are exposed to a vigorously turbulent hot environment that promotes rapid drying, gasification, and char burnout. In the bed EPI's proprietary design features provide continuous removal of oversized noncombustible materials. The hot gases from the bed are passed through a boiler to generate the high-pressure, superheated steam that is used either to produce electricity or for process applications.

The combustion technology offered by EPI is presently at the point of commercial availability. EPI has installed five furnaces in the U.S., with capacities of more than 50 Mg/d (60 t/d), burning an RDF fuel. Between 1982 and 1985, EPI designed and built three wood-waste-fired, gasification-mode fluid bed systems. They also have acquired in-house operating experience with RDF in their pilot plant gasifier; but at the time of this study, they had no operating commercial-scale plants on RDF in the gasification mode.

Therefore, in matters of technical maturity and commercial verification, the EPI system can be implemented with limited risk in the combustion mode. The gasification mode is much less developed and will require some additional testing, operating experience, and design maturation. Thus potential users will encounter substantially greater risk at present.

2. TPS Termiska Processer, AB

TPS Termiska Processer (Thermal Processes), or TPS, is a small, independent Swedish company with about 50 employees, working in the specialized field of energy and environmental process research and technology development. Their technology involves the starved-air gasification of RDF in a combined bubbling- and circulating-type fluid bed. Following the gasification bed, they insert a second circulating-bed "cracker." In the second bed, ground dolomite is injected to catalyze the conversion of high-molecular-weight gasification by-products into much lower molecular-weight compounds. This system generates fuel with a medium heat content.

The technology offered by TPS is presently close to the point of commercial availability. In 1992 a commercial, two-bed unit was installed in Gréve-en-Chianti in Italy. It had a combined capability of 30 MW to gasify 100-percent pelletized RDF fuel. Limited RDF availability since early 1995 had led to the use of biomass (coarsely shredded wood or agricultural wastes) from time to time.

The manufacturing methods for the TPS-design gasifier systems, the long-term operability of their beds with acceptable management of bed solids, the projected emissions control performance, the feeders, etc., have been tested at Gréve in MSW-based RDF service. Therefore, in matters of technical maturity and commercial verification, the TPS system can most likely be implemented with only moderate technological risk.

3. **Proler International Corporation**

The Proler SynGas Process is a patented technology to reform hydrocarbon-containing wastes into a gaseous product. It is represented by a 1.8-Mg/h (2-t/h) demonstration plant in Houston, Texas. Although the process was originally developed for the gasification of automobile shredder wastes, limited runs have demonstrated its suitability for gasifying MSW. The process accepts preshredded material and feeds it into a rotating, kiln-like reactor. In the proposed commercial embodiment of the process, the reactor is fired with the exhaust from a "vitrifier" auxiliary that uses fuel gas, carbon char, and oxygen to melt the mineral residue. The process produces fuel gas with a medium heat content; after cleanup, this fuel gas is suitable for power generation. The residue is discharged in a form that is stated to be a commercially useful by-product.

According to Proler, the preliminary design work has been completed for a full-scale 865-Mg/d (960-t/d) commercial facility using MSW as feedstock. The facility consists of two process lines at 18 Mg/h (20 t/h) each. However, some technical issues require resolution before successful commercialization for MSW can be ensured:

- Although the demonstration plant is processing RDF at a top size of 5.08 cm (2 in.), the commercial plant is expected to accept shredded material with a top size of 15.24 cm (6 in.). This premise has not yet been sufficiently tested.

- The demonstration plant has operated with shredded MSW on a limited basis only. An extended campaign of operation appears essential to evaluate potential problems.

- The reliability and performance of the vitrifier and the integration of this equipment with the existing gasifier have not yet been accomplished.

- The planned commercial size at 11.3 kg/s (40 t/h) MSW represents a scale-up of 5.5:1 on a per-line basis. Past experience with other combustion and thermal process development scenarios indicates that such a substantial step implies a high risk factor when processing MSW.

Further testing with MSW to resolve these issues seems desirable. Proler has indicated an intent to guarantee the performance of its process.

4. **Thermoselect Inc.**

The Thermoselect system processes commingled MSW into what are stated to be environmentally safe products. The products include a reactor gas, vitrified solid granules, elemental sulfur, and sodium salts. No liquid effluents are discharged into the environment. The process is intended to minimize formation and emission of particulates and other pollutants.

Gasification is achieved at a high temperature. The mixture of solid refuse and char reaches 800°C (1472°F) as it reaches the discharge end of a preprocessing section, described by Thermoselect as the degasification channel. The products of gasification are then held in the reactor at 1200°C (2192°F) for more than 4 seconds. The resultant gas is quenched in a spray chamber to below 90°C (194°F). Data indicate that this combination of time and temperature destroys the complex organic compounds produced in the gasification process and yields a gaseous product that has nearly reached chemical equilibrium. The raw gas is cleaned in a gas purification system that removes acid gases, hydrogen sulfide, particulates, and volatile heavy metals. Air emissions result only from the combustion of the cleaned reactor gas as heat is produced in the boilers or from other means for generating electric power.

The Thermoselect demonstration facility is located at Fondotoce, Italy, near Lago Maggiore in the southern foothills of the Alps. The equipment consists of one process line with a nominal capacity of 4 Mg/h (4.4 t/h) or 100 Mg/d (106 t/d). The line at the pilot plant includes all of the process units (acid and alkaline scrubbers, hydrogen sulfide-removal scrubber, coke filter, etc.) that are envisioned in the full-scale commercial plant. Test results indicate only minute traces of organic compounds in the reactor gas. Other than traces of polychlorinated dibenzo p-dioxin (PCDD) and polychlorinated dibenzo furan (PCDF), no chlorinated aromatic hydrocarbons were detected.

This system should comply with U.S. environmental regulations. The demonstration plant is stated to have gone through 20,000 hours of operation and operates continuously for 5 days a week, processing unshredded municipal and industrial wastes. The plant uses product gas for driving an engine generator and heating the degasification channel.

Major unresolved areas appear to be:

- Optimization of energy use.
- Use of Thermoselect's reactor gas in gas turbines—untested as of early 1996, but not expected to be a problem.
- Replacement of natural gas (now used at Fondotoce) with reactor gas—should not be a problem.
- Waste-heat recovery to improve overall plant thermal efficiency, including finding uses for low-grade heat.
- Continuity and reliability of operation, since the demonstration plant has only been operated on a 5-day/week cycle. Continuous, around-the-clock operation is yet to be demonstrated.
- Scale-up. The current demonstration plant is reported to have a "nominal capacity of 4 Mg/h (4.4 t/h)," but experience to date shows that the unit appears to operate at an actual throughput of only 3.8 Mg/h (4.2 t/h). The "Standard Design" two-line capacity is 10 Mg/h (11 t/h) or 240 Mg/d (264 t/d). Therefore, there is a scale-up factor of about 2.7:1 based on actual operating

240 Mg/d (264 t/d). Therefore, there is a scale-up factor of about 2.7:1 based on actual operating experience. The success of the planned commercial-size facility is yet to be proved.

5. **Battelle**

The Battelle High Throughput Gasification System (BHTGS) uses indirect heating in a twin, circulating fluidized bed (CFB) gasifier and combustor. RDF is gasified in a CFB using steam as the fluidizing medium to generate an 18.6 to 22.4 MJ/Nm^3 (500 to 600 Btu/sft^3) medium-heating-value gas without oxygen. Residual char is consumed in an associated CFB combustor. A circulating sand phase provides heat transfer between the separate reactors.

Tests demonstrated the technical feasibility of the gasification process and provided the basis for preparing detailed process conceptual designs and projecting economics. In 1989 testing was conducted in a 25-cm (10-in.)-ID, 6.9-m (22.7-ft)-high gasifier and a 1.0-m (40-in.) ID, 3.5-m (11.5-ft)-high combustor. Throughput was 0.65 Mg/h (0.72 t/h). The longest continuous operating run was approximately 100 hours at 9.1 Mg/d (10 t/d) with dry RDF. A 200-kW gas turbine installed on their Process Research Unit (PRU) has operated with recharges from wood for about 60 hours as an integrated gasifier/turbine system.

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

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

Battelle's process development began in 1977. Detailed process development activities were begun in 1980 with the construction of Battelle's PRUs. Experimental data have been generated in 15-cm (6-in.) diameter and 25-cm (10-in.) diameter gasifiers with dry RDF throughputs of 0.22 and 9.1 Mg/d (0.24 and 10 t/d) respectively. Data from these showed that extremely high throughputs, over 19.5 $Mg/h{\bullet}m^2$ (4000 $lb/hr{\bullet}ft^2$) could be achieved.

Important process issues relate to fuel preparation and reactor gas cleanup. The specific level of fuel preparation necessary for the process has not yet been determined, but data suggest that there will not be a requirement for fine shredding of the feedstock. Feed size range will be dictated by the feed system requirements. Product gas cleanup, to include tar cracking and particulate removal, is also important. Additional operation at PRU scale is necessary to confirm the preliminary results obtained during the 1989 study at Battelle. The overall design concept needs to be expanded from a development focused on gasifier technology to a full plant with all auxiliaries and subsystems.

6. **Pedco Incorporated**

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

The Pedco Rotary Cascading Bed Combustor (RCBC) is, in essence, a robust solid-fuel burner and heat-recovery system. It is not a gasifier. Among other solid fuels, such as coal or wood chips, it can burn prepared MSW. Pedco's basic business is the design of combustion systems using the RCBC concept.

The RCBC burner comprises a rotating, horizontal, cylindrical combustion chamber. A bundle of boiler tubes projects into one end of the chamber. The rotational speed of the chamber is high enough to keep a substantial fraction of the bed material continually airborne. This activity produces an environment similar to that of a fluid bed but, in this case, a mechanically fluidized bed. The hot falling solids cascade across the whole diameter so that the boiler tubes are submerged in hot fuel and bed material. The hot solids recycle preheats the combustion air, drying and igniting the incoming fuel.

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

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

Pedco has yet to develop and adopt a front-end waste system to produce a sized RDF feed for the RCBC system. Indeed, Pedco has only limited experience with RDF and has not yet established a firm basis on which to specify their optimum top size. Development of a generalized RDF flowsheet should not be a problem. However, almost all RDF facilities have required extensive redesign and reconstruction to bring RDF processing elements to an acceptable level of reliability and performance.

A few hours' operation of a robust combustor with RDF, however successful, does not constitute an adequate basis for facility design, nor for process and emissions guarantees, air pollution and other permit submissions, and long-term operating contracts. Of particular importance relative to the RCBC are:

- Fouling and plugging, separately or in combination, of the ash handling chutes with wire and oversized noncombustible materials
- Similar fouling problems for the boiler tubes
- Abrasion and corrosion problems.

These problems could result in both frequent equipment outages, affecting plant throughput and electrical revenue, and high maintenance expense. Experience with the cluster of boiler tubes inserted into the RCBC device has been limited to relatively low-pressure, saturated steam. To achieve maximum power production, higher pressures and superheated conditions are preferred. Higher skin temperatures on the tubes may affect their erosion and corrosion sensitivity and should be evaluated before making a commitment to a full-scale facility.

7. ThermoChem, Incorporated

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

Pulse Enhanced™ indirect heating, combined with fluidized bed and steam reforming, provides a process for converting organic material in RDF to fuel gas while separating the inorganics without oxidation or melting. The heart of the process is the Pulsed Enhanced™ heater that is immersed in the fluidized bed. The organic waste fed to the fluidized bed steam reformer reacts with steam to produce fuel gas.

MTCI's development efforts began in 1984. Experimental data have been generated in reactors from 9.1 to 2722 kg/h (20 to 6000 lb/h) using various biomass and waste feedstocks. In 1991 and 1992, a 13.6-Mg/d (15-t/d) demonstration unit was operated on rejects from a cardboard recycle paper mill in Ontario, California. Later, this same unit was relocated to ThermoChem's test facility in Baltimore, Maryland, to process coal, wood chips, and straw.

Based on 6.8-kg/h (15-lb/h) pilot plant tests, the ThermoChem Process appears to comply with EPA's NSPS for municipal waste combustors. Tests indicate the residue meets EPA Toxicity Characteristics Leaching Procedure (TCLP) criteria set for landfill disposal as a nonhazardous waste. Wastewater contains only trace amounts of organic materials.

ThermoChem envisions no problem areas when operating with RDF. They believe that tube corrosion, erosion, and plugging will not be a problem. However, experience in other RDF-based technologies strongly suggests that until full-scale trials are conducted over an extended period, the risks and potential cost of these problems should not be ignored. Other development experiences also suggest that there are many other issues that must be resolved satisfactorily to "marry" a workable process to a workable, reliable facility. The materials handling system needs work. The cyclones are subject to plugging, just as they are in conventional atmospheric fluid beds. The removal of solids from the bed can be a problem. Considerable demonstration work is clearly needed to address remaining uncertainties regarding air emissions; residue quality; plugging of the spaces between the tubes with wire, metal, and rocks; etc. These uncertainties translate into persistent risks that should be carefully considered before adopting this technology.

E. RESULTS

The review showed that an intense developmental activity applicable to the thermal processing of MSW is under way in the U.S. and Europe. We identified over 40 discrete efforts at some stage of process development. Most of the processes are based on MSW gasification, as opposed to full combustion. In part, the focus on gasification reflects the current stringent regulatory situation regarding the control of air emissions in both the U.S. and Europe. Thus processes that allow cleanup of the reactor gases before their combustion offer potential cost savings, since the volume of flow treated is small. The cleaned fuel gases can be burned in either gas engines or gas turbines to generate electricity or can be sold as a fuel for use in conventional fossil-fuel-fired boilers.

Although many of the 40 processes are still at the bench or laboratory scale, several have progressed to a pilot or semiworks level, where the difficult problems of reliability, flexibility, and the like begin to show themselves. The seven processes selected for detailed study in this assignment are all very near to commercialization. Indeed, one technology has been implemented in four, full-scale commercial facilities. However, most processes still present some risk to a prospective owner. This risk could show itself as higher capital or operating costs, less reliability, or lower energy-recovery efficiency than have been forecast at this time. The development record for new MSW processing technologies suggests that such problems are probable for some processes as they move into full-scale commercialization.

The overall conclusion that can be drawn from the study is that competitive alternatives to conventional mass-burn or RDF combustors exist. The alternatives may not offer exceptional economic advantages. Almost all of the processes studied present a significantly lower air emissions profile than do conventional plants. This fact may merit investigation by communities or regional jurisdictions considering volume reduction technology. The economic analyses in Tables 1.2a and 1.2b are intended to provide perspective; they are not directly applicable to any one situation. To be fair to both the potential user and to the developers, cost issues should be addressed directly with the firms.

Based on data from pilot facilities, each of these processes should be able to achieve full compliance with the U.S. EPA MACT standards and the NSPS for Municipal Waste Combustors that were promulgated in final form in December 1995. Since only one of the processes matches the technology groups used by EPA in their standard setting and many are gasifiers and not the full-combustion systems identified in the EPA standards, there is some uncertainty in knowing how the Federal standards will be applied. As with most permitting issues, the ultimate resolution of the questions must wait until actual permits have been submitted and final regulatory action is required.

The residues from the processes do not present problems in the TCLP leaching tests. However, the quantity of data in this area is limited, and experience in mass-burn plants suggests that significant variations can be expected in TCLP results. Two of the processes, Thermoselect and Proler, include process steps where the residues are melted (vitrified). For these processes, the TCLP results are exceptionally low because the metals are bound in a glass structure and cannot be readily solubilized. Both firms believe that the vitrified residue granules may be marketable and thus that their processes will have lower operating costs than are shown in Table 1.2a and Table 1.2b. As yet, however, the value of the granules, if any, has not been established in the U.S. marketplace.

F. CLOSING

The project team was very impressed with the professionalism, the high technical standards, and the business commitment in most of the development firms studied. Many developers have access to the capital resources that are so critically important to technology demonstration and evolution. Capital is crucial for the seven developers if they are to further the evolution and maturation of their technology and present to the marketplace convincing proof of the ability of their processes to meet the demands of MSW management.

Section 2

INTRODUCTION

A. PROJECT OBJECTIVES

The project covered in this report was conducted to identify developers whose gasification or other innovative thermal processing technologies have the potential for treating the organic constituents in municipal solid waste (MSW). The processes recover heat directly, produce a fuel product, or produce a feedstock for a chemical process. Each of the seven technologies selected for detailed study, from more than 40 originally screened, is on the brink of commercial availability.* Each has passed the idea stage, moved through laboratory and bench-scale testing, and finally been proved feasible at the prototype level at an MSW feed rate of at least several tons per hour.

This report summarizes project activities, describes the current status of each technology, and identifies the selected developers, all of whom have expressed an interest in applying their technology to MSW treatment. This section covers the Project Team's approach to the work; discusses the data requested of project participants; and evaluates business, cost, and economic issues. Sections 3 through 9 are detailed discussions of each project participant's technology. And finally, Section 10 presents a concise review and summary of the information gathered during the study.

B. PROJECT APPROACH

The initial task in the project was the preparation of a comprehensive Work Plan. After the plan was completed, the Team began a two-stage screening process. Candidates to be evaluated in detail were selected from companies with thermal processes under development worldwide. The two-stage screening process was followed by a candidate evaluation phase, during which such aspects as technical, environmental, and financial suitability were explored. The regulatory issues facing developers were also examined. Process evaluations, facility inspections, and preparation of this summary report formed the balance of the project.

1. Screening Phase

The overall objective of the screening effort was to narrow the number of processes under consideration from over 40 to the final 7. The final candidates were those judged to have the greatest near-term promise of technical and commercial success for MSW applications. They were *not* the only viable thermal processes among the many processes identified. Many others not as far along in their development at the time of the project (mid-1995) or those that were focused on other feedstocks (e.g., wood waste or sewage sludge) may be quite appropriate for another type of application now or for application to MSW at some time in the future, after additional testing and development are completed.

*Commercial availability in this case means that process developers could plausibly, in the near term, offer their processes as technically, economically, and environmentally sound alternatives for municipal waste management

a. Initial Screening

The Project Team contacted each of the more than 40 firms identified as possible candidates (Appendix A). Basic process information was requested in the course of this initial conversation (Appendix B). The preliminary process information and the candidate characterization data collected during these calls became the basis for the initial screening to approximately 20 firms. The full list was discussed at a May 1995 project meeting with the project Steering Committee, during which a 20-firm short list was confirmed.

b. Final Screening

The remaining 20 candidates were scrutinized through further telephone interviews, during which additional information was solicited. The evaluation was a critique of the 20 according to the relative likelihood that their processes could be commercially implemented. These factors were considered:

- State of Development
- Technical Issues
- Business Issues

The detailed data received were analyzed in light of these additional screening criteria. The final seven processes were recommended, discussed, and confirmed.

2. Candidate Evaluation Phase

The scope of the detailed evaluation effort for the seven selected technologies was broad. Data for the evaluation were obtained from the developers based on a faxed request (Appendix C) and a detailed questionnaire (Appendix D).

The evaluation included exploration of technical issues affecting basic process feasibility, reliability, worker safety, operability, and maintainability. Environmental issues covered the total emissions profile of the operations. Environmental acceptability is a basic requirement for the viability of any process, and generally, any process can comply with environmental regulations if sufficient resources are assigned to the task. This requirement for environmental acceptability ensures that each process system includes the necessary features, equipment, and staff to achieve 1996 emissions codes. Business issues revolve around the financial and manpower resources of the developers to achieve commercial viability as well as the potential for the process to attract outside investment capital. Since grant funds to construct facilities are not available, the selected firm must demonstrate its ability to carry the new technology through the long and costly steps of finding clients, selling plants or service contracts within a competitive environment, and generating a positive cash flow. An important aspect of the potential for business success is the net cost of operation, including all capital costs, operating expenses, and by-product revenues reflected in a net management fee associated with solid waste disposal.

a. **Technical Issues**

The technical summary and review for each process includes a description of the proposed technology. When provided by the respondent, this description includes a comprehensive process flow diagram, identifying each item of major equipment and its function. The usual measures of performance for mass-burn systems were used for the technologies studied. Such measurements include feed rate [kg/h (lb/h)], steaming rate [expressed as kg steam/kg feed (lb/lb) MSW], electrical generation [kWh/Mg (kWh/t) MSW], and boiler efficiency.

The various key pieces of a system are identified in the flow diagrams and schematics. Standardized nomenclature for chemical reaction, heat transfer, material handling, etc., facilitated comparisons and enhanced communication.

The state of development of each process step was characterized by asking the following questions:

- Which process steps are straightforward and well proved by the developers or elsewhere in conventional solid waste practice?
- Which are innovative and unique to the specific process?
- Which of the innovative or unique steps are critical to the success of the process?
- How many hours of continuous operation have been logged by these emerging system elements?
- What scale-up factor characterizes the ratio between demonstrated and commercial throughput rates?

The proposed requirements of the MSW preparation system were considered for each selected process. A typical, sorted MSW was assumed for all seven technologies studied. The MSW was, of course, sized to the developer's specifications, along with any other process-specific feed preparation requirements. The analysis included MSW handling and preparation steps and feed- and residue-handling steps.

MSW handling is one of the major challenges to successful implementation of any MSW system. Today's mass-burn systems employ combined manual/automatic equipment systems, which rely to a large extent on gravity feed and a mass of MSW as a pressure seal. Equipment includes a pit, a crane and bucket, a chute that provides a seal, and a feeder/stoker. The material in the chute provides a plug to prevent the hot gases from escaping to the atmosphere. This simple strategy is preferred over valves or lock hoppers because it results in continuous MSW feeding. Some batch feed systems use an arrangement of lock hoppers that periodically admit MSW to the combustion process. Such arrangements are usually found in small combustion systems. Many of the technologies studied during this project are in this size range, and they use such lock-hopper feeding systems.

Because most of the gasification technologies require precise control of the air entering the system, tramp air control of the MSW handling and metering subsystems is an important feature. Systems that operate under negative pressure are particularly vulnerable and are subject to process upset if the air is not metered properly. Likewise, systems that operate under positive pressure require special valving and seals to prevent the escape of hot gases. All mass flows entering and leaving the handling and preparation subsystems are accounted for in the mass and energy balances. Handling and preparation systems for operating facilities were carefully evaluated during the site visits.

A detailed heat and mass balance is essential to assess the energy conversion efficiency and to identify the liquid, solid, and gaseous sidestreams that require either additional treatment or disposal. The objective was to construct the balances using a "Reference Refuse" of consistent composition as the starting material—the feedstock for any refuse preparation systems, but not necessarily the feed to the gasifier. However, differences in the methods of analysis among the developers made this goal impossible. The heat balances provided by the developers were carefully reviewed and confirmed by data and calculations. Product gas was characterized by relative heat content (RHC) class:

- Low RHC gas [4 to 12 MJ/Nm^3 (100 to 300 Btu/sft^3)]
- Medium RHC gas [12 to 24 MJ/Nm^3 (300 to 600 Btu/sft^3)]
- High RHC gas [>24 MJ/Nm^3 (>600 Btu/sft^3)].

Typically, the methanation reactions are important in lower-temperature systems, while the reforming reactions are more prominent in high-temperature systems. The reactions that predominate in the gasifier strongly depend on the presence of oxygen, water vapor, or a combination of the two. The team looked particularly at the means provided to control the input of the oxidant. It also focused on the reliability and state of development of the instrumentation and control system and on its effectiveness in achieving maximum gasification efficiency and avoiding upsets.

The basic objective of gasification-based processes is to convert a solid fuel with handling and pollutant-emissions problems into a combustible gas containing the maximum remaining heating value. In many cases, the combustible gas is burned in a gas engine or turbine combustor to generate electricity. Where warranted, heat recovery from the exhaust produces steam; the steam, in turn, is converted to a second quantity of electricity using a conventional steam turbine/generator. The total fuel energy cycle from raw waste to power is thus a reproducible scheme to compare a spectrum of processes.

An important measure of efficiency of a gasification system is the "cold gas efficiency." It is defined as the higher heating value (HHV) of the total gas flow at 15.5 °C (60°F) divided by the HHV of the MSW. Such a process evaluation can be extended to include combustion of the gas with recovery of heat as high-pressure steam and its subsequent conversion to electricity. However, all of the gasification technologies studied where gas clean-up was extensive used the combined-cycle alternative. The "yardstick" of comparison for each evaluated gasification system was thus a mass-burn, waste-to-energy (WTE) plant where the steam is generated at 6.2 MPa (911 lb/in^2-gage)/440°C (830°F) and where power is produced in an optimized, conventional Rankine steam cycle. For the seven technologies studied, the following data were requested:

- Material Balance. A summary material balance was requested that shows the MSW and all other streams entering the waste processing system and the gasification system, as well as the streams leaving the system or consumed internally. The balances were to show the gas product(s); liquid and solid by-products; char and ash; the water leaving with product(s), with ash, or by evaporation; and any plant fuel. An illustration of such a balance, on the basis that the MSW can be characterized by an elemental analysis, is shown in Table 2.1.

In addition to the composition shown in the table, the characteristic variables of pressure, temperature, and flow rates for all the major streams was sought. Each of the seven technologies was characterized by a size parameter—Mg/d (t/d) MSW entering the facility.

Table 2.1 MSW Characterization Parameters

Input	
Oxidant	Air, Oxygen, or Enriched Air
Waste Analysis	C, H, O, N, S, Cl, Ash, Moisture and Heavy Metals (wt%)
Heating Value	MJ/kg (Btu/lb) HHV
Auxiliary Fuel: Waste	MJ/Mg (Btu/t)
Additives: Process Specific	kg/Mg (lb/t)
Output	
Raw Gas Composition	CO, H_2, CO_2, H_2O, N_2, CH_4, C_nH_m, H_2S, COS, NH_3, HCN, HCl, Cl_2, and "Tars" (Vol%)
Residue	kg/Mg (lb/t) waste and its leachability
Wastewater	Volume/mass waste and its treatability (metals, BOD, COD, etc.)
Heating Value	MJ/Nm^3 (Btu/sft^3)

- Energy Balance. The Project Team sought to provide a comprehensive energy balance that shows the total heat release of the MSW entering the system and accounts for the entering MSW and fuel heating values in streams leaving the system. The balance was to show the energy flow associated with the gas product, liquid by-products, char, and export steam or power. Heat losses were to be accounted for by the latent heat of evaporation, stack sensible heat, and radiation losses.

- Plant Thermal Efficiency. The plant thermal efficiency was calculated from the energy balances as the output of the various power and potential fuel product energy divided by the MSW heat input. In most cases the potential fuel product fuel gas is converted to power with add-on systems

- Other Considerations. Minor contaminants and constituents that might seriously affect performance were considered in the evaluation. These contaminants include sulfides, heavy metals, and tars in sidestreams and in scrubber and cooling tower blowdown streams. Some of the minor constituents contain carcinogens as well as biologically active and other potentially dangerous constituents.

Other efficiency parameters such as kWh/Mg (kWh/t) MSW were determined, and comparisons were made between the technology under investigation and a reference mass-burn system. Although such a comparison did not always show a gas-producing technology to best advantage, it served as a consistent and real-world basis of comparison. Systems that generate both power and heat often have higher overall thermal efficiencies than power-only systems because the engine inefficiencies are not accounted for. Evaluation of systems that require elaborate waste preparation subsystems included their power input as part of the overall thermal efficiency calculation.

Another important consideration is the discharge rate of the minor sidestreams and pollutants that are an inherent part of energy release for gasification processes operating with a deficiency of oxygen.

An objective of the evaluation was to view and correlate each thermal processing technology in a consistent manner with MSW feedstock and then to compare inputs, outputs, efficiencies, emissions, side effects, etc. The objective of the overall project, however, was not to pick the "best" process. Defining "best" requires a *client-specific* set of values. The objective was simply to describe the seven very promising processes in a consistent manner.

b. **Environmental Issues**

Environmental issues are recognized as critical to the viability of refuse processes. While air emissions often dominate the "political" assessments of a given process, problems with all effluents and environmental consequences must be resolved as part of the permitting process.

1.) **Regulatory Context**. The new refuse gasification processes and other novel process technologies enter the regulatory arena without the regulatory history that characterizes older, conventional technologies in the existing regulatory structure. Appropriate questions include:

- Is a gasifier a "Municipal Waste Combustor"?
- Is the combustor burning fuel gas from a refuse gasifier a "Municipal Waste Combustor"?
- If the fuel gas contains carcinogens (e.g., benzene), does that make the combustor a "hazardous waste" incinerator?
- Into what category under the Clean Air Act Amendments (CAA) or New Source Performance Standards (NSPS) does a new rocking kiln or gasification-mode fluid bed furnace concept fall?

The answers can profoundly affect costs and acceptance by the public and the regulators.

2.) **Data Sought.** Process developers provided data or correlations concerning the uncontrolled and controlled air effluents, water effluents, solid and sludge residues, and any sidestreams. Data concerning effluents that are of interest include:

- Mass rate
- Chemical composition
- Relationship to the feed stream, such as the observation that "X" pounds of pollutant "Y" are formed for each ton of refuse processed
- Treatability, such as the BOD and COD and biodegradation or other treatment technology characteristics of wastewater streams
- Prospective environmental impact, such as "very low" or "nil" for heavy metals trapped in a glassy slag
- Preferred or tested control technologies—what has been tested and with what results?

3.) **Data Presentation in Process Evaluations.** The environmental data are summarized and presented in tables that present the emissions measured in existing pilot plant facilities (where available). The data include:

- Uncorrected concentration rates (e.g., concentration per unit volume of flue gas or wastewater as emitted)
- Corrected concentration rates (e.g., concentration per unit volume of flue gas corrected to a dry basis and to a 7% oxygen concentration).
- Comparison with NSPS or current regulatory limits.

c. **Business Issues**

Similar to the evaluation in the screening process, issues relating to commercialization and implementation were evaluated to a limited degree. Issues explored included:

- Is the commercialization effort likely to bear fruit?
- Did the developer appear to understand the marketplace and acceptable cost and business relationships?
- Did the developer appear to understand the Federal and State regulatory and permitting requirements?
- Did the developer appear to have sufficient internal or outside funds?

d. **Cost/Economics Issues**

Although technical considerations in the analysis of the selected candidates are important, the evaluation eventually narrows to an issue of costs. If the technology is feasible, is it economically acceptable? Although they may be less innovative, are any of the proposed technologies economically more attractive than others? Are any of the candidates at such a primitive level of development that the cost of commercial-scale application is difficult to estimate with any degree of confidence? And, finally, what are the scale-up factors needed to reach full-scale application from the pilot stage?

1.) **Capital Costs**. Capital costs are recognized as still-evolving processes that cannot be established with any degree of confidence. However, estimates from the developers, adjusted to reflect Project Team experience and to provide a "level playing field" for similar process steps, provide a consistent, if approximate, cost picture. Cost elements included:

- *Additional Development Costs.* Present-day costs and costs at the point of design and guarantee for the first commercial plant include future equipment, process and other experimentation, construction of pilot plant and other test facilities, cost of sales, and other business development.

- *Projected Scale-Up Factor*: Rather than assume a range of design capacities to determine its costs, the analysis was limited to a practical plant size for the specific system under consideration.

- *Range of Ancillary Equipment Needed.* This category encompassed bag openers, feeders, gas cleaning equipment, the required size of building, etc. The capital cost of the RDF facilities and the facilities used to convert fuel gas or steam to electricity were developed for all seven technologies using cost curves generated by the Project Team (Figure 2.1 and Figure 2.2).

- *Facility Envelope.* Costs were evaluated at the delivery point of the gas-producing facility (i.e., in the form of product gas, electric power or steam but exclusive of any capital and operating costs borne by the ultimate user).

- *Time Lapse to Commercial Acceptance.* The time needed to ready the design for commercial application was estimated.

- *Modifications Needed To Reach Full-Scale Application.* In part, such modifications are waste- and residue-handling systems, materials of construction for the process vessel, needed gas-cleaning equipment, and control and instrumentation systems.

The developer's prototype costs as well as his estimates of full-scale costs were the starting point for capital cost estimates. The Team also drew heavily on its professional experience, vendor quotations, and other cost data to arrive at realistic capitalization estimates for the overall facility.

2.) **Operating Costs.** Resolution of the issues listed previously established the design of the facilities, their size, and their complexity. From this process scenario, manpower to operate the system was estimated and utility consumption and maintenance costs were projected. The cost analysis drew heavily on the Project Team's experience with many waste-to-energy facilities to resolve these cost elements into a fair and realistic estimate of net operating cost. As for the capital cost, operating costs associated with RDF preparation and energy conversion were developed as cost curves (Figures 2.3 and 2.4). The conversion analysis included a curve predicting the gross annual electrical generation

(MWh/y) for combustible gas burned in either a gas engine or combined-cycle gas turbine and for a steam Rankine cycle as a function of hourly energy flux (as gas HHV or steam enthalpy), as shown in Figure 2.5. Cost data provided by the developers, such as developer-based labor, chemical use, power use, etc., were used.

To achieve the closest possible comparison, processes developing a fuel intermediate were assessed for capital and operating costs to the point of generation of the basic energy product. Then the costs for energy conversion to steam and to electricity were applied to produce the net cost for solid waste management on a $/unit mass basis.

3.) **RDF Preparation and Energy Conversion Costs.** This portion of the investigation focused on thermal processing elements—the unique combustion or gasification step that distinguishes the several processes investigated. In general, the technology developers also direct their interests and energies toward the thermal processing element of the process. For that reason, a set of common cost curves was prepared to link the capital and operating costs for MSW preparation to a 10-cm (4-in.) top size and to conversion of either a fuel gas or steam to electricity in a stand-alone electricity-generating plant. In cases where a fuel gas is generated, the gas could also be marketed "over the fence" as a fuel for industrial or power plant boilers.

(a.) **RDF Processing Facility**

System Description. For many of the thermal processing systems evaluated, feedstock waste must be preprocessed into a 10-cm (4-in.) top-size fluff. Therefore, a conventional RDF processing facility prepares the solid waste material before it is subjected to the thermal processes. The proposed RDF processing facility consists of the following components:

- Refuse Receiving and Storage Area
- RDF Processing Area
- RDF Storage Area
- Building.

The refuse receiving and storage area receives refuse deliveries and temporarily stores the raw waste before processing. The layout of the receiving and storage area is designed to accommodate packer, roll-off, and transfer trailer vehicles. Refuse vehicles enter the totally enclosed receiving building and tip their loads directly onto the tipping floor. A front-end loader stockpiles the waste before it is processed. Concrete push-walls facilitate stockpiling. Storage of raw refuse for 3 days is incorporated into the design. This storage capacity provides a degree of flexibility during periods of high refuse deliveries and allows continued operation during periods when deliveries are not received (e.g., holidays).

The RDF processing equipment is housed in a separate processing area. Two, independent processing lines are proposed, each sized to handle 50 percent of the design throughput in 16 hours. Two lines are recommended to permit a degree of flexibility in the event that one line needs to be shut down unexpectedly for maintenance. Each processing line includes a shredder, ferrous magnet, screen/trommel, and a series of belt conveyors.

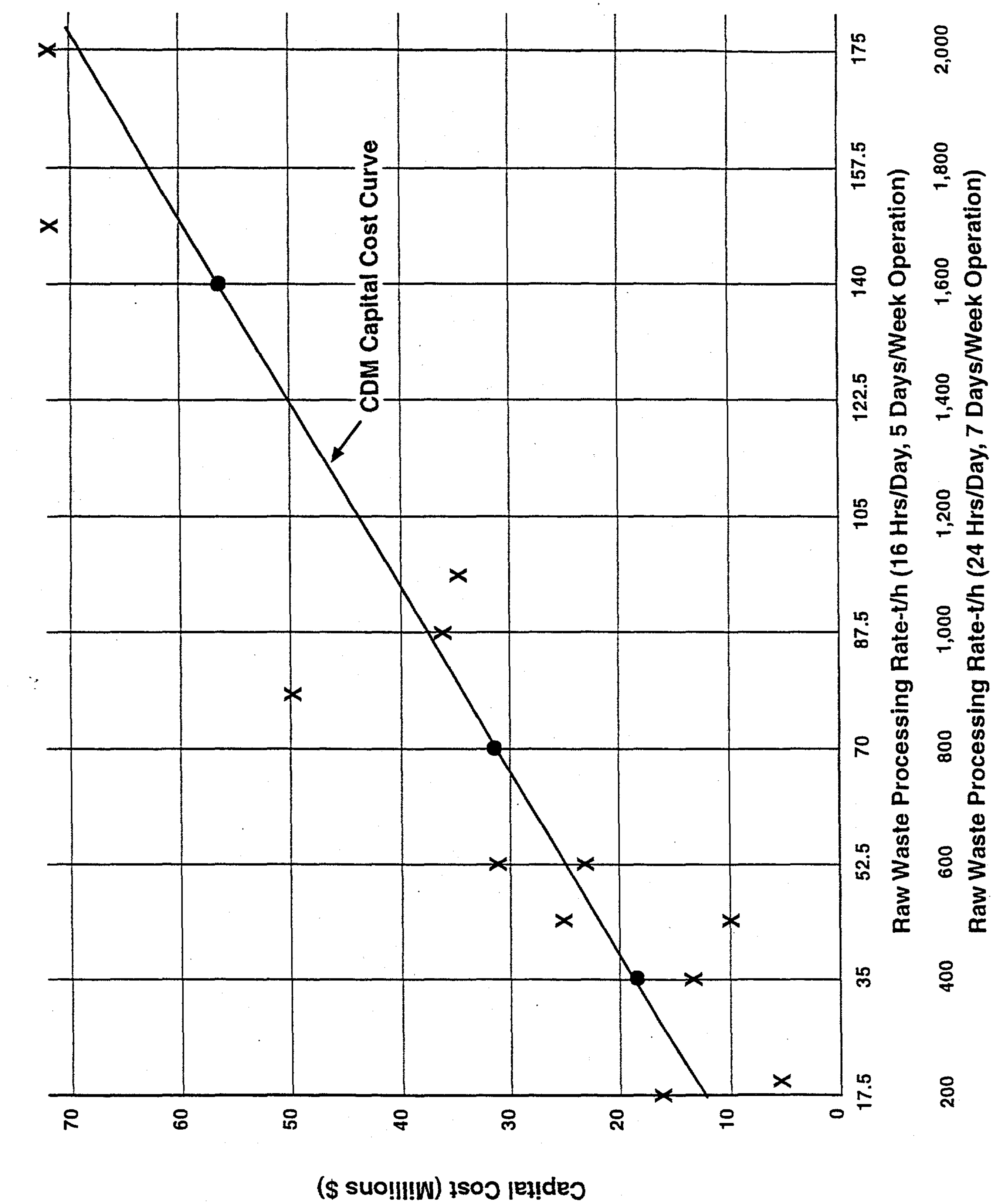

Figure 2-1
RDF Processing Facility
Capital Cost Correlation

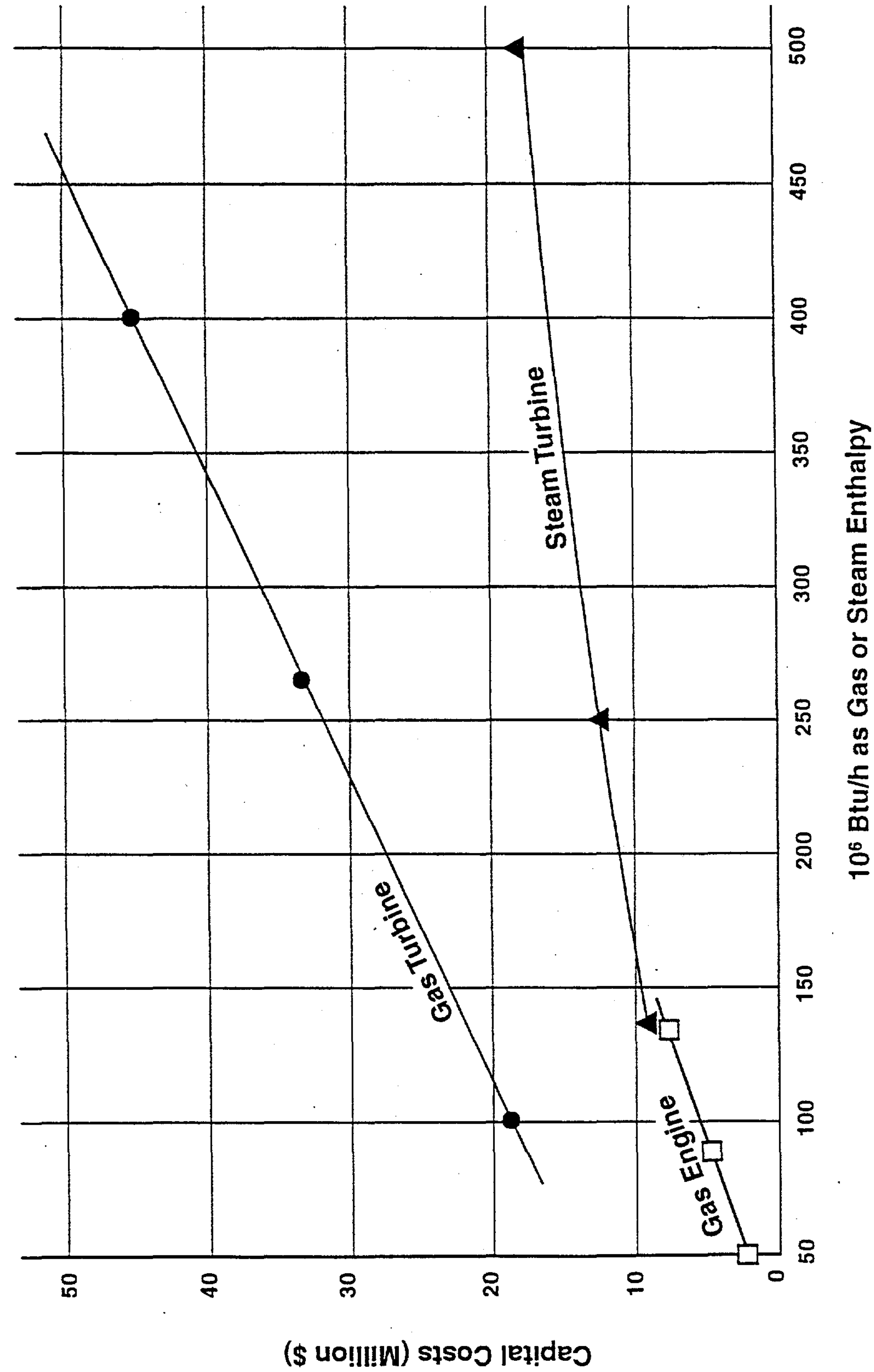

Figure 2-2
RDF Processing Facility Operating Costs

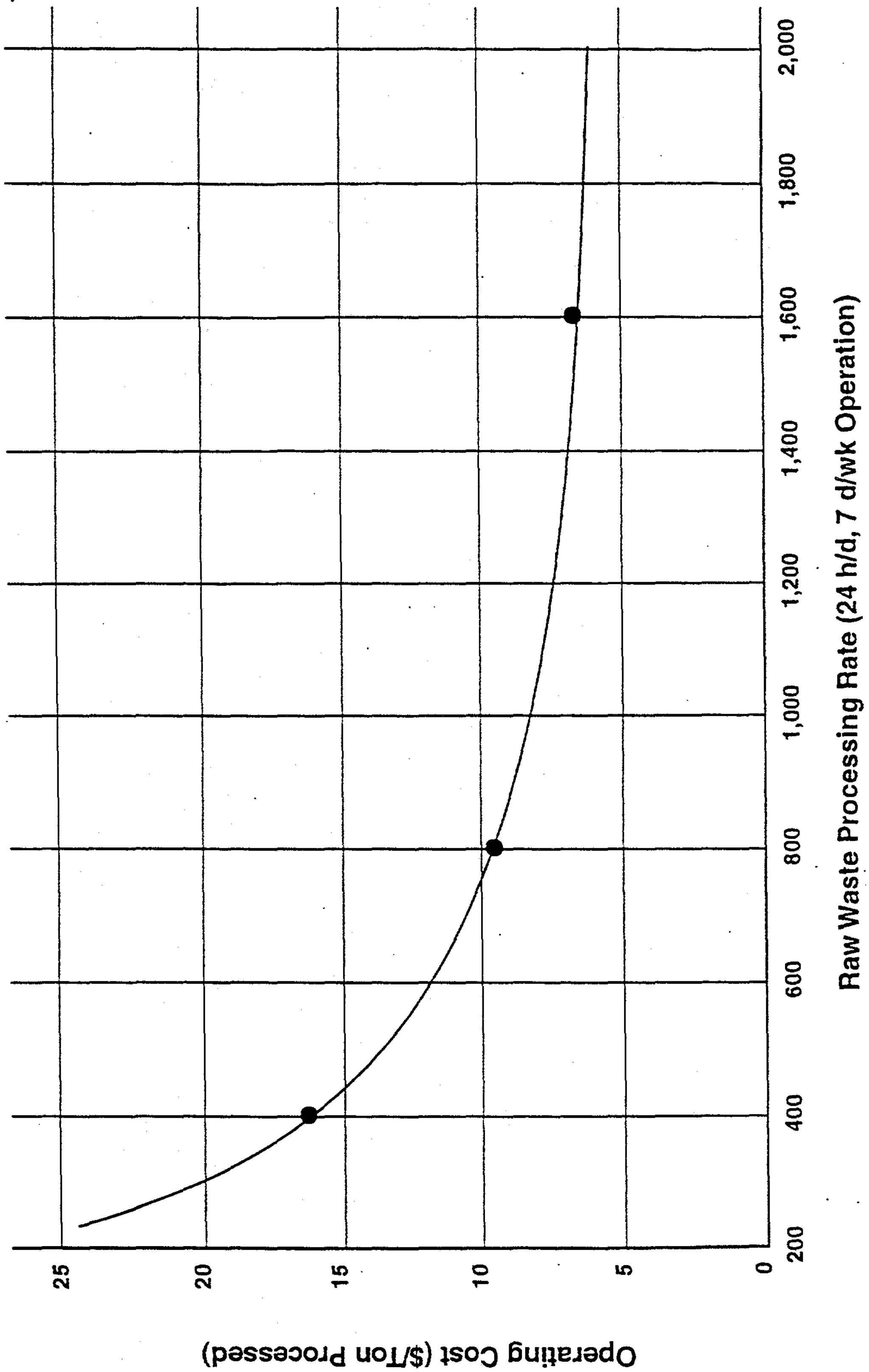

Figure 2-3
Power Generation System Capital Costs

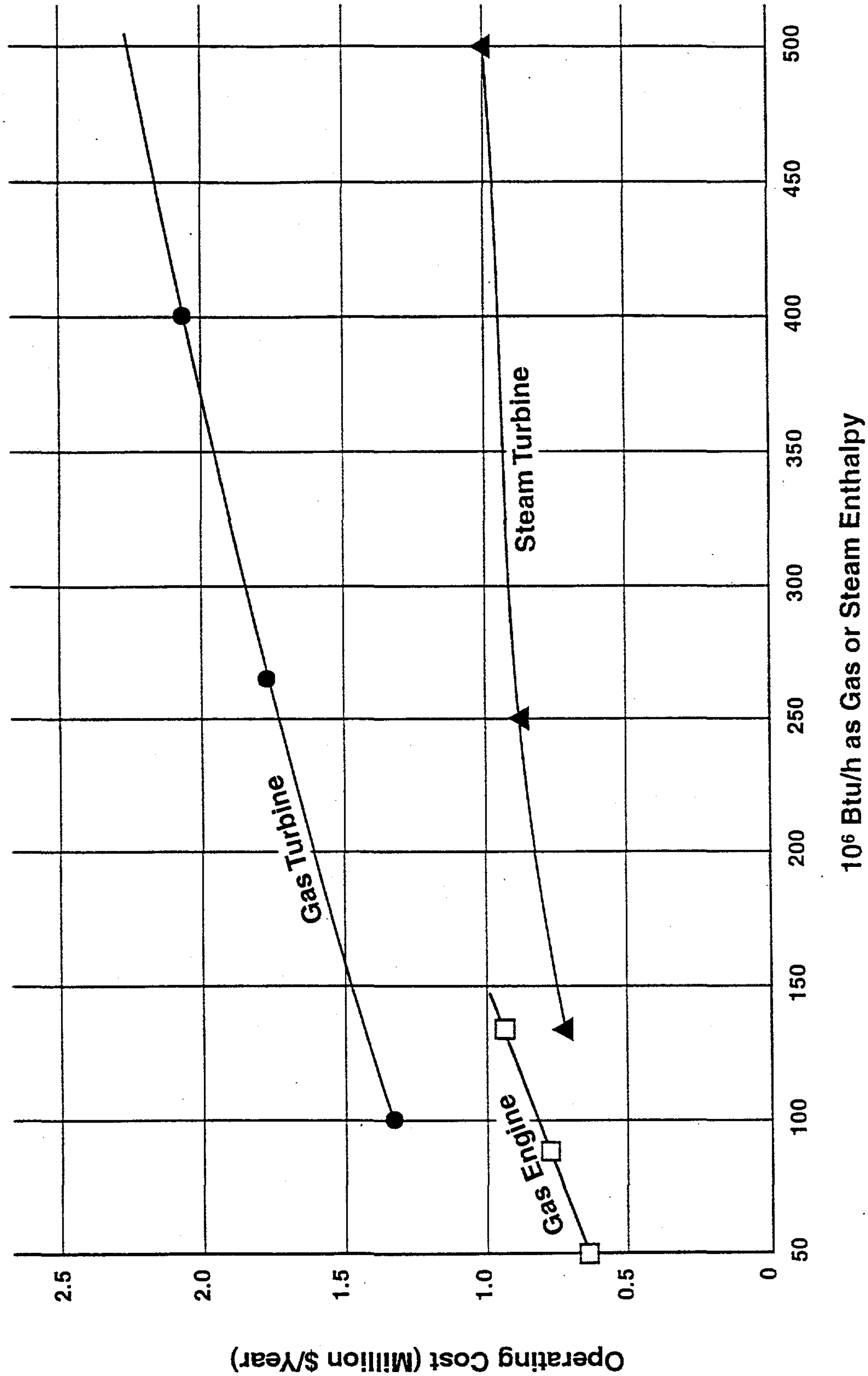

Figure 2-4
Power Generation System Operating Costs

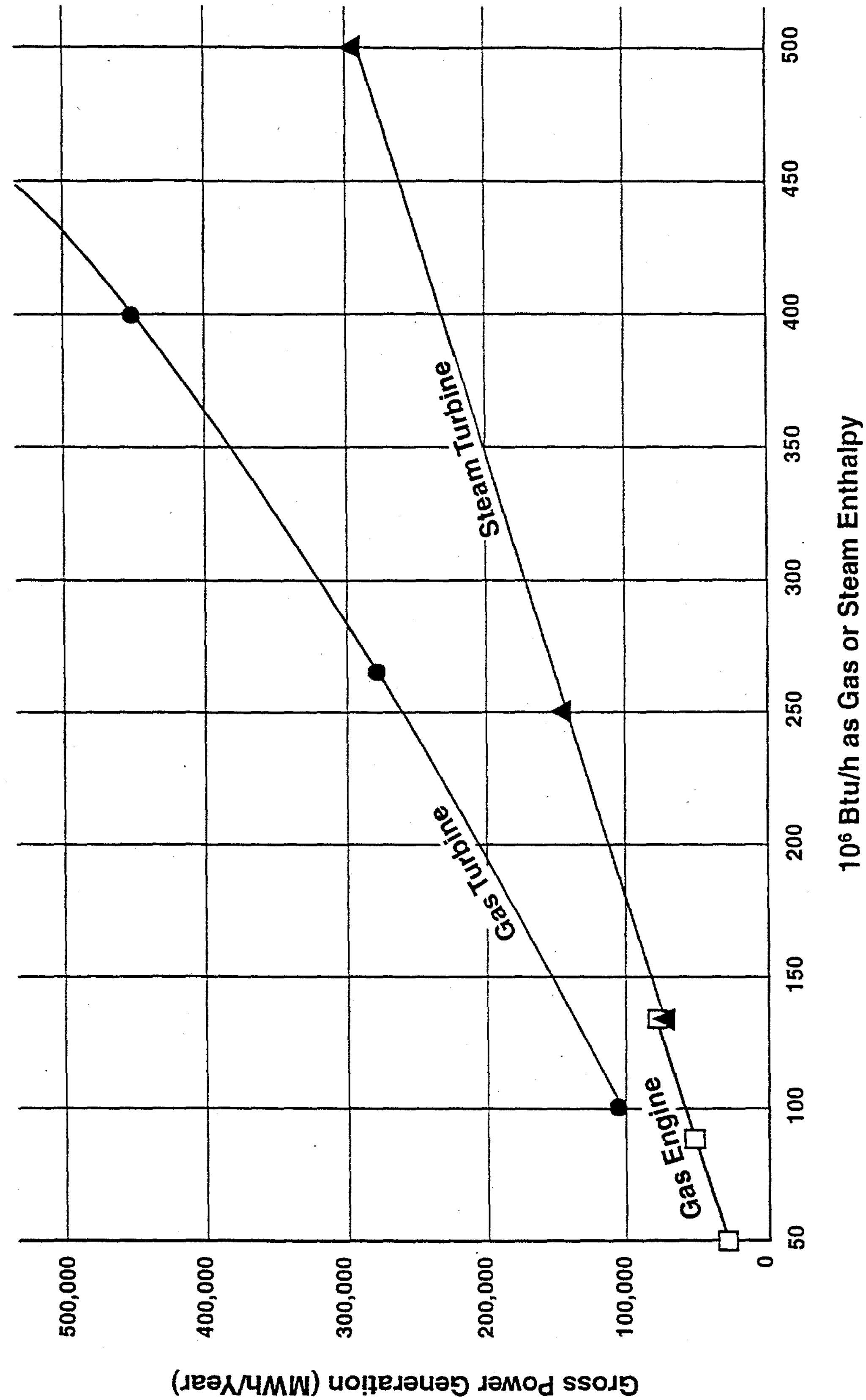

Figure 2-5
Gross Power Generation

The final product consists of a 10-cm (4-in.) nominal size fluff material free of glass, dirt and other fines, and ferrous metals. A front-end loader stacks the RDF fluff material and feeds the in-feed conveyors to the thermal processing system. The processing lines operate on a two-shift/day, 5-day/week basis. The hourly capacity of the processing equipment is greater than that of the thermal treatment system, which operates on a 24-hour/day, 7-day/week basis. Equipment maintenance is performed on the "off" shift or on weekends.

The RDF fluff material discharged from the processing lines is stockpiled on the floor in a dedicated storage area. The RDF storage area contains sufficient volume to store 3 days of material, permitting the thermal processing system to continue to operate over weekends and during holiday periods.

Capital Cost Estimates. The estimated capital costs for RDF processing facilities (Figure 2.1) are expressed as a function of both the "design" raw waste received and its processing rate and the "design" thermal processing rate. Investment estimates in terms of raw MSW for 18 dedicated and stand-alone RDF preparation facilities are plotted in Figure 2.1 against the cost correlation. The abscissa scale reflects operation in terms of raw waste passing through the processing system for 16 hours/day, 5 days/week and the thermal processing system for 24 hours/day, 7 days/week. The capital cost estimates include the equipment and building components listed earlier. Allowances of 10 and 20 percent were included for engineering and contingency respectively. No allowance was included for property costs.

Operating Cost Estimates. Operating costs estimates for RDF processing facilities, (Figure 2.3) are expressed as a function of the raw waste thermal processing rate. They include labor, utilities, maintenance, and insurance. Labor costs include regular time plus a 10-percent overtime allowance. Utility costs include electricity for lighting and equipment operation, as well as natural gas for building heating. Maintenance costs include annual allowances of 3 percent of equipment costs and 1 percent of building costs for equipment and building repair respectively. Insurance costs are based on 1 percent of the equipment and building costs.

(b.) Energy Conversion Alternatives

Energy Forms. Each of the thermal processes recover energy from the waste. If the waste material is in a solid form, nominally 10 cm (4 in.) or longer, it can be burned on a grate or in a fluidized bed. The systems in this study that burn waste in fluidized beds recover energy in a Rankine cycle—a boiler generating steam combined with a steam turbine and electric generator. If the waste material is converted to a gas, then the gas can be recovered in a combined cycle, a gas engine or turbine, and a heat-recovery steam generator combined with a steam turbine and electric generator. In a gas engine, the heat exchanger fluid is hot water from cooling the engine. The heated water generates low-pressure steam for heating or process purposes. Gas engines are now made in capacities up to 20 MW. With a gas turbine, the exhaust temperature is high enough to consider generating high-pressure steam. Thus power can be generated in both the gas turbine and the steam turbine. Gas turbines are now available in capacities as low as 2 kW. For this study a capacity of 10 MW was chosen as the general breakpoint—gas engines for less than 10 MW and turbines for more than 10 MW. Raw waste can be used as a direct feed in a mass-burn system in a Rankine cycle. This approach has been the system of choice for the last three decades.

Steam Turbine Generator Facility. The steam turbine generator facility consists of a common, condensing steam turbine coupled with a generator. Ancillary systems include steam condensers, surface and dump; cooling tower; electrical switchgear; piping and instrumentation; and controls. All of the equipment, with the exception of the cooling tower, is enclosed in a two-level building. The turbine is on the upper level, or deck, and the condensers and other ancillary systems are on the lower level. The cooling tower is outdoors.

Steam from each thermal treatment processing line is combined in a main steam header and piped directly to the steam turbine. The turbine is coupled to a generator. Exhaust steam from the turbine is condensed in a surface condenser. Heat removed in the condenser is dissipated to the atmosphere using an evaporative cooling tower. The condensate from the wet-well of the condenser is recirculated to the thermal treatment process boiler feedwater system. The dump condenser is a means to condense the high-pressure steam if the turbine generator is unavailable because of maintenance.

Gas Engine Generator Facility. The gas engine generator facility consists of multiple gas engines and generator sets. Ancillary systems include instrumentation and controls, piping, and electrical switchgear. All equipment is enclosed in a single-story preengineered building.

Low-heat-content gas from each thermal treatment processing line combines in a main gas line and is burned in gas-fired internal combustion engines. The gas engines are compression-ignition engines using auxiliary fuel, or they are spark ignited to enhance combustion in the event of low gas quality. Each gas engine is outfitted with a generator set.

Gas Turbine Generator Facility. The gas turbine generator facility consists of a combined-cycle gas-fired turbine generator as the primary power generation equipment, with secondary power generation from a waste-heat boiler to recover heat from the turbine exhaust , and a steam turbine generator. Ancillary systems include surface and dump condensers, a cooling tower, boiler feedwater treatment, instrumentation and controls, piping, and electrical switchgear. All the equipment, with the exception of the cooling tower, is housed inside a two-level building. The cooling tower is outdoors.

Low-heat-content gas from each thermal treatment processing line is combined in a main gas line and burned in a gas-fired turbine. The gas turbine is connected directly to a generator. Waste heat in the turbine exhaust generates high-pressure steam in a heat-recovery steam generator. The high-pressure steam is directed to a steam turbine coupled to a generator. Exhaust steam from the turbine is condensed in a surface condenser. Heat removed in the condenser is dissipated to the atmosphere in an evaporative cooling tower. A bypass condenser is available to directly condense the steam generated in the waste-heat boiler when the steam turbine generator is off line for maintenance. Condensate from the condensers is recirculated to the boiler feedwater treatment system.

Capital Cost Estimates. The estimated capital cost for the alternative power generation schemes is presented in Figure 2.2. Capital costs are expressed as a function of the gross heat input (10^6 Btu/h), measured as gas fuel value or steam enthalpy, depending upon the process under evaluation. The capital cost estimates include the equipment and building components described earlier. Allowances of 10 and 20 percent are included for engineering and contingency respectively. No allowance has been made for property costs.

Operating Cost Estimates. Operating cost estimates for each power generation alternative are presented in Figure 2.4. Operating costs are expressed as a function of the gross heat input (10^6 Btu/h), measured as gas or steam enthalpy. The operating costs include labor, maintenance, and insurance. Maintenance costs were estimated at 3 percent of the equipment capital cost plus 1 percent of the building cost. Insurance costs were estimated at 1 percent of the total equipment and building costs.

Power Generation Estimates. Gross power generation estimates for each alternative are presented in Figure 2.5. Gross power generation (MWh/y) is expressed as a function of the gross heat input (10^6 Btu/h), measured as gas heat content or steam enthalpy.

e. **Operating Issues**

Because MSW is a bulky, biologically unstable material, the reliability and continuity of disposal/processing operations are essential features of useful processing technologies. Highly skilled and attentive operators, along with intensive maintenance, are important issues affecting both cost and system availability.

1.) **Data Collected.** Information collected regarding operation included numerical data, anecdotal information solicited from process development personnel, and engineering judgments made by the inspection team in the course of reviews and inspection visits. The information and perspectives include:

- Operator and maintenance staff skill requirements
- Sensitivity of the process to changes in waste characteristics
- Operating experience (on-line hours in 24-hour, 7-day service at rated capacity), to include frequency and severity of outages, nature of the problems precipitating shutdowns, and plans to resolve the problems, if they still persist
- Operating and maintenance staff requirements as a function of facility throughput.

2.) **Data Presentation in Process Evaluations.** A portion of the information collected under this category is reported in the technical discussion of the process—particularly in discussions concerning remaining areas for process development and problem solving. Staffing requirements are summarized in a table as a function of facility throughput. The staffing data and characterizations of needed staff skills, which affect hourly labor cost, are incorporated into the operating cost analysis. Reliability issues, if the Project Team believed they could not be solved, are incorporated into the cost analysis on the basis of their impact on the annual throughput and selection of the facility installed capacity needed to meet a given waste management requirement.

f. **Implementation Issues**

This portion of the process presentation summarizes technical, regulatory, financial, and business issues and any other issues that might help or hinder the commercialization process. All of the seven candidates were close to commercialization. However, with the exception of EPI, most will need further equipment development, confirmation of process control concepts, scale-up of key unit operations, or other refinement/development steps. These steps must be successful before the developer firm and its financial partners are prepared to accept the responsibility for a commercial waste management contract. Realistic assessment of these implementation issues provides a clear checklist of the problems and uncertainties that must be resolved before committing to the technology.

3. Regulatory Aspects of the Gasification and Novel Thermal Technology

Environmental regulations have become the most important force shaping the physical and economic character of waste processing and disposal facilities. Regulations may mandate process features or force add-on facilities before permits to construct, and subsequently to operate, are issued. These restrictions have a direct impact on capital and operating costs, and they often have consequences regarding such items as layout, reliability, and the design features of instrumentation and control systems.

All of the processes evaluated in this project involve an energy product or a chemical feedstock product for use by others. If the permitting process is extended to the prospective users of process fuels, steam, or chemical feedstocks derived from refuse, there could be a significant delay in market penetration by these emerging technologies. A user of fuel could be embroiled in a complex, costly, and highly public permitting process. Naturally, there is usually a level of market resistance bred of uncertainty about the performance and reliability of new processes. However, if the purchase makes the buyer seek a permit as a municipal waste combustor, such resistance will probably be enhanced.

There is an argument, however, that says that the refuse thermal processing system is a *manufacturing process* that is making a *product*—a fuel gas or synthesis gas. In that case, the identity of the original feedstock is substantially lost in the process, and the emissions and permitting requirements for gas users should be based on documented emissions of *specification* gas in boilers equipped with the burner type, excess air level, and other combustor features—*not* on use as a municipal waste combustor (MWC). The validity of this argument will only be known when a specific permit application is placed before a State or Federal agency.

a. Meeting With EPA Office of Air Quality Planning and Standards

As a first step and to gain input for the project, the Project Team, the Department of Energy and NREL, and the EPA Office of Air Quality Planning and Standards (OAQPS) met in Research Triangle Park, North Carolina. The objective of the meeting was to discuss the position that EPA might take when considering the seven new thermal processing and gasification processes being reviewed. This is a specific example of the situation for any new process where there is no regulatory history and little, if any, emissions data from commercial-scale plants.

The results of the discussion are an indication of the direction EPA might take when considering commercial-scale installation of the technologies reviewed in this report. They are *not* reported as a final policy decision by the EPA. Their position appeared clear. The Agency retains the linkage between the feedstock and the permit requirements until data and clear, replicable performance indicate that a new source category has emerged. In the near term, users of a fuel gas that involves combustion must meet all requirements for a *Municipal Waste Combustor,* with evaluation on a case-by-case basis for any specific new installation.

If the new technologies are permitted as MWCs, they would fall under Section 129 of the 1990 Clean Air Act (CAA) Amendments. In the special case of co-fired plants where MSW is less than 30 percent or less of the total weight fired, Section 129 exempts the system from the MWC provisions summarized in Table 2.2.

Most likely, any MWC systems will be required to meet the Good Combustion Practices requirements for MWCs (Table 2.3), although the proper category is often uncertain. Emissions limits for air toxics will probably be at least as stringent as the NSPS for MWCs (Table 2.4).

b. **Ongoing Regulatory Activity (Winter 1995-1996)**

The Innovative Technology Program of the Texas Natural Resources Conservation Commission (TNRCC) is exploring the regulatory issues surrounding the burning of synthesis gas made using a gasification technology applied to biomass. There are several synthesis gas users in the Houston Ship Channel area. In some of these industries, the gas is generated from wastes (some hazardous in nature) but meets definitive specifications regarding its higher hydrocarbon content, chlorine and sulfur content, etc. This gas is normally pumped into the "synthesis gas header" at the facility. Primarily, the gas is used as the starting point in making various petrochemicals, methanol, etc. To a varying degree, a portion of the gas flow is diverted to use in process heaters and boilers. This raises the question: "Is the ultimate combustor an incinerator or just a combustor with a known fuel and with known emissions characteristics?". The exchange of memoranda between the TNRCC and EPA's Clean Air Act Rule Interpretation Office in Washington DC has continued since November 1995. EPA's initial conclusion that the emissions should be considered as though they had been generated in a "BIF" source—a boiler or industrial furnace burning hazardous waste and thus treated as a Resource Conservation and Recovery Act (RCRA) facility—is being challenged. This preliminary finding parallels the counsel given in the OAQPS meeting described earlier. The outcome of the TNRCC/EPA dialogue is important, however, since it is a "real case" that could have a direct impact on the permitting requirements for municipal waste gasifiers.

c. **Residue Regulations**

Recent U.S. Supreme Court decisions have clarified the status of the solid residues from MSW thermal processes. They are regarded as waste streams that may or may not require the special disposal measures taken for a hazardous waste, as determined by Toxicity Characteristics Leaching Procedure (TCLP) testing. In most cases, residues from MWC systems and the gasification and combustion technologies studied during this project pass such tests—particularly residues from the Proler International and Thermoselect Inc. processes, which are inherently vitrified in the process..

Table 2.2 Basis for Maximum Achievable Control Technology (MACT) Performance Performance Requirements—Municipal Waste Combustors*
(40CFR Part 60, *Federal Register*, December 19, 1995)

Final Requirements		Basis for Emissions Limits†
Emissions Guidelines (EG)—Existing Plants		
Small:	>35 to 225 Mg/d (>38.5 to 247.5 t/d)	GCP + DSI + ESP + CI
Large:	>225 Mg/d (>247.5 t/d)	GCP + SD/ESP (or SD/FF) + CI + SNCR§
New Source Performance Standards (NSPS)—New Plants		
Small:	>35 to 225 Mg/d (>38.5 to 247.5 t/d)	GCP + SD/FF + CI
Large:	>225 Mg/d (>247.5 t/d)	GCP + SD/FF + CI + SNCR

* Technologies providing equivalent or better performance may also be used.

† GCP = Good Combustion Practice

ESP = Electrostatic Precipitator

DI = Dry Injection of Sorbent (FSI = Furnace Sorbent Injection and DSI = Duct Sorbent Injection)

CI = Carbon Injection

SD/ESP = Lime Spray Dryer Absorber and ESP

SD/FF = Lime Spray Dryer Absorber and Fabric Filter Baghouse

SNCR = Selective Noncatalytic Reduction

§ No NO_x Control Requirements for small MWC plants or large, existing mass-burn refractory combustors.

Table 2.3 Good Combustion Practice Requirements for MWCs (40CFR Part 60, *Federal Register*, December 19, 1995)

1. Requirements				
	CO Emissions Limits			
Type of Combustor	EG Limit,* ppm	Average Time, h	NSPS Limit, ppm	Average Time, h
Mass-Burn Waterwall (MBWW)	100	4	100	4
Mass-Burn Refractory Wall (MBRW)	100	4	100	4
Mass-Burn Rotary Waterwall (RWW)	250	24	100	24
Mass-Burn Rotary-Wall Refractory (RWR)	100	24	100	4
Refuse-Derived Fuel Stokers (RDF)	200	24	150	24
Fluidized Bed Combustors (FBC)	100	4	100	4
Modular Combustion Units (MCU)	50	4	50	4
Coal/RDF Mixed Fuel-Fired				
— Spreader/Stokers (Coal-RDF/SS)	250	24	150	24
— Pulverized Coal (Coal-RDF/PC)	150	4	150	4
2. Load not to exceed maximum load demonstrated during most recent PCDD/PCDF compliance tests.				
3. Particulate matter control device inlet temperature not to exceed 17°C (31°F) above the maximum temperature demonstrated during most recent PCDD/PCDF compliance tests.				
4. Chief facility operator, shift supervisors, and control room operators must meet training and certification requirements.				

* EG = Emissions Guidelines

Table 2.4 Emissions Limits for Municipal Waste Combustors*
(40CFR Part 60, *Federal Register*, December 19, 1995)

Pollutant Measurement	Guideline Limits —Existing Plants (or Percentage Reduction)		NSPS Limits—New Plant (or Percentage Reduction)
	Small >35 to 225 Mg/d (38.5 to 247.5 t/d)	Large >225 Mg/d (247.5 t/d)	Large and Small ≥35 Mg/d (≥38.5 t/d)
PCDD/PCDF, ng/dscm^3 [ ]†	125 [30]	60§ [15]	13 [17]
Particulate Matter, mg/dscm^3	69	27	15
Opacity¶,%	10	10	10
Cd, mg/dscm^3	0.10	0.04	0.01
Pb, mg/dscm^3	1.6	0.50	0.10
Hg, mg/dscm^3	0.08 (85)	0.08 (85)	0.08 (85)
HCl, ppm(v)	250 (50)	35 (95)	25 (95)
SO_2, ppm(v)**	80 (50)	35 (75)	30 (80)
NO_x, ppm(v)**	None	200-250¶,**	150¶,§§

* All emissions corrected to 7-percent 0_2.

† Average of three stack tests using EPA Method 23. Values are weight of total tetra-through octa-cogeners. Values in brackets for [emissions limits to qualify for less frequent testing].

§ Emissions limit for ESP-based air pollution control systems. Systems not ESP-based must comply with a 30 ng/dscm^3 limit or the "less frequent testing" requirement.

¶ EPA Method 9. Limit for 6-minute averages.

** 24-hour averaging time.

†† 200 ppm(v) for MBWW, 250 ppm(v) for RWW, 250 ppm(v) for RDF, 240 ppm(v) for FBC, no NO_x control requirement for MBRW, and 200 ppm(v) for others.

§§ Applies to large plants only; 150 ppm(v), except 180 ppm(v) is allowed for the first year of operation.

4. Background Assumptions in Evaluations

It is not the purpose of this report to compare technologies. Inevitably, comparisons incorporate the value system of the evaluators, their organizations, or both, and these comparisons are necessarily tied to a particular or local set of needs and priorities. There is value, however, in clustering many of the quantitative descriptions of the processes, especially the costs, around general norms for facility throughput, etc., and in using a consistent set of values or unit costs for input waste characteristics, labor, fuel, capital, etc.

a. Solid Waste Quantities and Characteristics

In the evaluation of processes, all the "Reference Waste" compositions and properties used by the developers were different. There was reluctance on their part to recalculate, redesign, or otherwise generate new systems to match a standard waste composition proposed by the Project Team. Thus the characteristics of the raw MSW and RDF considered in the technical and economic analyses differ slightly from process to process.

b. Furnace and Facility Capacities

Capital and operating costs are important characteristics of solid waste processing facilities. Because of factors such as the economy of scale or the effect of labor efficiency in larger facilities, cost comparisons vary with design and with actual throughput rate. Some of the technologies reviewed are tied to the low throughput rates of individual furnaces. These low rates may reflect actual process limitations or the predisposition of the developer at the time of this study. In any event, not all processes could be scaled to a common furnace size and facility throughput.

c. Unit Costs and Economic Factors

Table 2.5 shows unit costs and cost relationships. To keep a uniform basis of evaluation, the unit costs were used where possible for operating cost evaluations.

Table 2.5 Unit Costs and Costing Relationships

Labor (Fully Burdened)	$/h	
Supervisor/Plant Manager	45.00	
Senior Operator	32.00	
Senior Maintenance	35.00r	
Operator	30.00	
Laborer	25.00	
Materials/Services	**Metric Units**	**English Units**
Fuel (Natural Gas)	$\$3.79 \times 10^{-3}$ /MJ	$\$4.00/10^6$ Btu
Process Water (potable)	$\$0.47/m^3$	$1.80/1000 gal
Wastewater Treatment	$\$0.57/m^3$	$2.15/1000 gal
Lime (100% active CaO)	$93.50/Mg	$85.00/t
Limestone	$33.00/Mg	$30.00/t
Liquid Ammonia (100%)	$310.20/Mg	$282.00/t
Activated Carbon	$1,100.00/Mg	$1,000.00/t
Liquid Oxygen (merchant, delivered)	$42.50/Mg	$38.66/t
Liquid Nitrogen (merchant, delivered)	$38.50/Mg	$35.00/t
Bypass Waste Landfill Disposal	$44.00/Mg	$40.00/t
Electricity (Purchase or Revenue)	---	$0.04/kWh
Other Cost Categories	**Calculations**	
Financing Interest Structure	8.0%, 20 years (CRF=10.19%)	
Maintenance (annual charges)	3.0% of Capital (unless data available)	
Insurance (annual charge)	1.0% of Capital	

Note: Mg = Megagram (metric ton), CRF = Capital Recovery Factor.

Section 3

ENERGY PRODUCTS OF IDAHO (EPI)

A. SUMMARY

EPI is a limited partnership with headquarters in Coeur d'Alene, Idaho. The company was formed in 1973 as Energy Products of Idaho. Idaho Energy Limited Partnership purchased the assets, technology, and business lines of EPI in July of 1994. EPI's basic business is involved with the design and fabrication of fluid bed combustion systems. Although their corporate experience favors the full-combustion mode for their systems, they have pilot plant and commercial plant experience (three commercial furnaces) in a "starved-air," gasification mode.

The EPI full-combustion system uses a bubbling-type fluid bed concept, accepting a prepared 10-cm (4-in.) top size, refuse-derived fuel (RDF). Within the bed, the RDF particles are exposed to a vigorously turbulent hot environment that promotes rapid drying, gasification, and char burnout. EPI proprietary design features in the bed provide for the continuous removal of oversized nonburnables. The hot gases arising from the bed pass through a waste-heat boiler to generate high-pressure, superheated steam for electricity generation or, potentially, for process applications.

EPI has four full-scale combustion furnaces in the U.S., with their first plant having started up in 1981. The plants have shown reliability in excess of 85 percent, full compliance with environmental emissions limits, and good operability and maintainability characteristics.

B. FINANCIAL AND BUSINESS ASPECTS

1. Projected Capital and Operating Cost

The capital cost of a total EPI system burning prepared 10-cm (4-in.) RDF and generating electricity is shown in Table 3.1. The twin-furnace plant receives 782-Mg/d (860-t/d) raw waste that it processes to 545-Mg/ d (600-t/d) RDF. Combustion takes place in two 273-Mg/d (300-t/d) EPI fluid beds. Limestone is injected into the bed to absorb SO_2. Carbon and a lime slurry are added downstream of the boiler at the entrance to a spray-dryer/absorber. Particulates are controlled with a fabric filter. Steam from the boiler is converted to electricity with a conventional, condensing steam turbine-generator (Rankine cycle).

Table 3.2 presents operating cost estimates for such a plant. The net cost is $52.71/Mg ($47.85/t). No credits have been assumed for any recovered materials.

Table 3.1 Capital Cost: Energy Products of Idaho Thermal Processing System

System:	782 Mg/d (860 t/d) MSW 545 Mg/d (600 t/d) RDF Two Bubbling-Bed Fluid Bed Furnace/Boiler Systems		
Air Pollution Control (APC):	Bed addition of limestone (SO_2 control) NO_x control via ammonia injection into boiler (SNCR) Carbon injection in dry scrubber Lime slurry injection in dry scrubbers (HCl control) Fabric filter		
Facility Capital Investment:			**Source**
Fuel Preparation:		$35,000,000	CDM
Combustion/Heat Recovery/ APC Train:			
Equipment	$13,700,000		Developer
Installation	6,850,000		Developer
CEM System	1,000,000		CDM
Combustion Core Cost	$21,550,000		
Engineering & Contingency (30% of Combustion Core)	6,465,000		CDM
Subtotal		28,015,000	
Electrical Generation (Steam Turbine)		16,400,000	CDM
Total		$79,415,000	
		per Mg/d MSW:	$101,800
		per t/d MSW:	$ 92,340

Table 3.2 Operating Costs for EPI Full Combustion System

Cost Element	No./Shift	Basis	Unit Cost ($)	Annual Cost (000)	Source
Labor					
Superintendent	—	1	45.00/	$99	CDM
Operator (Op.)	1	4	32.00/	$280	CDM
Auxiliary Op.	2	8	30.00/	$526	CDM
Feed System Op.	1	4	30.00/	$263	CDM
Plant Attendant	2	8	25.00/	$438	CDM
Elect./Inst Maintenance	2	8	35.00/	$613	CDM
Mechanical Maintenance	1	4	35.00/	$307	CDM
Nat. Gas (10^6 Btu/y)		6000	4.00/10^6 Btu	$24	CDM
Lime (t/yr)		0	85/t	$0	CDM
Limestone (t/y)		3,150	30/t	$95	CDM
Liq. NH_3 (t/y)		740	292/t	$216	CDM
Carbon (t/y)		265	1,000/t	$265	CDM
Maint.- Supplies	$28,015,000	Allowance	1.5% of Capital	$420	CDM
Maintenance	$28,015,000	Allowance	3% of Capital	$840	CDM
Insurance	$28,015,000	Allowance	1% of Capital	$280	CDM
Compliance Testing		Allowance		$300	CDM
Residue Landfill		81,600	40/t	$3,264	CDM
	Total Cost for Combustion Core			$8,229	
Contingency	10% of Combustion Core Cost			$823	CDM
Debt Service	$79,415,000		10.19% of Capital	$8,092	CDM
RDF Operations	N/A	267 x 10^3 t/y	9.60/t	$2,563	CDM
Electric Gen. Operations.	N/A	393 x 10^6 Btu/h		$960	CDM
			Total Gross Cost	$20,668	
Electrical Revenue ($000)					
Gross Generation (Mwh/y)	393 X 10^6 Btu/h	240,000			CDM
RDF Power Use (MWh/y)		(6,675)			CDM
Internal Use (MWh/y)		(36,000)			
Net to Export (MWh/y)		197,325	$0.04/kWh	($7,893)	
			Net Annual Cost	$12,775	
			Unit Cost/Ton	$47.85	
			Unit Cost/Mg	$52.71	

2. Business Aspects

With over 5 million hours of operating experience in more than 70 fluid bed energy systems, EPI has established itself as a major participant in U.S. and international fluid bed technology. In 1972 EPI supplied the first fluid bed system in the U.S. to convert waste biomass (wood waste) to energy. Since that time the company has continued to provide systems for the disposal of waste materials, including three facilities that burn prepared RDF. They have also supplied three commercial systems that operate in the gasification mode to produce a low-heating-value gas.

In late 1995, EPI's operation supplied systems based on their proprietary fluid bed boilers. Their responsibility generally starts at the fuel metering bin and continues through fuel feeding, the fluid bed air supply, ash management and combustion systems, the boiler and all aspects of energy recovery, and air pollution control. This scope of supply includes all applicable process controls and systems for data collection and archiving. The RDF preparation facilities, general buildings, foundations, roads, and other civil works, plus all electrical generation equipment and switchgear, are normally designed and furnished by others.

As of late 1995, EPI's main office address and communications numbers were:

Energy Products of Idaho (EPI) Ltd. Partnership
4006 Industrial Avenue
Coeur d'Alene ID 83814

Tel: (208) 765-1611
Fax: (208) 765-0503

C. IMPLEMENTATION FEASIBILITY

The combustion technology offered by EPI is at the point of commercial availability. EPI has installed five furnaces in the U.S. that burn RDF, with capacities of more than 55 Mg/d (60 t/d). They include:

- For the City of Tacoma, Washington: A two-bed heat-recovery facility started in 1988
- For the Northern States Power Co. in LaCrosse, Wisconsin: The first of two boilers in 1981 and a second conversion in 1987.

These facilities do not routinely practice 100-percent RDF firing using RDF derived from MSW. Limited RDF availability leads to the use of biomass, a coarsely shredded wood, or coal for the four beds. The fifth furnace, started in 1990, burns a variety of prepared industrial plant wastes—wood, corrugated paper, plant "trash," polymer scrap, for example, at an adjacent E. I. DuPont de Nemours & Co. medical film plant in Brevard, North Carolina.

EPI has also designed and built three wood-waste-fired, gasification-mode fluid bed systems (1982-1985). They have acquired, as well, in-house operating experience with RDF in their pilot plant gasifier, but at the time of this study (late 1995-1996), they had no commercial-scale plants operating on RDF in the gasification mode. However, whether for gasification or full combustion, the manufacturing methods for the furnaces, the long-term bed operating reliability with acceptable management of bed solids, emissions control performance, the feeders, etc., have all been proved in MSW-based RDF service.

In matters of technical maturity and commercial verification, the EPI combustion system should be considered highly implementable with limited risk. The gasification mode is much less developed and will require some additional testing, operating experience, and design maturation. Thus the gasification mode currently presents potential users with substantially greater risk.

1. Process Issues and Problem Areas

The EPI system is a fully developed, commercial system available for full-combustion mode operation at RDF capacities from 25 to 230 Mg/d (50 to 500 t/d) per furnace. RDF has been burned successfully on a continuing basis for over 8 years in facilities at Tacoma and LaCrosse, with more than 85-percent availability. Maintenance costs have been acceptable.

Gasification with an RDF feedstock has been studied by EPI in pilot plant facilities. However, no commercial-scale RDF gasification units are in the field at this time.

2. Operating Issues and Problem Areas

Corrosion of the old coal boilers at Tacoma has not been a problem. But there has been an attack on the welds in the Types 309 and 310 stainless steel bed tubes. The fluid bed includes 471 m^2 (5077 ft^2) of half-submerged bed tubes to remove 250,000 MJ/h (229 x 10^6 Btu/h) heat while evaporating 137 Mg/h (300,000 lb/h) water directly from the fluid bed. The present "fixes" for this problem have involved flame spraying of protective materials, extra-thick (Schedule 320) tubes for the submerged portion of the bed tubes, and coarse fins added to the bed tubes to break the bubbles.

There is some buildup of clinkers in the flue ducts and in the superheater, despite the furnace gas cooling with the bed tubes. The high alkalinity of the wood ash has been suggested as being a low-melting binder for ash. Clinker buildup is a problem, since the massive ash accumulations may break off, fall into the bed, and bend or crush the bed tubes.

Air emissions from the fabric filter have been acceptable—opacity; particulates; SO_x; NO_x; and, during operation, CO have been in compliance. Beyond the natural alkalinity of the wood ash, limestone ($CaCO_3$) is added to the bed for acid gas reduction. Because the air-supply ductwork was constructed of carbon steel, with a maximum working temperature 400°C (752°F), start-up presents a problem with excessive CO emissions. The plant has had occasional problems with back-end temperatures exceeding 200°C (392°F), threatening the fabric filter.

3. Remaining Research and Development Needs

There are no major equipment developments needed for commercialization.

D. PROCESS DESCRIPTION

1. General

A fluid bed combustor is a cylindrical or rectangular chamber containing coarse sand or a similar bed material. A gas passes through the bed at a rate that causes the sand bed to expand and to bubble, much as a liquid would. Contact between gas and solids is intimate, facilitating solids drying and size reduction. The large mass of the sand ("thermal inertia"), compared with that of the gas, acts as a flywheel to stabilize bed temperature.

The fluid bed concept was originally developed as a solids-to-gas contacting device for catalytic operations in the petroleum field. The principles of fluidization were soon extended to drying; ore processing; and ultimately, to combustion. Early interest in the fluid bed as a combustor was chiefly focused on the combustion of wastewater treatment sludge. In that application, the thermal inertia of the bed, its tolerance for high-moisture-content feedstocks and its effective and flexible response to changing feed characteristics made it especially useful. The fluid bed can present problems when burning refuse-based materials because of the accumulation of massive non-burnables (stones, pieces of metal, etc.) in the bed. Thus the development of effective and reliable bed cleansing techniques was an important key to employing fluid beds for MSW applications.

As the feed to the furnace becomes drier and drier (i.e., as the feed becomes more like a fuel), the bed temperature rises. Eventually, the system approaches the state of bed defluidization, where the sand becomes sticky. Control of excess bed temperature by increasing the air rate is not desirable when heat recovery is important. Further, raising the level of excess air greatly augments the size of the air pollution control equipment and its cost. New technology added boiler surface area, removing heat from the bed walls and bayonet* tubes and from within the bed itself. These developments provided an important key to the use of the bubbling fluid bed as a general-purpose combustor for solid fuels such as coal, refuse, and wood.

2. Combustion Mode

Fluid bed technology has been used for refuse burning in several plants in Europe and in Japan and Korea, using "circulating fluid bed" technology. In this technology, the slow burning time of the solids is compensated for by:

- Increasing the flow velocities to transport all of the solids from the bed
- Putting a cyclone or other device in the exit gas flow to capture and recycle or discharge the solids.

In time, an acceptable level of burnout is achieved.

A second approach to the use of fluid bed technology involves modification of existing coal furnaces (suspension fired or stoker fired) or construction of new facilities that incorporate the distribution plate, high pressure air supply, sand management and other features of a bubbling fluid bed. RDF, coal, wood or almost any other feedstock that is compatible with a reasonable overall energy balance can be fed to the bed. The critical requirements incorporate features that can adequately handle the segregation and discharge of noncombustible material—called "tramp material" by EPI—and to remove enough heat from the bed to avoid fusion and bed defluidization.

* Bayonet tubes are "U"-shaped pipes projecting into the fluid bed and fed with boiler feedwater.

EPI has developed such a tramp-tolerant system with acceptable heat control and has installed it in both the LaCrosse and Tacoma facilities and in several industrial applications. A typical flowsheet for a full combustion system is shown in Figure 3.1. The key elements of the system are the RDF preparation system, the intermediate RDF storage system, the RDF reclaiming and feeding system, the fluid bed boiler, and the air pollution control system.

a. **RDF Preparation**

Fuel preparation equipment is not normally supplied by EPI. Clearly, however, the quality and characteristics of the fuel are important to the process. The RDF fed to the fluid bed is produced through a sequence of mechanical processes—horizontal shaft hammermill or shear shredder-type primary shredding, secondary hammermill shredding, magnetic separation, air classification, and disc screening of the fines to remove glass and grit. In the Tacoma system, the RDF product is about 50 wt% of the original MSW stream.

The RDF feed specifications for the Tacoma system comprise:

- 100 percent <15 cm (<6 in.)
- 95 percent <7.6 cm (<3 in.)
- Glass content <0.5 percent
- Ferrous metal content <0.1 percent
- Total noncombustibles <11 percent

b. **Intermediate RDF Storage**

Generally, RDF processing facilities operate for only one or two shifts daily. Because the installed processing capacity is often so high, such operation provides for protection if there is a prolonged outage as a result of explosions or major maintenance as well as for regular access to the equipment for routine maintenance. Thus it is common to incorporate some kind of intermediate RDF storage as a buffer between RDF preparation and the combustion facility. In some urban locations, the intermediate storage is a covered, live-bottom bin-type system that minimizes the opportunity for the processed RDF to compact and knit together. Subsequent withdrawal of the agglomerated RDF from storage thus becomes difficult. When space permits, a floor dump with reclaim from the top has proved low in cost and reliable.

c. **RDF Reclaiming and Feeding**

RDF is reclaimed from storage, moved to a small feed hopper and then fed to the furnace. The Tacoma plant recovers the RDF and biomass with a ladder-type chain reclaimer that "digs" the waste from the storage piles and deposits it onto a flat drag chain conveyor that runs the length of the building. The drag chain deposits the feed onto a belt conveyor for elevation to the feed-hopper level. Limestone can be added to provide in-bed absorption of acid gases (HCl and SO_2). An auger removes the RDF fuel from a holding hopper; it then passes through a rotary valve and chute to the combustor.

d. **Fluid Bed Boiler**

The heart of the EPI process is the fluid bed boiler. The system is a rectangular, atmospheric (bed operating at about 1 atm), bubbling-type bed. Feed is distributed across the bed by pneumatic spreader/ stokers designed by EPI. Twin refractory-lined 5.5-m (18-ft)-diam hot cyclones are interposed between

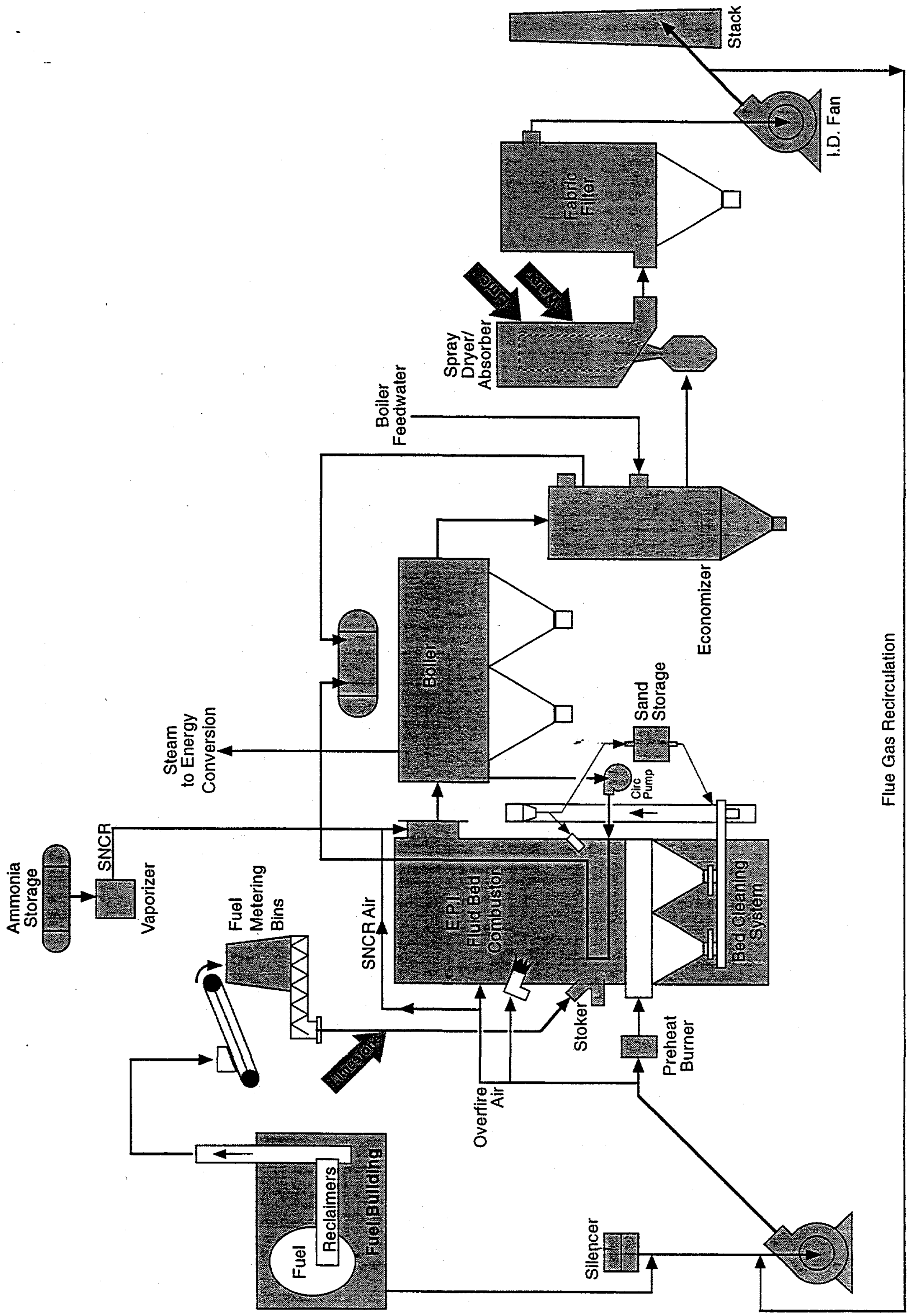

Figure 3-1
Energy Products of Idaho Process Flowsheet

the bed and the main boiler to capture and recycle the larger particles carried out of the combustion zone. The solids recycled by the cyclone significantly reduce the net unburned carbon losses. The beds can operate over a 2:1 range of heat-release rate. The bed is fitted with a number of shielded bayonet tubes mounted in the bed wall; they are equipped for forced-flow, in-bed cooling, using boiler water, to maintain bed temperature in a target range near 800°C (1500°F). At this temperature SO_2 absorption is at a maximum, and NO_x generation is low. The bed operates from 45- to 60-percent excess air in refuse service with typical RDF heat content and in-bed tubes for temperature control. This level of excess air is lower than the 90 to 110-percent typical of mass-burn units.

Unlike the 1100°C (2000°F) combustion temperatures found in mass-burn systems, fluid bed combustion temperatures are relatively low, approximating 760 to 870°C (1400 to 1600°F) in the higher density regions of the bed. Furnace absorption of HCl is effective at these temperatures; and with an average gas residence time of over 5 sec, burnout of combustible pollutants is excellent. Burnout of the combustible fraction of particulate matter is good; typically, less than 0.5-percent carbon content is observed. Combustion of the smaller fragments of RDF in the space above the fluidized bed—the "freeboard"—results in a final gas temperature of about 890°C (1800°F) where the gas enters the boiler convection banks.

One of the most important, and proprietary, features of the EPI design is the bed drawdown system. The system allows bed media to flow from an array of cone-shaped drains making up the bottom section of each combustor, with eight cones for each combustor. The material flows down the cones, through timed slide gates, and onto a divided, vibrating-pan conveyor. The vibrating pan is divided into two layers by a screen; the smaller particles are recycled, and the larger "tramp" material is rejected, removing the large quantities of oversized, noncombustible materials—rocks, metal, and glass—present in the fuels from time to time.

e. Air Pollution Control

In addition to the acid gas control achieved through in-bed lime addition, the combustion train is normally equipped with fabric filters for particulate reduction. Demonstrated sulfur oxides removal is over 70 percent. Ammonia injection is EPI's preferred approach for NO_x control. Experience has shown about 80 percent NO_x reduction at ammonia-to-NO_x ratios of 3.4:1. Carbon injection can be provided for mercury control, although none of the existing RDF-burning plants included this feature. EPI offers a conventional spray dryer/absorber and fabric filter combination when there is a need for enhanced acid gas and condensible vapor removal. Because the fluid bed operates at lower excess-air, the size and capital cost of the spray dryer and the fabric filter are reduced by about one-fourth compared with conventional mass-burning systems of similar capacity.

f. Typical Plant Configurations and Performance

EPI can provide their fluid bed equipment in two styles:

- As a separated, waterwall construction, "combustion chamber," discharging hot gases into an existing boiler (e.g., Tacoma facility)
- As a combustion system integrated with the boiler furnace (e.g., LaCrosse, facility).

Design heat-release rates of operating EPI beds range from 26,000 to 127,000 MJ/h (25 to 475 x 10^6 Btu/h), corresponding to daily RDF rates ranging from 23 to 230 Mg/d (50 to 500 t/d). Air pollution trains, plus limestone added to the bed for acid gas control, would normally contain a fabric filter unit such as that installed at the Tacoma facility. For reliability, most owners of MSW-burning plants would favor a twin-furnace configuration.

3. Gasification Mode

An alternative illustration of the EPI fluid bed technology involves intentionally running the beds air-lean (substoichiometric) to produce a low-heat-content [0.16 to 0.26 MJ/Nm^3 (150 to 250 Btu/sft^3)] fuel gas. The gasification reactor is considerably smaller and thus is lower in capital cost than a reactor in a full-combustion system. The high-pressure high-energy-consumption forced-draft fan and air pollution control system are also smaller and more cost-effective.

Although EPI has not constructed or operated commercial MSW-fired units in the gasification mode, three wood-waste-based systems have been built in the southeast and northwest U.S. In addition, EPI has carried out a comprehensive pilot plant exploration of RDF gasification performance using their 46-cm (18-in.)-diam fluid bed. In the gasification mode, sufficient air (oxygen) is supplied to oxidize most of the fixed-carbon fraction of the fuel. Heat from this reaction evaporates RDF moisture and volatilizes the remainder of the fuel. For a given operating temperature, the product gas heating value depends inversely on the RDF moisture content—the higher the moisture, the lower the heat. As the operating temperature drops, the gas quality improves, assuming there is no fall-off in the combustion efficiency for the fixed carbon. The optimum bed temperature is between 600 and 650°C (1100 and 1200°F).

Wood-fired units have met energy and air pollution guarantees. Product gas characteristics are shown in Table 3.3. There have been problems with some feeding equipment—especially rotary "star" valves—and with boiler slagging. Although a proposed solution to the slagging problem is insertion of a cyclone between the gasifier and the boiler, the resultant carbon loss would degrade energy efficiency. EPI recommends more development work in this technical area.

E. ENVIRONMENTAL ASPECTS

1. Process Emissions Characteristics (Air, Water, Solids)

a. Air Emissions

Data are available from stack tests of the City of Tacoma system. The data in Tables 3.4 and 3.5 are for Tacoma when burning a blend of RDF, coal, and wood, as required by their permit. These data show that the plant complies with the applicable emissions codes.

Table 3.3 EPI Fluid Bed Off-Gas Analysis (Gasification Mode)

Component	Vol% (Dry Basis)	Percentage of Heating Value
CO_2	15.80	None
O_2	0.80	None
N_2	51.90	None
CO	17.50	32.53
H_2	5.80	10.88
Methane	4.65	27.19
Acetylene	0.18	1.51
Ethylene	1.49	13.89
Ethane	0.23	2.33
Propylene	0.00	5.49
Propane	0.01	1.95
Other (as C_6)	0.15	4.21
Unknown	1.50	0.02
Total	100.00	100.00

Table 3.4 Measured Air Emissions from Tacoma EPI System

Pollutant	Measured Emissions Rate
CO	1 ppm
Particulate Matter	0.013 $gr/dsft^3$ (7% O_2)
HCl	101 ppm (7% O_2)
HF	0.405 ppm (7% O_2)
PAH	< Detection limit
VOC	<10 ppm

Table 3.5 Measured Polychlorinated Dioxin and Furan Data for Tacoma EPI System

Dioxins and Furans	Measured Value (ng/Nm^3)	Detection Limit (ng/Nm^3)
TCDF	0.018	0.008
TCDD	0.014	0.002
PeCDF	< Detection Limit	0.002
PeCDD	< Detection Limit	0.002
HxCDF	0.001	0.0006
HxCDD	0.011	0.0014
HpCDF	< Detection Limit	0.0015
HpCDD	0.023	0.0027
OCDF	< Detection Limit	0.0021
OCDD	0.044	0.0271
Total PCDD/PCDF	0.110	N/A

Although process developers cannot publish emissions guarantees without associating them with a specific fuel analysis and system description, the emissions listed in Table 3.6 are "typical" of those they would expect from burning RDF in their system.

b. **Wastewater Emissions**

Other than boiler and cooling tower blowdown streams, there are no wastewater streams.

c. **Residue Characteristics**

Data from Toxicity Characteristics Leaching Procedure (TCLP) ash leaching tests for RDF combustion are limited. Table 3.7 presents data from EPI pilot plant testing using several mixed fuels. Although none of these data are for "pure" RDF, it is significant that the results are consistently more than an order of magnitude below the limit.

2. **Potential for Regulatory Compliance**

As described in "Section C. Implementation Feasibility," EPI has emissions data and ash characteristics from several full-size facilities burning RDF materials, data that can be the basis for permitting submissions.

Table 3.6 EPI Emissions Guarantees

Pollutant	EPI Guaranteed Maximum Emissions Rate	U.S. EPA - New Source Performance Standards*
Particulate Matter	15 mg/Nm³ (7% O_2)	15 mg/Nm³ (7% O_2)
SO_2	30 ppm(v) or 80% reduction	30 ppm(v) or 80% reduction
HCl	25ppm(v) or 95% reduction	25 ppm(v) or 95% reduction
CO	100 ppm(v)	100 ppm(v)
NO_x	150 ppm(v)	150 ppm(v)
Total Hydrocarbons	---	---

*Large Municipal Combustors.

Table 3.7 E.P. Toxicity and TCLP Tests for Ash From Pilot-Scale EPI Tests*

Leaching Test Results (ppm mg/*l*)					
Element	TCLP Series 1†	TCLP Series 2§	E.P. Toxicity Series 3¶	E.P. Toxicity Series 4**	Limit (mg/l)
Arsenic	< 0.2	< 0.2	< 0.2	< 0.2	5.0
Barium	0.1	0.5	0.5	< 0.2	100.
Cadmium	< 0.01	0.53	0.76	0.53	1.0
Chromium	< 0.1	< 0.1	< 0.1	< 0.1	5.0
Lead	0.8	1.2	1.2	0.5	5.0
Mercury	<0.005	<0.005	0.037	<0.005	0.2
Selenium	< 0.02	< 0.02	0.2	< 0.02	1.0
Silver	< 0.1	< 0.1	< 0.1	< 0.1	5.0

*Tested using Test Methods for Evaluating Solid Waste, July, 1987, Method 1310.
†Series 1 - Cyclone catch burning RDF and wood.
§Series 2 - Baghouse catch burning 30% coal/21% RDF/49% wood.
¶Series 3 - Baghouse catch burning 20.7% tires/17.6% RDF/61.7% wood.
**Series 4 - Ash burning RDF, coal, and wood.

F. FLOWSHEET

1. Heat and Material Balances

a. Combustion Mode

Figure 3.2 is the process flow schematic for a single, full-combustion-mode EPI furnace system burning 680 Mg/d (600 t/d) RDF. This unit size corresponds to a plant receiving approximately 780 Mg/d (860 t/d) raw waste. Heat and material balances for this EPI system, given in Tables 3.8a and 3.8b (metric and English units respectively), show the system from the subsystem feeding prepared through the combustor, heat-recovery boiler, and air pollution control system to the steam header.

b. Gasification Mode

As noted earlier, EPI has not constructed a gasification mode system for RDF. However, a 95-MJ/ h (90 x10^6 Btu/h) heat-release unit was started up in North Powder, Oregon, to accept chipped wood and tires. This system produces low-heat-content gases [5.6 MJ/Nm^3 (150 Btu/ft^3), which are burned in an open-bottom A-type boiler rated at 27 Mg/h (60,000 lb/h) of 30-bar (425 lb/in^2-gage) steam at 218°C (825°F).

2. End Product

a. Combustion Mode

In the combustion mode, the EPI fluid bed boiler system generates steam for process or electrical generation. Units can be constructed to generate either saturated or superheated steam.

b. Gasification Mode

Operation of an EPI bed in the gasification mode produces a hot gas with a fuel heat content dependent on feed moisture. Because of the high dilution with nitrogen (from the air), refinement of this gas as a synthetic gas feedstock is unlikely; rather, it would be burned in a boiler for power generation. Gas cleaning before combustion is as option because of the high cost of particulate and acid gas control of the larger volume of burned gases. However, fluid bed off-gas cooling and cleaning results in the loss of up to 25 percent of the net heat content—the combination of sensible heat and fuel energy in the gas and particulate carbon. Losses of this magnitude and the capital and operating problems of adding this step suggest the merits of limiting precombustion gas cleanup to cyclone removal of particulates using a multicyclone and of using heat-recovery surface (a boiler) to cool the gases. This steps would reduce slagging in the boiler. Gas characteristics were described earlier.

3. Proposed Interface With Other Processes

The EPI fluid bed in the full-combustion mode can be combined with a boiler as an external combustor, made integral with the boiler, or used to generate a low-heat-content gas for use as a boiler fuel. In

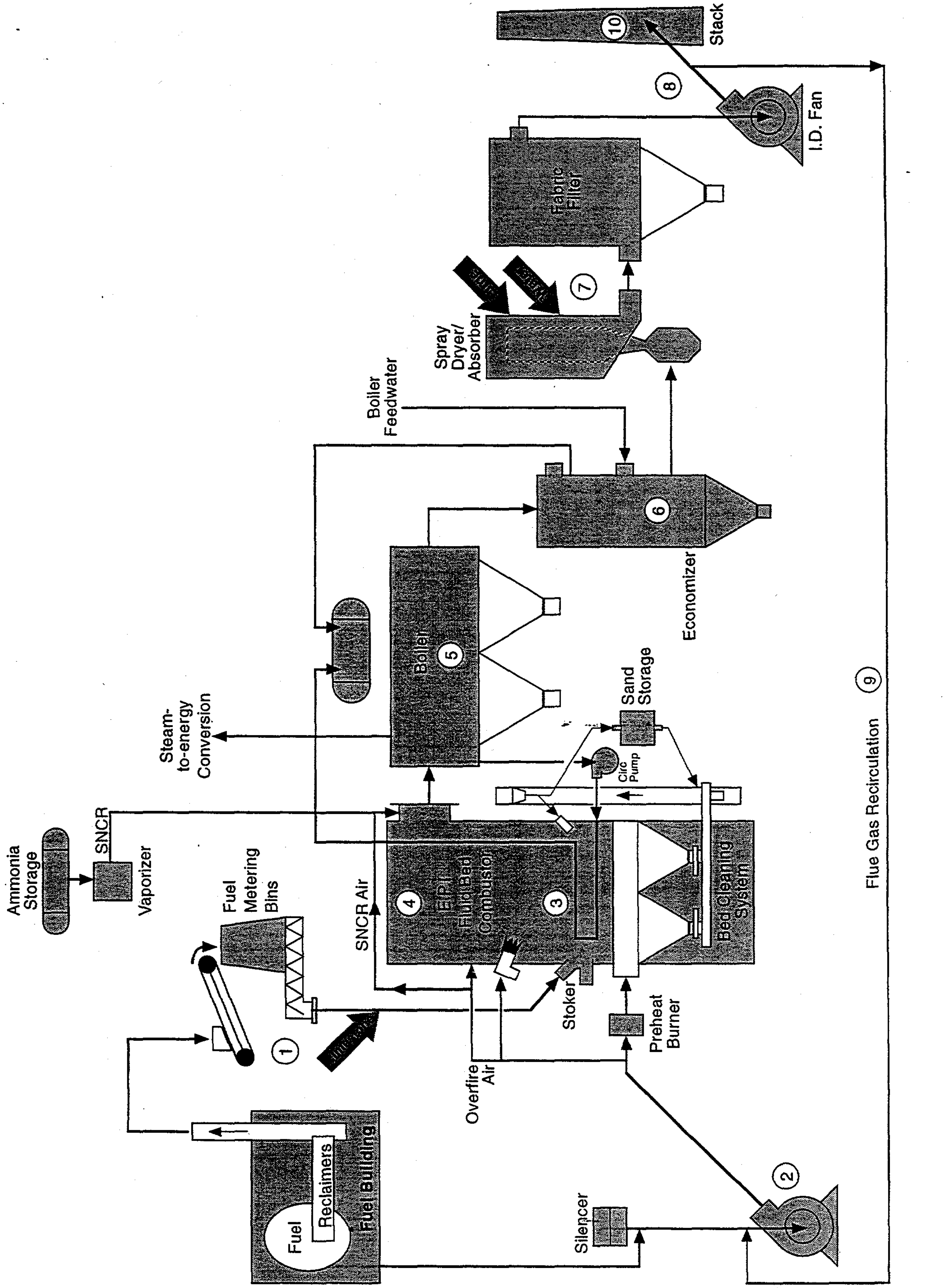

Figure 3-2
Energy Products of Idaho Process Flowsheet

Table 3.8a Process Flow Diagram (Metric Units)—600 Mg/d RDF (Typical)

Station/ Item	Description	Fuel Mix
1/Fuel	Pellet RDF, wt%	0.0
	Loose RDF, wt%	100.0
	Natural Gas, wt%	0.0
B.D. Blend Analysis (Dry)	Carbon, %	41.90
	Hydrogen, %	5.60
	Sulfur, %	0.00
	Oxygen, %	35.90
	Nitrogen, %	0.70
	Chlorine, %	0.00
	Ash/Other	15.90
	Total	100.00
	As-Fired Moisture, %	15.00
	As-Fired HHV, MJ/kg	17.9
	As-Fired LHV, MJ/kg	16.5
	Flow Rate, kg/h	22,708
	Limestone, kg/h	0
2/ F.D. Fan	Ambient Air, kg/h	135,172
	Total Airflow, kg/h	163,023
	Temperature, °C	52
	Actual m^3/min	2,500
	Pressure Drop, kPa	2.0
	Theoretical Power, kW	7.46
	Excess Air,%	36
3/ Bed	Size, m	9.8
	Temperature, °C	848
4/ Vapor Space	Temperature, °C	921
	Velocity, m/s	3.0
	Gas Flow, kg/h	185,704
	Actual m^2/min	10,473

Station/ Item	Description	Fuel Mix
5/ Boiler	Gas, °C	921
	Gas Flow, kg/h	185,704
	Actual m^3/min	10,471
	Gas Enthalphy, MJ/h	201,780
	Enthalpy Change, MJ/h	127,920
	Steam Temperature, °C	399
	Steam Pressure, MPa	3,9988
	Steam Flow, kg/h	128,822
	Ash, kg/h	785
6/ Econo-mizer	Gas In, °C	371
	Gas Flow, kg/h	184,932
	Actual m^3/min	5,616
	Gas Duty, MJ/h	73,500
	Feedwater Flow, kg/h	131,398
	Feedwater Inlet, °C	140
	Feedwater Duty, MJ/h	99,159
	Feedwater Outlet, °C	183
	Enthalpy Change, MJ/h	40,871
7/ Baghouse	Gas In, °C	177
	Gasl Flow, kg/h	184,296
	Actual m^3/min	3,908
	Ash, kg/h	1,723
8/ I.D.	Actual m^3/min	3,922
	Pressure Drop, kPa	5.2
	Theoretical Power, kW	522
9/ Flue Gas Recir-culation	% of Flue Gas	18
	Mass Flow, kg/h	27,851
10/ Stack	Gas, °C	183
	Gas Flow, kg/h	154,722
	Actual m^3/min	3,324
	Gas Duty, MJ/h	27,641
	O_2, vol%	3.9
	H_2O, vol%	15.2

Table 3.8b Process Flow Diagram (English Units)—600 t/d RDF (Typical)

Station/ Item	Description	Fuel Mix
1/Fuel	Pellet RDF, wt%	0.0
	Loose RDF, wt%	100.0
	Natural Gas, wt%	0.0
B.D. Blend Analysis (Dry)	Carbon, %	41.90
	Hydrogen, %	5.60
	Sulfur, %	0.00
	Oxygen, %	35.90
	Nitrogen, %	0.70
	Chlorine, %	0.00
	Ash/Other	15.90
	Total	100.00
	As-Fired Moisture, %	15.00
	As-Fired HHV, Btu/lb	7,681
	As-Fired LHV, Btu/lb	7,088
	Flow Rate, lb/h	50,061
	Limestone, lb/h	0
2/ F.D. Fan	Ambient Air, lb/h	298,000
	Total Airflow, lb/h	359,400
	Temperature, °F	126
	Actual ft^3/min	88,300
	Pressure Drop, in. H_2O	55
	Theoretical Power, hp	1,000
	Excess Air, %	36
3/ Bed	Size, ft	32.0
	Temperature, °F	1558
4/ Vapor Space	Temperature, °F	1690
	Velocity, ft/s	10
	Gas Flow, lb/h	409,400
	Actual ft^3/min	369,800

Station/ Item	Description	Fuel Mix
5/ Boiler	Gas, °F	1690
	Gas Flow, lb/h	409,400
	Actual ft^3/h	369,800
	Gas Duty, 10^6 Btu/h	191.25
	Enthalpy Change, 10^6 Btu/h	121.52
	Steam, °F	750
	Steam Pressure, lb/in^2-a	580
	Steam Flow, lb/h	284,000
	Ash, lb/h	1,730
6/ Economizer	Gas In, °F	700
	Gas Flow, lb/h	407,700
	Actual ft^3/h	198,300
	Gas Duty, 10^6 Btu/h	69.72
	Feedwater Flow, lb/h	289,680
	Feedwater Inlet, °F	284
	Feedwater Duty, 10^6 Btu/h	93.99
	Feedwater Outlet, °F	361
	Enthalpy Change, 10^6 Btu/h	38.74
7/ Baghouse	Gas In, °F	350
	Gasl Flow, lb/h	406,300
	Actual ft^3\h	138,000
	Ash, lb/h	3,800
8/ I.D.	Actual ft^3/h	138,500
	Pressure Drop, in. H_2O	21
	Theoretical Power, hp	700
9/ Flue Gas Recirculation	% of Flue Gas	18
	Mass Flow, lb/h	61,400
10/ Stack	Gas, °F	381
	Gas Flow, lb/h	341,100
	Actual ft^3/min	117,400
	Gas Duty, 10^6 Btu/h	26,200
	O_2, vol%	3.9
	H_2O, vol%	15.2

concept, the gas could be cleaned up to the point where it could be used as the fuel for a diesel or gas turbine, combined cycle for electrical generation. However, this latter flowsheet has not been tested by EPI, nor do they offer it at this time.

G. DEVELOPMENT HISTORY

1. Current Status

EPI produces their RDF combustors and gasifiers as standard equipment products. They have four units operating in the incineration mode with municipal or industrial RDF. They have also installed three plants for gasification of wood waste. EPI has more than 60 other furnaces burning wood, wastewater sludge, agricultural wastes, petroleum coke, and bark. In all instances except for the DuPont Brevard industrial waste project, EPI 's scope of supply was solely the combustion equipment (generally from the feeder to the stack). For the Brevard case, EPI expanded their scope of services to include construction and operations services.

a. Combustion Mode

The twin-boiler, 135-Mg/h (150,000-lb/h) steaming rate at the LaCrosse facility of Northern States Power Co. involved the reconstruction of stoker-fired coal boilers, where the fluid bed replaced the stoker. The plant burns a mix of hogged, waste wood and RDF. The first conversion took place in 1981, and the second unit was brought on line in 1988. The facility has operated continuously since start-up.

In 1988, the Department of Public Utilities for the City of Tacoma retrofitted two 25-Mw stoker-fired boilers with fluid bed combustors. The fluid beds were configured as separate combustors, discharging hot gases into the boilers that had previously fired pulverized coal. In effect, the existing boilers became waste-heat boilers. Tacoma burns coal, hogged waste wood, and minus 7.5-cm (3-in.) RDF as fuels. The quantity of RDF available is much less than the burning capacity of the beds. The plant has operated for 8 years with an on-line availability exceeding 85 percent and acceptable owning and operating costs. The facility is equipped with the capability for adding limestone to control acid gas and a fabric filter (baghouse) for particulate control. Environmental emissions have been in compliance with Federal and State regulations. The system has been operated with 100-percent RDF from time to time. However, the system design and the air permit are based on burning a blend of 50-percent coal/35-percent wood/15 percent RDF, based on heat input.

RDF is prepared in a remote facility (10 miles away) near the Tacoma landfill. The MSW material is shredded to 1.9 cm x 10 cm (0.75 in. x 4 in.) using a 500-hp horizontal-shaft hammermill. Ferrous metal is removed from the product and heavies are separated with an "air slice." The RDF material contains between 2- and 10-percent ash and has a higher heating value of about 13.8 MJ/kg (6000 Btu/lb). The preparation plant achieves about a 50-percent yield of RDF and produces 10 to 11 loads [18.6 to 21 Mg (20 to 23 tons) per truckload each day. The preparation plant operates on day shift only, 5 or 6 days a week. Some compaction occurs during hauling, but the material "re-fluffs" well on handling.

RDF is dumped in a special area in the feed house—a large, covered, metal building-type structure with four bays that hold and feed the RDF and wood waste. The RDF is moved about, as required, using a large, front-end loader. The present permit limits the holding time for RDF to 3 days. Wood waste is received in large, open-top, "semi" trailer-truck bodies, and with an automatic, tip-up-type unloader, is emptied into a holding hopper. The wood is then conveyed by belt conveyor to one of several bays in the feed house. Each bay has a drag conveyor; its "bite" into the pile is adjusted by an operator working from a second-story office overlooking the waste piles. The wood or RDF is dragged to the back wall of the feed house, dropping onto a belt conveyor that runs the length of the building. Toward the end of the building, the conveyor inclines upward, and the feed is elevated to a holding and feeding bin on the roof of the boiler house.

The wood, coal, and RDF are fed from the holding hopper atop the boiler, across a vibrating feed table, and through a metering feed system. These feed system is a rotating vane that provides both a metering action and an air lock between the combustor and the feed storage. The material then discharges from four points above the bed. The RDF is regarded as a good fuel with reliable characteristics. The most serious problem in its use is irregular feeding. RDF tends to hang up and then spurt, in a repetitive manner. The RDF tends to compress, leading to packing, with the slightest reduction in cross-section of a flow path. The average fuel firing rates are shown in Table 3.9

The Tacoma fluid bed is about 1 meter (3 ft) deep [0.7-m (2-ft) slumped depth]. Most of the 23.25 MJ/kg (10,000 Btu/lb) subbituminous coal, with 10-percent moisture/ 30-percent volatile matter, burns in the bed at 790 to 815°C (1450 to 1500°F). The wood burns on the top of the bed. Refuse and coal fines burn in the freeboard at 870 to 900°C (1600 to 1650°F).

The DuPont industrial EPI fluid bed incinerator in Brevard, North Carolina, offers another approach to the application of fluid bed technology to waste management. At this facility, the waste stream includes shredded, disc-screened waste plastics, x-ray film, and plant trash. The shredders and disc screens produce a feed stream with 100 percent <6-cm (<3-in.) top size. SO_2 and NO_x are controlled with limestone and ammonia injection respectively. A fabric filter controls particulates. Since its start-up in 1991, the plant has provided up to 32 Mg/h (70,000 lb/h) steam to an adjacent manufacturing facility.

b. Gasification Mode

Gasification units installed by EPI include a 1985 biomass gasifier in Oregon. The gas can be burned to generate 27,250 Mg/h (60,000 lb/h) of 3.2 MPa (450 psig)/ 440°C (825°F) steam. In 1985 a 100,000 MJ/h (94 x 10^6 Btu/h) heat-release gasifier started up in Bloomfield, Missouri. It generates a low-heat-content fuel gas for a rotary kiln and fuel dryer. Finally, a 205-Mg/h (45,000-lb/h) boiler fueled by low-heat-content gas from biomass was installed in 1982 as part of the State of California's central heating plant in Sacramento

Because there have recently been changes in the economics of wood waste supply since their installation, the gasification units are not presently operating. However, there were no unusual or severe operating problems observed when the gasification units were on-line.

2. Project Development Posture

EPI's current efforts are primarily those of an equipment vendor. They offer a guaranteed hardware and process system, including fuel handling and burning, heat recovery, and air pollution control, but not the civil engineering "wrap-around"—buildings, foundations, road, and utility services, for example—nor energy conversion or other electrical and mechanical facilities. As in the case of Tacoma and LaCrosse, EPI is pleased to work with A&E engineering firms to develop a specific project.

Table 3.9 Typical Fuel Heat Release Rates inTacoma Facility

Fuel	Percentage Heat Release	Mass Rate		Heat Release Rate	
		(kg/h)	(lb/h)	(MJ/h)	(10^6 Btu/h)
Coal	50	17.25	38,000	387	367
Wood	35	34.10	75,000	286	257
RDF	15	12.70	28,000	116	110

In the special case of the DuPont system, EPI provided the complete hardware train on a turnkey basis. They also provided operating staff for the first several years of plant operation. The operations contract for the DuPont operation was sold off by EPI in 1993.

H. INTERVIEWS

In the course of evaluating the EPI technology, CDM engineers met with EPI personnel, visited the DuPont facility in Brevard, North Carolina, and visited the site in Brooklyn, New York, where one of the EPI gasification-mode beds has been relocated and is being reactivated. Those interviewed were:

- Ms. Joyce M. Ferris, Director of Business Development
  EPI, Philadelphia, Pennsylvania

- Mr. Thomas H. Daniels, Technical Director
  EPI, Coeur d'Alene, Idaho

- Mr. Dennis E. Haddock, Alternate Fuels Boiler Plant Manager
  Precision Energy Services, Inc., Brevard, North Carolina
  (re: DuPont facility)

- Mr. Thomas Polsinelli, Vice President
  Atlas, Inc., Brooklyn, New York
  (re: Reconstruction of gasifier)

Section 4

TPS TERMISKA PROCESSER AB (TPS) TECHNOLOGY

A. SUMMARY

TPS Termiska Processer (Thermal Processes), or TPS, is a small, independent, Swedish company with about 50 employees, working in the specialized field of energy and environmental process research and technology development. The main TPS office is near Nyköping, Sweden. Between 1991 and 1995, TSP focused on process development for small- to medium-scale electricity production plants using biomass and refuse-derived fuel (RDF) as feedstocks. Their technology involves starved-air gasification of RDF in a combined bubbling- and circulating-type fluid bed. Following the gasification bed, they insert a second, circulating-bed "cracker." In the second bed, ground dolomite (mixed magnesium-calcium carbonate) is injected as the catalyst for the conversion of high-molecular-weight gasification by-products ("tars") into much lower molecular-weight compounds. This conversion allows reduction of the gas temperature using heat-recovery boiler tube surfaces, without losing a significant fraction of the gas heating value from condensation of the high-molecular-weight compounds. Scrubbers are used by TPS before combustion of the fuel gas in a gas engine or gas turbine energy conversion system.

The product of the TPS effort is a well-developed and demonstrated technology for gasification of RDF with subsequent conversion to electricity. The technology offered by TPS is presently close to the point of commercial availability. Fuel gas generated at the plant is either burned in a boiler to generate electricity or used as a fuel in an adjacent lime kiln operation.

B. FINANCIAL AND BUSINESS ASPECTS

1. Projected Capital and Operating Cost

Data on the capital cost of a TPS facility are based on estimates by TPS for the fluid bed vessels and their support equipment. The capital cost of a two-line TPS system burning prepared, but unpelletized, RDF is shown in Table 4.1. The vessels generate a fuel gas with an estimated higher heating value (HHV) of 7.5 MJ/Nm^3 (224 Btu/sft^3). Each furnace, running at capacity, produces gas at the rate of 249,350 MJ/h (236.5 10^6 Btu/h). The fuel gas is subsequently converted to electricity using a gas turbine-based, combined-cycle system. Additional electricity is generated from steam derived from several gas cooling steps.

Table 4.2 presents operating cost estimates for such a plant. Internal electrical use is based on TPS estimates (12.4 MW or 16.7 percent of the gross generation of 74.5 MW). The net cost for waste disposal is $38.91/Mg ($35.37/t) raw MSW. No credits for any recovered materials have been assumed.

Table 4.1 Capital Cost: Termiska Processer Thermal Processing System

System:	1600 Mg/d (1760 t/d) MSW 1200 Mg/d (1387 t/d) RDF Two Circulating Fluid Bed Gasifier Systems		
Air Pollution Control (APC):	Second CFB with Dolomite Addition for Hydrocarbon Cracking and Acid Gas Control Acidic Wet Scrubber for Removal of Ammonia Alkaline Wet Scrubber for Removal of H_2S, HCl, HF, etc. Baghouse Filter		
Facility Capital Investment:			**Source**
Fuel Preparation:		$62,800,000	CDM
Process/Heat Recovery/ APC Train:			
Building	$ 3,750,000		Developer
Equipment (CFB Systems)	38,000,000		Developer
CEM System	2,000,000		CDM
Process Core Cost	$43,750,000		
Engineering & Contingency (30% of Process Core)	13,125,000		CDM
Subtotal		56,875,000	
Electrical Generation (Two Combined-Cycle Gas Turbines and Steam Turbine System)		51,000,000	CDM
Total		$170,675,000	
		per Mg/d MSW:	$106,700
		per t/d MSW:	$ 96,970

Table 4.2 Operating Costs for TPS Thermal Processing System

Cost Element	No./Shift	Basis	Unit Cost	Annual Cost (000)	Source
Labor					
Superintendent	—	1	\$45.00/h	\$99	CDM
Operator (Op.)	2	8	\$32.00/h	\$561	CDM
Auxiliary Op.	1	4	\$30.00/h	\$263	CDM
Feed System Op.	2	8	\$30.00/h	\$526	CDM
Plant Attendant	2	8	\$25.00/h	\$438	CDM
Elect./Inst Maintenance	2	8	\$35.00/h	\$613	CDM
Mechanical Maintenance	1	4	\$35.00/h	\$307	CDM
Nat. Gas (10^6 Btu/y)		0	\$4.00/10^6 Btu	\$0	Developer
Lime (t/yr)		0	\$85/t	\$0	Developer
Dolomite (t/y)		17,100	\$30/t	\$513	Developer
Liq. NH_3 (t/y)		0	\$292/t	\$0	Developer
Carbon (t/y)		0	\$1,000/t	\$0	Developer
Maint.- Supplies	\$56,875,000	Allowance	1.5% of Capital	\$853	CDM
Maintenance	\$56,875,000	Allowance	3% of Capital	\$1,706	CDM
Insurance	\$56,875,000	Allowance	1% of Capital	\$569	CDM
Compliance Testing		Allowance		\$300	CDM
Residue Landfill		130,200 t/y	\$40/t	\$5,208	CDM
	Total Cost for Process Core			\$11,955	
Contingency	10% of Process Core Cost			\$1,195	CDM
Debt Service	\$170,675,000		10.19% of Capital	\$17,392	CDM
RDF Operations	N/A	546 x 10^6/y	\$7.85/t	\$4,286	CDM
Electric Gen. Operations.	N/A	473 x 10^6 Btu/h		\$2,160	CDM
			Total Gross Cost	\$35,661	
Electrical Revenue					
Gross Generation (MWh/y)	473 X 10^6 Btu/h	501,900			Developer
RDF Power Use (MWh/y)		(9,425)			CDM
Internal Use (MWh/y)	16.70%	(83,817)			Developer
Net to Export (MWh/y)		408,658	\$0.04/kWh	(\$16,346)	
			Net Annual Cost	\$19,315	
			Unit Cost \$/t	\$35.37	
			Unit Cost \$/Mg	\$38.91	

2. Business Aspects

TPS is an offshoot of Studsvik, a public-sector organization established in the 1940s as a semiprivate research company for the development of nuclear energy. During the 1970s, Studsvik ventured into the areas of energy use and production development. The Thermal Engineering Laboratory assumed primary activity in this technical area. TPS was separated from the Thermal Engineering Laboratory and established as an independent, private company in 1992.

The focus of the company's operation is basic and applied research, process and product development, and process design within the heat and power generation sector, with special emphasis on the environment. Commercialization of the new techniques developed by TPS normally progresses through demonstration plants to commercial operating plants. In this case, however, their path has been technology licensing or joint venture activities. Between 1991 and 1995, TPS has focused on process development for small- to medium-scale electricity production plants using biomass and RDF as feedstocks. During that period, exclusive worldwide licenses for circulating fluid bed combustors (CFBCs) were granted to Babcock & Wilcox, USA.

As of late 1995, TPS had not pursued the municipal solid waste market in the U.S.—either by themselves or through their licensee. TPS was selected to construct a 30-MWe wood-fueled Circulating Fluid Bed Gasifier (CFBG) combined-cycle plant for installation in Brazil (start-up in 1999). A second unit, fueled with biomass harvested during short-rotation forestry (clear-cutting of rapid-growth species on a 3-year cycle) is expected to enter start-up in the United Kingdom in 1998.

In late 1995, the firm's main office address and communications numbers were:

TPS Termiska Processer AB
Studsvik
S-611 82 Nyköping, Sweden.

Tel: 011-46-155-22-13-00
Fax: 011-46-155-26-30-52

C. IMPLEMENTATION FEASIBILITY

Ansaldo Aerimpianti SpA (Italy) constructed twin, 15-MW each [54,000-MJ/h (51 x 10^6 Btu/h)] CFB gasification units according to TPS specifications for operation in Grève-en-Chianti, Italy. The gasifiers were commissioned in 1992 to gasify pelletized RDF or biomass. The resultant fuel gas can be passed to an adjacent cement plant kiln or burned in a boiler to generate steam. Present economics favor electrical generation. Limited RDF availability since early 1995 has led to the use of biomass (hogged wood or agricultural wastes) from time to time. New RDF facilities near Florence, Italy, constructed to serve the Grève facility are expected on-stream in mid-1996.

The manufacturing methods for the TPS-designed systems, the long-term operating reliability of their beds with acceptable management of bed solids, the projected emissions control performance, the feeders, etc., have all been tested in MSW-based RDF service. Therefore, in matters of technical maturity and commercial verification, the TPS system should be considered as highly implementable with only moderate technological risk.

1. **Process Issues and Problem Areas**

The primary area remaining for process development relates to the gas cleaning train following the dolomite cracker and preceding a gas engine or gas turbine. The equipment installed at Grève did not include gas refining with, for example, a dolomite cracker bed or a scrubber. The next step after the gasification bed was direct firing in the boiler to generate steam. If an engine or turbine energy-conversion option is to be used in future commercial applications, a scheme for gas clean-up will be required. The successful achievement of this development is likely, and the time frame should be short.

TPS should also confirm that their feeding devices and the CFB reactor itself can accommodate nonpelletized RDF. To date, all RDF experience has involved material that was pelletized to facilitate transport and storage. However, if material in pellet form is actually required for the TPS process, the process would be economically encumbered with another capital and operating cost increment for the pelletizing equipment.

2. **Operating Issues and Problem Areas**

At the Grève plant, where the raw gas is burned directly in a boiler, a problem has been experienced with slag accumulation on the boiler tubes. The problem has been severe enough to cause a plant shutdown and longer-than-acceptable outages for boiler cleaning and rework. However, the Grève plant boiler was somewhat undersized and was not well-configured for burning a high-ash fuel. In any future plant designed according to the flowsheet illustrated in Figure 4.1, a boiler must be designed to avoid this problem. A possible solution is to custom-design the boiler to provide greater gas cooling before to the tube banks so that the slag particles are cold and dry when they hit the tubes.

3. **Remaining Research and Development Needs**

Data are needed on the characteristics of the TPS process residue. The mechanism to obtain such data is the Toxicity Characteristics Leaching Procedure (TCLP) leaching tests. Although no particular problems are foreseen, such information is needed to allow proper planning for residue disposal.

Further, the dioxin compound data collected at Grève should be augmented with similar data from the area following the dolomite cracker. To facilitate evaluations in the U.S., the results should be reported on a "total dioxin and furans" basis as well as in the Toxic Equivalents (TEQs) used to date.

D. PROCESS DESCRIPTION

1. **General**

A bubbling fluid bed reactor has a cylindrical or rectangular chamber containing coarse sand or a similar bed material. A gas passes through the bed at a rate that causes the sand bed to expand and bubble, much like a liquid. Contact between gas and solids is intimate, facilitating solids drying and reduction by solids attrition. The large mass of sand ("thermal inertia") in comparison with the gas stabilizes the bed temperature. The bed can be designed and operated by setting the feed rate high relative to the air supply, so that the air rate is lower than the theoretical oxygen quantity needed for full feed material oxidation attrition. Under these conditions, the product gas and solids leaving the bed contain unreleased fuel

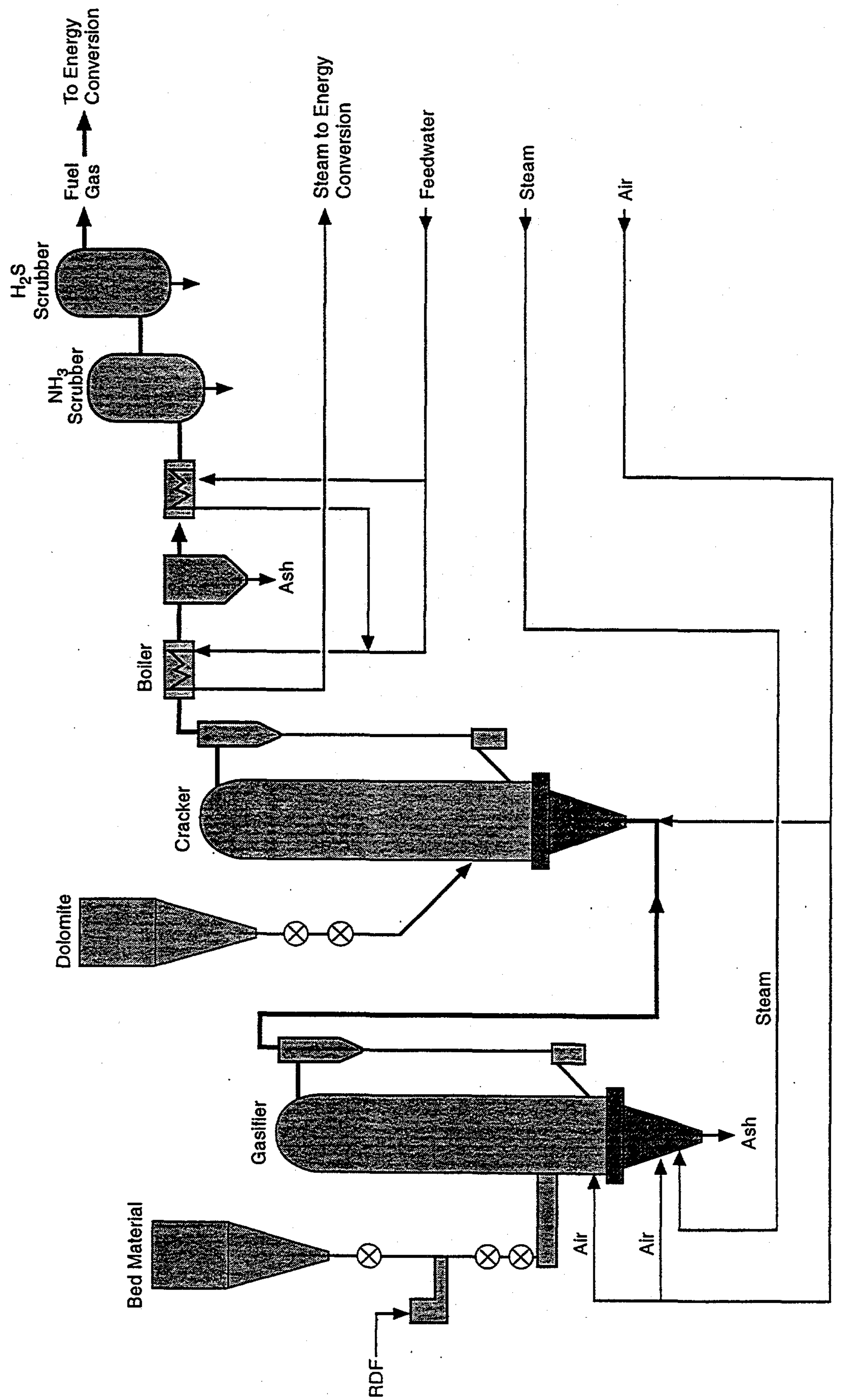

Figure 4-1
TPS Termiska Processer AB –
Process Flowsheet

value. The heating value of the gases and the char increases as the air setting decreases relative to the theoretical oxygen demand. This is the *gasification mode* of operation.

As the gas velocity increases, the bed of solids continues to expand, and an increasing fraction of the particles is blown out of the bed. If a medium- to low-efficiency particulate collector is interposed, perhaps one collecting 100 percent of particles with greater than a 30-micron aerodynamic diameter, the larger particles can be captured and returned to the bed. This embodiment of the suspended-combustion concept is called a circulating fluid bed.

The fluid bed concept was originally developed as a solids-to-gas contacting device for catalytic operations in the petroleum field. The principles of fluidization were soon extended to drying, ore processing, and ultimately, to combustion. Early interest in the fluid bed as a combustor focused mainly on the combustion of sludge. In that application, the thermal inertia of the bed, its tolerance for high-moisture-content feeds, and its effective and flexible response to changing feed characteristics made a fluid bed combustor especially useful. The fluid bed can present problems when burning refuse-based materials because massive nonburnables (stones, pieces of metal, etc.) tend to accumulate in the bed. Thus the development of effective and reliable bed-cleansing techniques was an important catalyst to the use of fluid beds for refuse applications.

As the bed temperature rises, the system can approach the state of bed defluidization—bed temperature approaches the fusion point and sand becomes sticky. Operation in the gasification mode has the advantage that the operating temperature for satisfactory gasification is considerably below that where RDF ash fusion is likely.

Circulating fluid bed technology to gasify prepared refuse, RDF, has been adopted in several plants in Europe. With this operating concept, the overall bed air-to-fuel ratio can be dropped below the stoichiometric point (reducing conditions), lowering the bed temperature. Under these conditions, a very large fraction of organic refuse components and biomass materials (e.g., wood) breaks down into volatile components. The remainder is found as a solid char. A cyclone or other device in the exit gas captures and returns the solids so that an acceptable level of carbon burnout is achieved.

The feasibility of the CFB as a gasifier is greatly enhanced by the large fraction of the organic material present as volatile matter. This quality of the RDF is reported in a proximate analysis and reflects the fraction of the waste that is distilled upon heating. This favorable circumstance is not the case for most coals, where the dominant product with bed heating would be fixed carbon. If the volatile fraction is low, steam is often added to the fluidizing medium to enhance gasification of the carbon via the water gas reaction:

$$C + H_2O \rightarrow CO + H_2$$

The volatilized organic matter can appear in the reactor gas in various forms. For convenience, they can be categorized as:

- Basic *reactor gas*—carbon monoxide and hydrogen
- Low- to medium-molecular-weight *hydrocarbons*—those with boiling points at or below 100°C (212°F)
- High-molecular-weight hydrocarbons—sometimes called *tar*.

The combination of heating values of these gases and tar-like compounds constitutes the fuel value of the resultant gas. Another energy form found in the CFB reactor gas is the heat associated with gas temperature or enthalpy.

The overall heat balance of the bed and reactor gas suggests a relationship between gas temperature, waste moisture content, and the reactor gas heating value. When any one of the three quantities increases, it is detrimental to the others. For example, if the moisture content of the waste increases, either the gas temperature or the heating value, or both to some lesser extent, must fall. Note also that the reactor gas is diluted with the nitrogen brought in with the combustion air. Therefore, a shift to oxygen-enriched air or pure oxygen will increase reactor gas heat content—at the price of increased operating cost.

The tar-like material in the reactor gas can be a problem. If the gas is cleaned with a water scrubber, the tars condense and their heating value is lost. In addition, a portion of the sensible heat will be lost if a boiler is not installed between the CFB and the scrubber. The combustion of the tar-like compounds may be less complete than that of the lower-molecular-weight hydrocarbons and reactor gas components, possibly leading to soot formation. Once soot has formed, relatively severe combustion condition—temperature, and residence time—may be required for adequate burnout. Finally, the tars are quite odorous and believed by some to be potentially carcinogenic.

Because of these problems, TPS has added a second CFB and cyclone to their configuration, following the CFB gasifier. The second bed is fed with crushed dolomite, a naturally occurring mixed calcium and magnesium carbonate, which acts as a catalyst at about 900°C (1650°F) to crack the tars to lower-molecular-weight hydrocarbons. A small fraction of the cracking products remains in heavier molecules such as benzene, toluene, and naphthalene. Only an unimportant portion of the heating value of the tar-like organic compounds is lost in the dolomite gas cleaning/reforming processes. In the course of catalyzing the cracking reactions, the dolomite also scavenges the flue gases for acidic components such as hydrochloric acid (HCl) and sulfur oxides (SO_2 and SO_3).

2. TPS Termiska Circulating Fluid Bed Gasifier System

The TPS gasifier comprises a bubbling fluid bed into which RDF or RDF pellets are fed. The addition of secondary air part way up the furnace transforms the bed aerodynamic balance so that smaller, lighter particles are blown from the circulating bed. Heavy, still-burning "chunks" remain in the dense, bubbling fluid bed until they are consumed. Dolomite can be added in a second bed to catalyze breakdown of high-molecular-weight hydrocarbons into lighter products. The product gas can be cleaned to generate a fuel gas suitable for use in a gas engine or turbine or can be burned directly in a boiler or process furnace.

a. **RDF Preparation**

TPS does not normally supply fuel preparation. However, the quality and characteristics of the fuel are clearly important to the process. The RDF fed to the fluid bed is produced through a sequence of mechanical processes—horizontal-shaft hammermill or shear shredder-type primary shredding, secondary hammermill shredding, magnetic separation, air classification, and disc screening of the fines to remove glass and grit. For the TPS system at Grève and in the TPS pilot plant, pelletized RDF has been used to date. If pellets were required, another processing step would be added to RDF preparation. Considering the high degree of mechanical abuse in the Grève handling system, engineers at TPS believe that the actual RDF material fed to the gasifiers has degraded to a pelletized, "fluff" state. This degradation will be investigated during future testing.

The pelletized RDF feed specifications for the Grève system are:

- Diameter — 10 to 15 mm (0.4 to 0.6 in.)
- Length — 50 to 150 mm (2 to 6 in.)
- Bulk Density — 500 to 700 kg/m^3 (31 to 42 lb/ft^3)
- Net Calorific Value — 17.2 MJ/kg (7380 Btu/lb)
- Moisture (typical) — 6.5 percent
- Volatile Matter — 71.1 percent
- Fixed Carbon — 11.4 percent
- Sulfur — 0.5 percent
- Chlorine — 0.4 to 0.6 percent
- Total noncombustibles — 11 percent

b. **Intermediate RDF Storage**

RDF processing facilities are generally operated for only one or two shifts daily, a reflection of the often high processing capacity and a provision to protect the operation if there is a prolonged outage caused by explosions or the need for major maintenance or an outage that is the result of a need to access equipment for routine maintenance. Thus it is common to incorporate some kind of intermediate RDF storage as a buffer between RDF preparation and the combustion facility. In some urban locations, the intermediate storage is a covered, live-bottom bin-type system that lessens the opportunity for the processed RDF to compact, knit together, and resist subsequent reclaim. When space permits, a floor dump with reclaim from the top has proved low in cost and reliable. At the Grève facility, there are four 80-Mg (88-t) steel silos.

c. **RDF Reclaiming and Feeding**

RDF is reclaimed from storage, moved to a small feed hopper, and then fed to the gasifier. The Grève plant recovers the RDF or biomass from their storage silos using a twin-screw reclaimer that "digs" the waste from the silos and deposits it into a bucket conveyor. From the bucket elevator, the RDF is moved by a screw conveyor that runs the length of the building, discharging into the feed hopper. RDF fuel is removed from the hopper with a twin-screw auger/reclaimer; it passes through a rotary valve and is sent by chute into the gasifier.

d. **Fluid Bed Gasifier**

The heart of the TPS process is the fluid bed gasifier. A cylindrical, bubbling-bed type, the system operates at about atmospheric pressure. Feed is distributed across the lower "dense bed" and begins to volatilize. The temperature in this zone is approximately 700 to 800°C (1300 to 1500°F). Residence time for larger particles in the dense bed can be quite long. As the particles are reduced, they are lifted up and out of the dense, bubbling-bed zone. Steam can be added to the dense bed if required to facilitate gasification of carbon in wastes with a high fixed-carbon content. Above the dense-bed zone, secondary air is injected. The combination of heat release (i.e., temperature increase and density reduction) and greater mass flow raises the velocity of the gas flowing upward and facilitates carbon oxidation. The temperature rises to about 850 to 900°C (1560 to 1650°F) in the bubbling-bed zone, described by TPS as the "fast bed." In beds firing fuels with a limited moisture content, steam must be added to the fluidizing gas flow. Water is an oxidizer to gasify carbon to CO and hydrogen.

The gases leaving the bed pass to large-diameter refractory-lined cyclones for particulate recovery. They then pass to a large-diameter, refractory-lined cyclone, where additional particulate recovery occurs. The solids streams from the cyclone hoppers accumulate in a vertical pipe, forming an air seal or plug. At the very bottom of the accumulation pipe, a small amount of nitrogen is introduced to fluidize the lower mass of solids. Then, by gravity, the fluidized solids flow from the pipe and are reintroduced into the dense-phase bubbling fluidized bed. Oxygen-free gas is used as the fluidizing medium to avoid the high temperatures that would occur if air (with oxygen) were used to move the still-hot, ignitable char solids.

The off-gas from the cyclone is, then, a fuel gas comprising a mixture of product gas, hydrocarbons, and tars, with some residual particulate matter. The typical composition and heating value of the gas derived from RDF and the gas composition data from the Grève facility are shown in Table 4.3.

For combustors incorporating additional air pollution control systems, such as rotary cement or lightweight aggregate kilns or process furnaces, the gas can be used directly as a medium-heat-content fuel gas. Or, if this is not the choice, it can be burned in a boiler. A subsequent air pollution control train would be required to remove acid gases, particulates, etc.

Alternatively, the fuel gas can be cleaned to the degree required for combustion in a gas engine or gas turbine for the direct generation of electricity. Optimum electrical generation is found in the combined-cycle mode, where the exhaust gases from the engine or turbine pass through a boiler to generate steam for about one-third more power generation. The latter choice may result in the loss of the sensible heat of the fuel gas unless a dolomite-cracker circulating bed with an associated cyclone is appended to the gasifier. With such a cracker, loss of fuel gas heating value through condensation in water scrubbers is avoided. Almost all of the tar is converted into lower-molecular-weight compounds and a small amount of benzene, toluene, and naphthalene. Nitrogen-containing compounds and hydrogen cyanide decompose into either nitrogen gas or ammonia. Carbon-containing dust is gasified by the residual oxidizing gases (e.g., H_2O and CO_2) at the higher temperatures of the cracker bed.

Table 4.3 Typical Reactor-Gas Composition at Grève

Component	Vol%		Percentage of Heating Value
	Grève Data	"Typical" Data*	
CO_2	15.65	10	None
N_2 + Ar	45.83	40	None
CO	8.79	22	34.9
H_2	8.61	14	22.5
Methane	6.51	4	12.8
C_xH_y	4.88	2	29.7
H_2S	48.61 (ppm)	0.02	0.06
H_2O	9.48	8	None
Other	0.14	—	N/A
Total	100.00	—	7.53 MJ/Nm^3 (202 Btu/sft^3)

*For typical reactor gases at tar cracker discharge.

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e. **Air Pollution Control**

Following the cracker, a waste-heat boiler can be installed to bring the temperature down to about 200°C (400°F), where a fabric filter system can remove particulate matter. The particulates, consisting mainly of calcined dolomite and fine soot, are not abrasive.

Demonstrated sulfur oxides removal is over 70 percent. Carbon injection can be provided for mercury control, although the Grève data suggest that acceptable mercury emissions may be achievable without this feature. TPS offers a wet scrubber system when there is a need for enhanced ammonia, tar, acid gas (H_2S, HCl), and condensible vapor removal. At this point, the fuel gas is of a quality that can be burned in a boiler without further clean-up to generate steam or it can be cleaned for use as a fuel in a gas engine or turbine combustor for the generation of electricity.

f. **Typical Plant Configurations and Performance**

TPS can provide their fluid bed equipment in two styles of fuel generator to produce a fuel gas for firing a boiler or a process furnace or for use in a gas engine or turbine. Combined-cycle design for the latter alternative offers optimum energy conversion.

E. ENVIRONMENTAL ASPECTS

1. Process Emissions Characteristics (Air, Water, Solids)

a. Air Emissions

Data are available from stack tests of the Grève system. Data from tests made when the plant was burning RDF are listed in Table 4.4. Heavy metal data from Grève are given in Table 4.5. The complete TPS system, including tar cracker, baghouse filters, and scrubbers, appears able to meet all European and U.S. emissions standards.

b. Wastewater Emissions

Other than boiler and cooling tower blowdown streams, there are no major wastewater streams from the TPS process. Wastewater is produced in the scrubber systems. Pilot test data suggest that these streams can be treated in a biological system or in activated carbon filters.

c. Residue Characteristics

Data on the leaching characteristics of TPS process residues are not available.

2. Potential for Regulatory Compliance

The TPS system has emissions data and ash characteristics from a full-size facility burning RDF materials on which to base permitting submissions. In addition, there is a large body of data from the 20-Mg/d (22-t/d) pilot facility in Nyköping, Sweden. These data demonstrate compliance with all of the present requirements of the U.S. EPA New Source Performance Standards (NSPS) for municipal waste combustors.

F. FLOWSHEET

1. Heat and Material Balances

Figure 4.2 is the process flowsheet for a single, combustion-mode TPS furnace system receiving 388-Mg/d (427-t/d) RDF. This size corresponds to a plant receiving approximately 554-Mg/d (610-t/d) MSW. TPS system heat and material balances, Figure 4.3, shows the system from the feed subsystem to the combustor, the heat-recovery boiler, and the air pollution control system.

2. End Product

Because of the high dilution with nitrogen from the air, it is unlikely that the TPS gasifier product would be refined as a chemical feedstock. Rather, it would be burned as a process heating fuel or in a boiler or gas turbine for power generation. Gas cleaning before combustion is an option because of the high cost of particulate and acid gas control on the larger volume of burned gases. However, when the fluid bed fuel gas is cooled and cleaned, up to 25 percent of the net heat content is lost. Net heat content is defined as the combination of sensible heat and fuel energy in the gas and particulate carbon.

Table 4.4 Air Emissions Data: Grève-en Chianti Plant

Pollutant	Measured Emission Rates		Grève Regulatory Limits	
	11% O_2	7% O_2	11% O_2	7% O_2
CO, mg/Nm^3	2.5 - 5	1.8 - 3.6	50	35
Particulates, mg/Nm^3	3 - 7	2 - 5	10	7
HCl, mg/Nm^3	0.5 - 2	0.4 - 1.4	30	21
HF + HBr, mg/Nm^3	< 0.1	<0.1	2	1.4
SO_2, mg/Nm^3	5 - 15	3.6 - 10	100	71
Heavy Metals, mg/Nm^3	2.2	1.6	*	*
NO_x, mg/Nm^3	200 - 300	140 - 214	300	214
PCB, ng/Nm^3	163.0	116	0.1	<0.1
PCDD/PCDF, ng/Nm^3	13.1	9.3	2860	2040

* Refer to Table 4.5.

Table 4.5 Heavy Metals Emission Data for the Grève-en Chianti Plant

Metal	Measured Value (mg/Nm^3)	Italian Regulatory Limit (mg/Nm^3)
Lead (Pb)	max 0.005	3
Cadmium (Cd)	< 0.0004	0.1
Mercury (Hg)	0.008 - 0.05	0.1

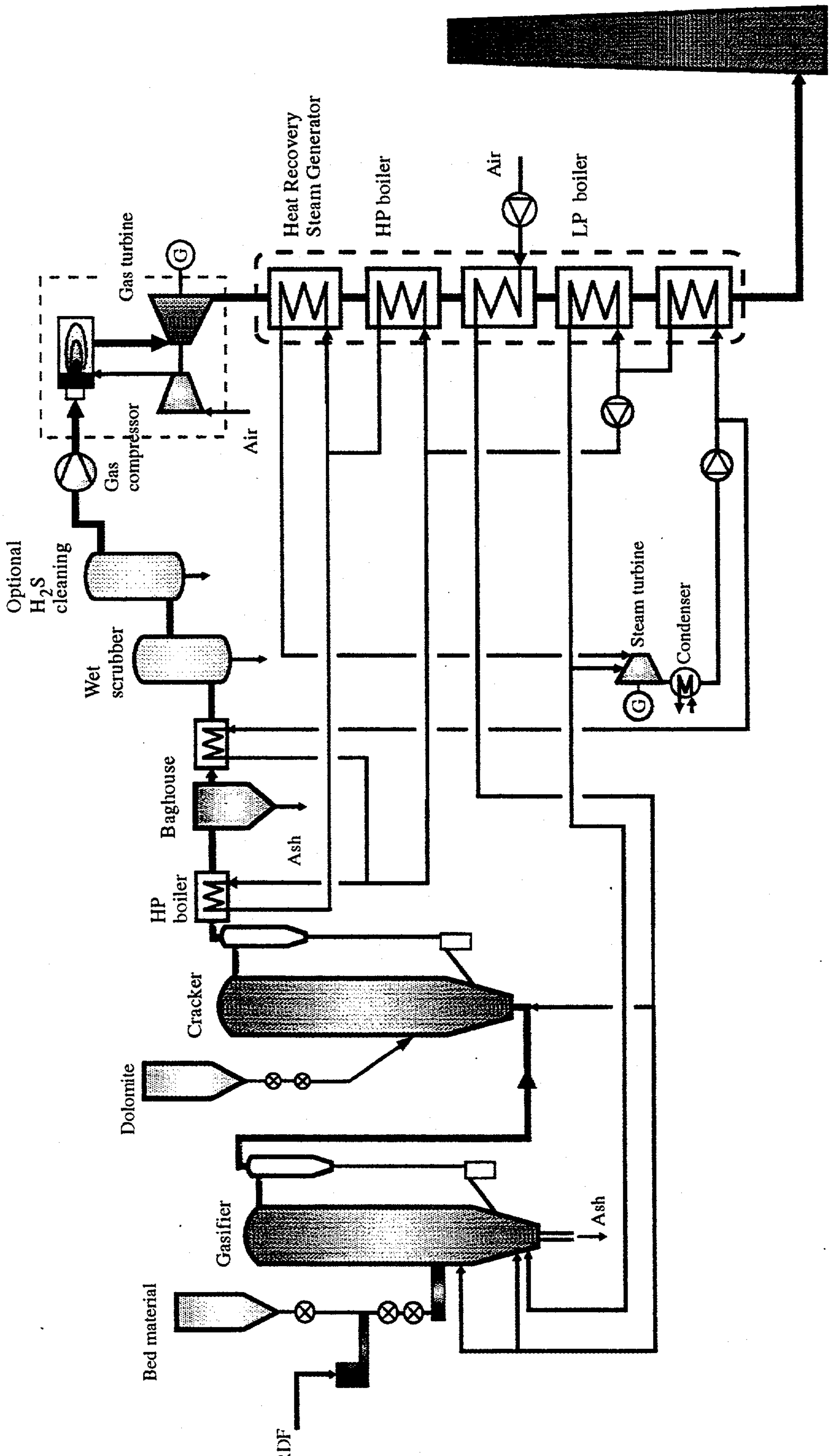


Figure 4-2
TPS Termiska System
Process Flowsheet

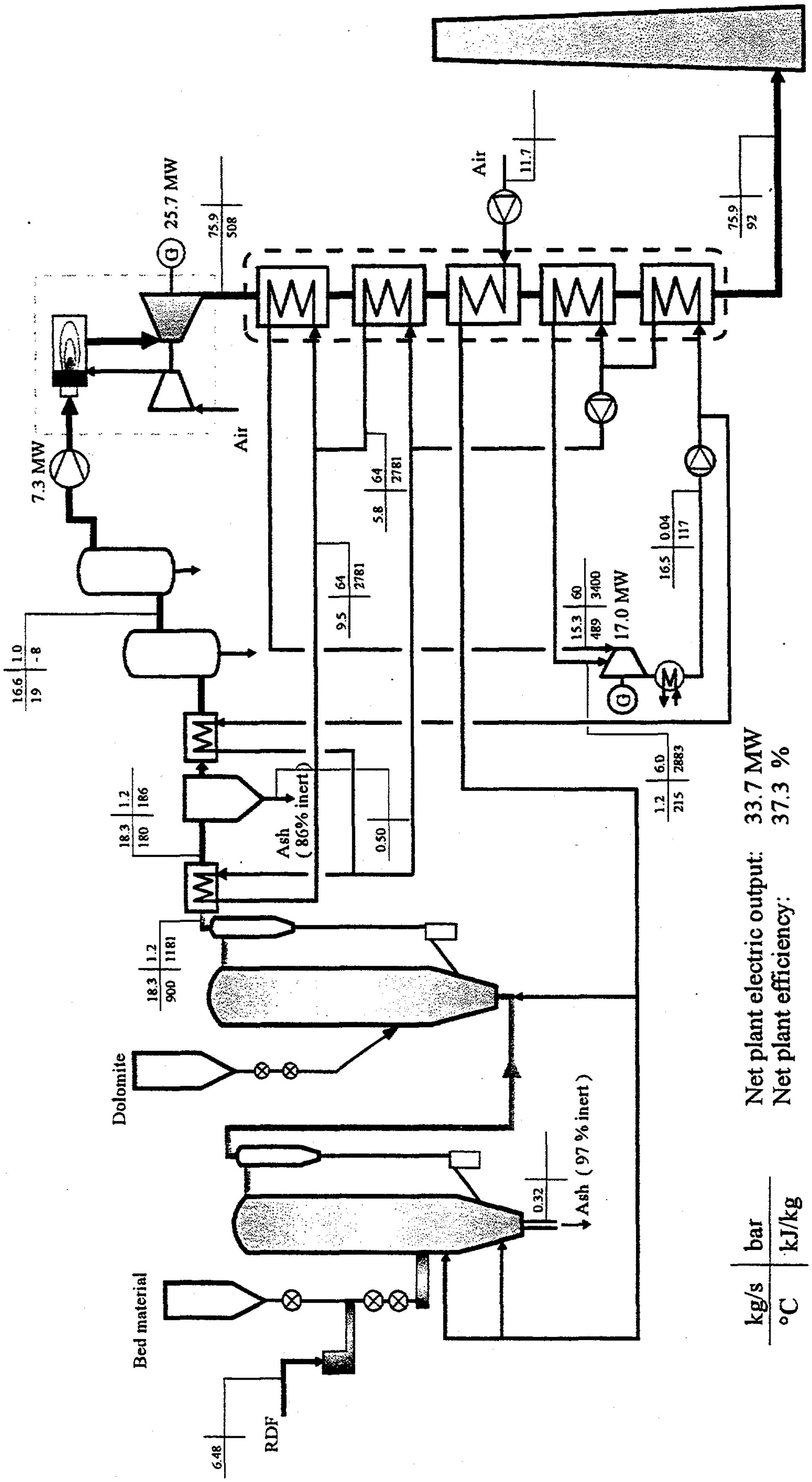


Figure 4-3
TPS Termiska System Heat and Material Balance

G. DEVELOPMENT HISTORY

1. Laboratory/Bench-Scale Studies

In 1978 TPS began its studies of the circulating fluid bed (CFB) gasification process using a small, plexiglass model. Between 1979 and 1980, subsequent test work was conducted in a 900-MJ/h (853,000 Btu/h) CFB reactor. This work included tests in an air-blown, atmospheric pressure CDF process fed with wood chips, sawdust, shale, and propane. These tests and subsequent work supported and complemented the design of a 7.2-MJ/h (6800-Btu/h) CFB prototype at their facility in Studsvik, Sweden, where further development work is being conducted.

2. Pilot Plant Studies

Pilot work with the 7.2-MJ/h (6800-Btu/h) prototype began in 1986. Since then, hundreds of hours of testing has been conducted with wood, industrial waste, and prepared RDF pellets. The pilot facility was expanded in 1988 to include a dolomite cracker and a modified, 500-kW shaft power, turbocharged, eight-cylinder, dual-fuel diesel engine. Filtered and scrubbed off-gases from wood chips and wood pellets were burned in the diesel in campaigns totaling 1300 hours overall, with 750 engine hours. Tar cracking produced a gas with sufficiently low tar content for satisfactory operation of a fabric filter downstream of the cracker. Pilot tests with RDF were conducted in 1990 and 1991 to develop a "clean-gas concept" for RDF feedstocks.

H. INTERVIEWS

In the course of evaluating the TPS technology, CDM engineers inspected the facilities in Grève-en-Chianti, Italy, and visited the TPS engineering offices in Nyköping, Sweden. Those interviewed were:

- Grève-en-Chianti, Italy (Facility Inspection)
  - — Giancarlo Polzinetti, Plant Manager
    S.A.F.I. SpA, Localita Testi
  - — Dott. Ing. Gianluca Barducci, Direttore Techico
    Tavolini, S.R.L.
    - — Dott. Ing. Raffaello Cellai Rustici, Sales Director
      IDC snc (Industrial Design Consultants)
- Nyköping (TPS Termiska Processer AB Headquarters)
  - — Michael Morris, Licensing Manager
  - — Lars Waldheim, Manager, Gasification
  - — William H. Blackadder, Manager, Laboratory Services
  - — Eva Olsson, Project Engineer

Section 5

PROLER INTERNATIONAL CORPORATION

A. SUMMARY

The PROLER SynGas Process is a patented technology that reforms hydrocarbon-containing wastes into a reactor gas. The process is being demonstrated in a 1.8-Mg/h (2-t/h) plant in Houston, Texas. Although the process was originally developed for the gasification of automobile shredder residue (ASR), limited runs have demonstrated its suitability for gasifying municipal solid waste (MSW). The process accepts preshredded material and produces a fuel gas suitable for power generation. The residue is discharged in the form of commercially useful vitrified by-products as well as wastes acceptable for landfills.

B. FINANCIAL AND BUSINESS ASPECTS

1. Projected Capital and Operating Costs

Capital and operating costs have been placed on a common basis according to the procedure described in Section 2. Capital costs for a projected two-line facility processing 1247-Mg/d (1370-t/d) raw waste are shown in Table 5.1. The costs for the required refuse-derived fuel (RDF) preparation plant, as well as a gas turbine combined-cycle power plant, are included.

Projected operating costs for the two-line facility are shown in Table 5.2. They include labor, maintenance, and oxygen and gas use for both the preprocessing facility and the power plant. The yearly total cost is $38.3 million gross, with a revenue stream from export power of $15.3 million. The net operating costs are $23 million—equivalent to $59.47/Mg ($54.06/t) MSW. Proler says that the ultimate, vitrified "ash" residue can be marketed at zero cost or with a modest income, and that the residue landfill cost may be greatly reduced or eliminated.

Proler believes that their process can tolerate very coarse RDF. Consequently, they believe that the capital and operating costs shown in Tables 5.1 and 5.2 for RDF preparation are higher than ultimately achievable.

2. Financial and Business Aspects

Proler International is a $100 million a year public company, with its stock traded on the New York Stock exchange. The company, through its joint operations on the East and West Coasts, states that it is the world's largest exporter of scrap steel. It is now the intention of the company to design, build, and finance complete waste gasification facilities while, at the same time, assuming the risk of guaranteeing the performance of the system.

Table 5.1 Capital Cost: Proler International Corporation Thermal Processing System

System:	1247 Mg/d (1370 t/d) MSW 872 Mg/d (960 t/d) RDF Two-Line Furnace/Boiler Systems		
Air Pollution Control (APC):	Hot, Pneumatic Separator Dry Cyclone Scrubber Fabric Filter		
Facility Capital Investment:			**Source**
Fuel Preparation:		$52,000,000	CDM
Process/Heat Recovery/ APC Train:			
Feeding System	$ 1,500,000		Developer
Reactor Equipment	28,000,000		Developer
Product Gas Treatment	12,600,000		Developer
Water Treatment	225,000		Developer
CEM System	2,000,000		CDM
Process Core Cost	$44,325,000		
Engineering and Contingency (30% of Process Core)	13,300,000		CDM
Subtotal		57,625,000	
Electrical Generation (Gas Turbine)		44,000,000	CDM
Total		$153,625,000	
		per Mg/d MSW:	$123,200
		per t/d MSW:	$ 112,100

Table 5.2 Operating Costs for Proler International Corporation

Cost Element	No./Shift	Basis	Unit Cost	Annual Cost (000)	Source
Labor					
Superintendent	—	1	$45.00/h	$99	Developer
Operator (Op.)	1+	5	$32.00/h	$350	Developer
Auxiliary Op.	1+	5	$30.00/h	$329	Developer
Feed System Op.	1+	5	$30.00/h	$329	Developer
Plant Attendant	1+	5	$25.00/h	$274	Developer
Elect./Inst Maintenance	—	3	$35.00/h	$230	Developer
Mechanical Maintenance	—	3	$35.00/h	$230	Developer
Accountant	1	1	$30.00/h	$66	Developer
Clerk	1	1	$25.00/h	$55	Developer
Nat. Gas (10^6 Btu/y)		175,000	$4.00/$10^6$	$700	Developer
Oxygen (t/y)		70,000	$7.00/t	$490	Developer
Consumables (chem., water)		Allowance	$2,220	$2,220	Developer
Maintenance Supplies	$57,625,000	Allowance	1.5% of	$864	Developer
Maintenance	$57,625,000	Allowance	3% of	$1,729	Developer
Insurance	$57,625,000	Allowance	1% of	$576	CDM
Compliance Testing		Allowance		$300	CDM
Residue Landfill		127,500	$40/t	$5,100	CDM
		Total Cost for Process Core		$13,939	
Contingency		10% of Process Core Cost		$1,394	CDM
Debt Service	$172,700		10.19% of	$17,598	CDM
RDF Operations	N/A	425 x 10^3 t/y	$7.70/t	$3,273	CDM
Electric Gen. Operations.	N/A	393 x 10^6 Btu/h		$2,100	CDM
			Total Gross	$38,304	
Electrical Revenue					
Gross Generation (MWh/y)	393 x 10^6 Btu/h	450,000			CDM
RDF Power Use (MWh/y)		(10,625)			CDM
Internal Use (MWh/y)	12.50%	(56,250)			Developer
Net to Export (MWh/y)		383,125	$0.04/kWh	($15,325)	
			Net Annual	$22,979	
			Unit Cost/t	$54.06	
			Unit Cost	$59.47	

As of late 1995, the firm's Main Office address and communications numbers were:

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

C. IMPLEMENTATION FEASIBILITY

The developer states that full-scale facilities for the processing of ASR and MSW are being negotiated with customers in Europe, Canada, and the U.S. However, a number of issues apparently must be addressed before successful commercialization for MSW in the U.S. can be achieved.

1. Remaining Development Needs

Proler states that preliminary design work has been completed for a full-scale 900-Mg/d (1000-t/d) commercial facility using MSW as feedstock and consisting of two process lines at 18 Mg/h (20 t/h) each. Major technical problems appear to be:

- Although the demonstration plant is processing RDF at a top size of 5.8 cm (2 in.), the commercial plant is expected to be able to accept shredded material with a top size of 15.24 cm (6 in.). However, only 18-Mg (20-t) coarse material have been tested. The material and energy balances for a full-scale facility will also need to be confirmed.

- The demonstration plant has operated with shredded MSW on a limited basis only. An extended campaign of operation appears essential to evaluate potential problems with refractory degradation, slag problems, and control of tramp air when there is seal deterioration.

- The reliability and performance of the vitrifier and the integration of this equipment with the existing gasifier is yet to be proved. The mechanism and rate of heat transfer from the vitrifier to the incoming feed must be demonstrated. The introduction of natural gas at the discharge end of the reactor is regarded solely as a source of auxiliary heat, while relying on the heat from the vitrifier as the main source.

- The planned commercial size at 36-Mg/h (40-t/h) MSW represents a scale-up of 11:1 over the demonstration plant or 5.5:1 on a per-line basis. Experience during municipal waste combustor (MWC) development efforts by several other firms would suggest that such a substantial step carries a high risk factor for systems processing MSW.

Further testing with MSW to resolve these issues seems desirable.

D. PROCESS DESCRIPTION

1. General

The Proler demonstration waste processing facility, located on the outskirts of Houston, Texas, was visited on October 30, 1995. The system, referred to as the Proler SynGas Process, is designed to produce recyclable solid by-products together with a clean fuel gas from ASR and other wastes, including MSW. It was developed and patented by Proler International Corporation's wholly owned subsidiary—Proler Environmental Services, Inc. The demonstration unit has a capacity of 1.9-Mg/h (2.0-t/h) shredded MSW, equivalent to 2.6-Mg/h (2.9-t/h) raw MSW. The unit includes a feeding system; a horizontal, rotary reactor; a gas-cleaning train; and a compressor that supplies cleaned fuel gas to a dual-fuel-fired engine/ generator. At the time of CDM's visit, shredded MSW was being processed, and the complete system was operating.

a. Detailed Description

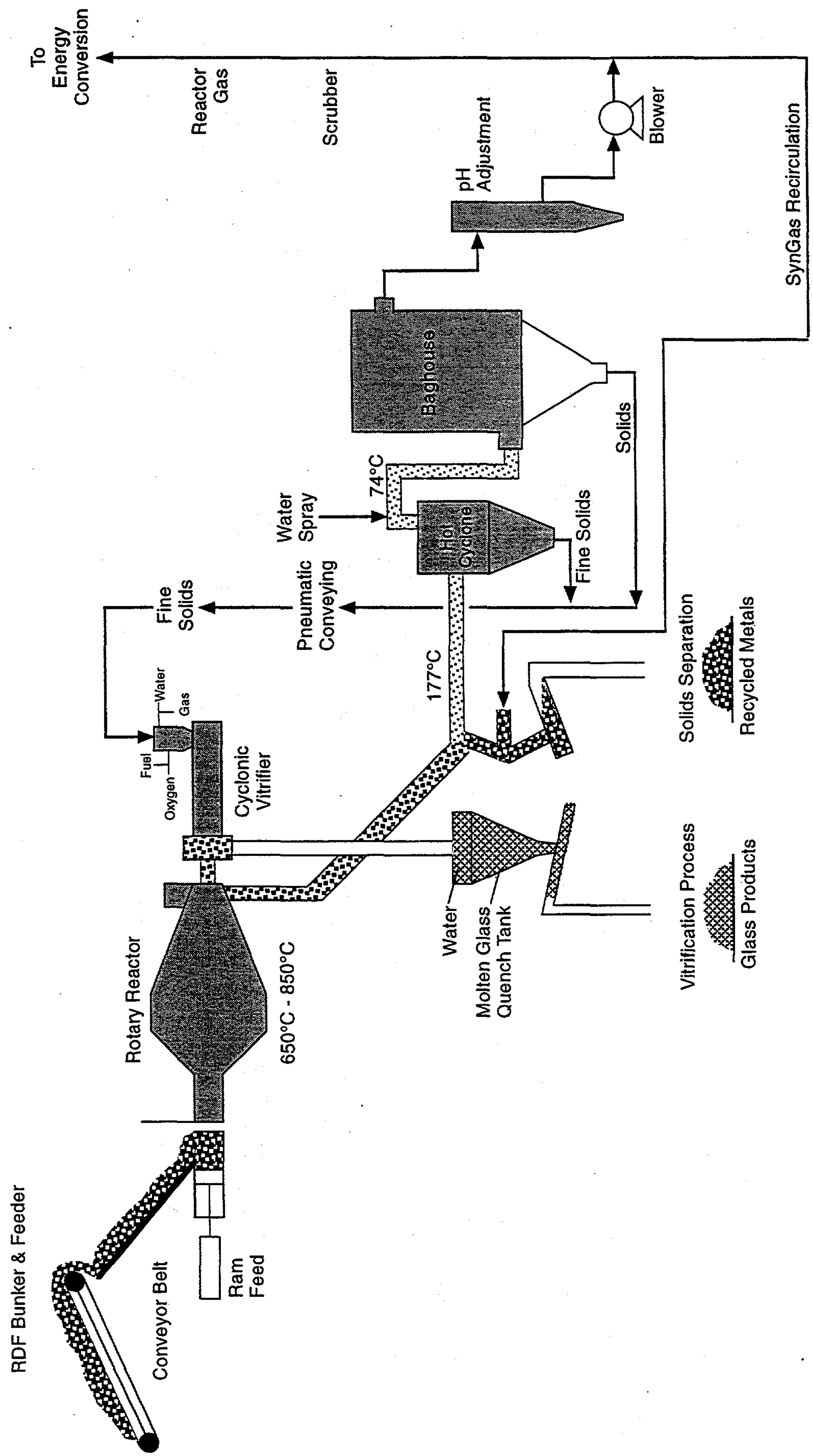
Figure 5.1 is a schematic of the gasification process as it now exists, with the exception of the "Cyclonic Vitrifier," which is not yet installed but is scheduled for early in 1996 (see Section c, Reactor Gas Characteristics, which follows). The RDF feed consists of waste material shredded to a top size of 15 cm (6 in.) after removal of the larger ferrous and nonferrous metal pieces for re-use.

The remaining, coarsely shredded "fluff" is delivered by truck from a Proler-owned shredding facility located off-site and is conveyed by a belt conveyor to a dual-ram feeder that pushes the waste into the reactor. An air-tight plug of feed forms a seal between the feed hopper and the reactor. The latter is a Proler-designed refractory-lined horizontal vessel, rotating between 1 and 2 rpm. Sealing air at both ends of the chamber, at a rate of 0.13 m^3/h (4.5 ft^3/h), finds its way into the chamber itself. Natural gas and oxygen are fired through oxyfuel burners to maintain a temperature of 650 to 850°C (1200 to1600°F) in a reducing atmosphere. As the material is being heated and gasified, the raw gas and solids exit at the discharge end into the Hot Pneumatic Separator (HPS). This unit contains a series of baffles that, by reversing the gas flow several times, drop out the larger solid constituents. The dirty gas is then cleaned in a "Hot Cyclone," followed by a baghouse and a wet scrubber. A Roots blower compresses the cleaned gas to 101 kPa (30 in. H_2O) and supplies it to a 186-kW (250-hp) reciprocating Diesel engine. For stable ignition, the engine uses auxiliary fuel at the rate of 10-percent heat input. A flare burns off any excess gas.

The large solids removed by the HPS contain recyclable metals—iron and copper, for example— which may have a commercial value. The remainder, as well as the fines separated by the scrubber and baghouse, is presently sent to a landfill. In the future the fines will be vitrified in the planned high-temperature vitrifier (Figure 5.1).

b. Vitrifier

Proler has obtained an exclusive, worldwide license to use TRW's cyclonic vitrification technology in recycling applications. TRW's vitrifier will be integrated into the existing plant by mid-1996. Tests are presently being run on these units with ASR fines mixed with electric-arc furnace residues. The plan for the ultimate system calls for recycling the fines collected in the baghouse into the vitrifier and firing it with gas/oxygen at 1350°C (3100°F). This heat will be the major source of process heat, with the off-gases passed from the vitrifier into the discharge end of the reactor. The granulated, nonleaching, glassy



5-1
Proler Process Schematic

material produced from the vitrifier is believed to be a by-product of value to the ceramics industry in such applications as tile manufacturing.

c. Reactor Gas Characteristics

Table 5.3 presented an analysis of the fuel gas currently produced without the vitrifier in operation. According to the energy balances, the value of the fuel gas appears to be independent of the use of the vitrifier. The heating value has been calculated at 11.3 MJ/ Nm^3 (302 Btu/sft^3), dry, with a theoretical flame temperature of 1775°C (3227°F). The contaminants in the fuel gas are listed in Table 5.4.

E. ENVIRONMENTAL ASPECTS

Environmental emissions were obtained from the exhaust gas leaving the existing dual-fuel- fired Diesel engine. Table 5.5 lists the tested contaminants normalized to 7-percent oxygen. The emissions are all below EPA's December 1995 Maximum Achievable Control Technology (MACT) limits and the New Source Performance Standards (NSPS). The second column shows the developer's projected values for an optimized system with "upstream ultrafiltration." With the addition of the vitrifier, Proler claims that the solids effluent is a usable by-product with superior leaching characteristics. Table 5.6 presents the heavy metals
content of the vitirfied glass material and the associated Toxicity Leaching Characteristics Procedure (TCLP) results. The TCLP results are well below EPA limits.

Table 5.3 Reactor Gas Analysis

Components	Vol%
Hydrogen	30.8
Nitrogen	4.6
Carbon Monoxide	31.2
Methane	5.7
Carbon Dioxide	17.8
Ethylene	1.7
Ethane	0.1
Acetylene	0.5
Water	7.1
Benzene	0.5
Total	100

Table 5.4 Cleaned Reactor Gas Contaminants

Contaminant	Value	Units
Fly Ash and Tar	0.04 - 0.216	gr/dsft^3
Chlorides/HCl	20 - 100	ppm(v)
H_2S	1 - 5	ppm(v)
NH_3	90 - 120	ppm(v)
K, Na, Ca, Salts	1 - 2	ppm

Table 5.5 Environmental Emissions Data

Parameter	Corrected Values*	Estimated Values**
Particulates	4.6 - 9.2 mg/Nm^3 (0.002 - 0.004 gr/sft^3)	2.3 mg/Nm^3 (<0.001 g/sft$^{3)}$
HCl	5-10 ppm(v)	3 ppm
Fluorides	3-4 ppm(v)	1 ppm(v)
CO	75-100 ppm(v)	25 ppm(v)
Organic Compounds (as C)	3-5 ppm(v)	0.065 ppm(v)
Sulfur Oxides (as SO_x)	4-5 ppm(v)	2 ppm(v)
Nitrogen Oxides	100-150 ppm(v)	40 ppm(v)
Metals: Sb, Pb, Cr, Cu, Mn, V, Sn, As, Co, Ni, Se^4, Te	0.2-0.4 ppm(v)	0.2 ppm
Cd	0.02-.03 ppm	0.01 ppm
Hg	<.01 ppm(v)	<0.01 ppm(v)
Dioxins and Furans (total mass emissions)	<10 ng/dNm^3	<3.5 ng/dNm^3

* Data for dual-fuel reciprocating internal combustion engine exhaust normalized to 7-percent oxygen.

** Estimates for an optimized combustion system with up-stream ultra-filtration to remove a greater amount of submicron particles at 7 percent oxygen.

Table 5.6 Heavy Metal Content in Vitrified Glass Product

Element	Elemental (ppm)	TCLP Leachability (ppm)
Lead	1100	0.05
Chromium	34	0.01
Copper	1500	0.15
Zinc	400	0.02
Nickel	200	0.01
Cadmium	8	0.01
Mercury	3	0.002

F. FLOWSHEETS

Figures 5.2 and 5.3 show the mass and energy balances for the gasification system as currently constituted and as planned respectively. As stated earlier the difference arises out of the addition of the vitrifier to the final system.

Both figures summarize the major streams in and out of the process for both the existing and planned systems. An analysis of the data, together with the mass/energy balances, reveals that the existing demonstration plant produces approximately 1000-Nm^3/t (33,000-ft^3/t) fuel gas from shredded MSW. This amount is expected to increase to 1100 Nm^3/t (35,000 ft^3/t) after adding the vitrifier. The heating value of the gas in both cases remains at 10.35 MJ/m^3 (278 Btu/sft^3), wet.

The explanation for the increase in fuel gas output is explained by the gasification of carbon and volatiles with the vitrifier. Without the vitrifier, these benefits were lost in the solid waste streams from the existing plant. In confirmation of this projection, the vitrifier is expected to reduce the solids discharges from 400 to 280 kg/t (800 to 560 lb/t), the difference being accounted for by the organics content in the solids. As further evidence, Proler expects the overall thermal efficiency of the process to rise from 74 percent to 85 percent with the addition of the vitrifier.

Although there is no substantial change to the rate of oxygen use [about 240 kg/Mg (460 lb/t)], natural gas consumption is expected to drop from 49.2 to 17.5 m^3/Mg (1565 to 612 ft^3/t), or 60 percent. Both cases produce an aqueous effluent of 33 and 37 *l*/t (8.8 and 9.8 gal/t) respectively. After treatment, this effluent can be discharged to a sewer.

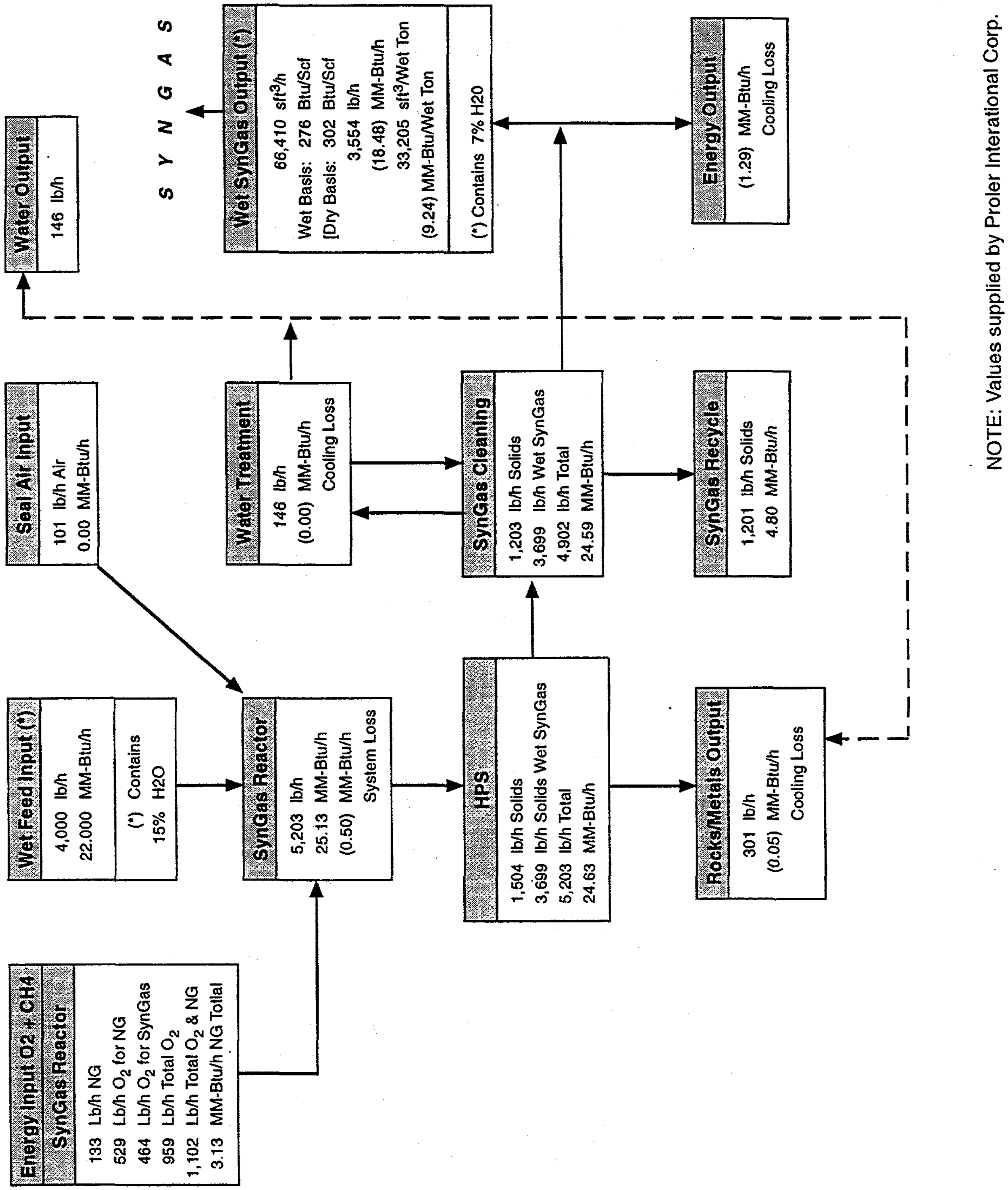


Figure 5-2
Mass & Energy Balance (MSW) of Demonstration System

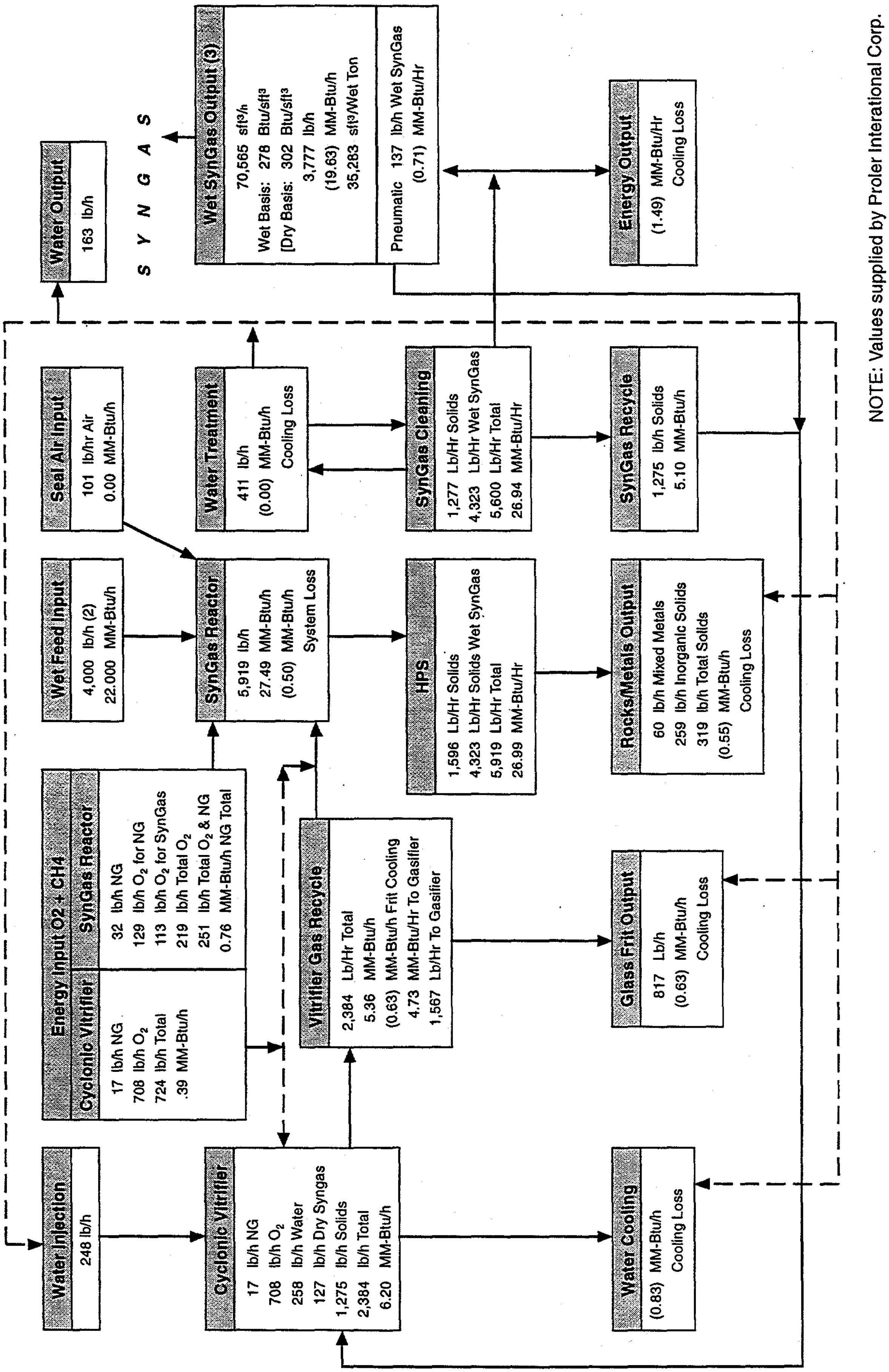


Figure 5-3
Mass & Energy Balance (MSW)
of Commercialized System

The complete, integrated system at 36 Mg/h (40 t/h) RDF will process 864 Mg/d (1000 t/d) or 270,000 Mg/y (300,00 t/y) at 85-percent availability. Output of energy, in the form of fuel gas, is expected to be 411,000 MJ/h (390 x 10^6 Btu/h). A plant of this capacity would warrant combined-cycle power generation—(gas turbine/steam turbine combination)—with an estimated capacity of 60 MW.

G. DEVELOPMENTAL HISTORY

Proler began development of this gasification technology in 1989, primarily for the processing of ASR. The Project Team member visited a demonstration unit that was said to represent the fifth generation and that had been in operation for 4 years. The technology was originally developed to solve the problems associated with recycling the nonmetallic components found in automobiles. In the past this material had been disposed of in a landfill. Although initially developed to solve an internal solid-residue recycling problem, Proler is now involved in discussions with companies throughout the world about applications of its proprietary technology.

In operation since June 1991, the current demonstration plant without the vitrifier has a design capacity of 1.8-Mg/h (2.0-t/h) prepared RDF. Proler claims that "the system has gasified over 136-Mg (150-t) MSW, 36-Mg (40-t) paper processing waste, 9-Mg (10-t) tire chips, and over 1200-Mg (1300-t) ASR." The longest extended run has been approximately 100 hours, with unscheduled downtimes of 3 percent and 17 percent caused by "materials conveying problems." The facility normally operates for 2 to 3 days a week. For a total plant operating time of over 4000 hours, 320 runs have been made, according to Proler.

Almost 100 percent of the pilot experience to date used RDF shredded to less than a 5-cm (2-in.) top size. In a short-duration trial run (10 hours maximum), 18-Mg (20-t) coarser [15-cm x 15-cm (6-in. x 6-in.)] RDF was processed without difficulty. Further tests are needed to qualify this system for coarse feed.

The fuel gas is tested on-line with a chromatograph. Additional tests have been conducted in the past by outside commercial laboratories. Proler stated that "independent outside analysis has shown that the fuel gas is also suitable for being fired in boilers and in gas turbines, or for producing either methanol or ammonia."

H. INTERVIEWS

In the course of evaluating the Proler technology, meetings were held with Proler personnel in the Houston area, site of the Proler pilot plant. Those interviewed were:

- Steven F. Gilliland, President and CEO
- Dennis L. Caputo, Vice President, Environmental and Safety Compliance
- Harold B. Burnham, Vice President, Business Development
- Norman Bishop, Vice President (originator of the gasification process)
- Donald Gene Taylor, Consultant