Section 6

Thermoselect Inc.

A. SUMMARY

The Thermoselect process embodies a fully developed method of gasifying municipal solid waste (MSW) and industrial raw wastes without apparent adverse impact on the environment. The residue is converted into what are described as commercially useful by-products. A standard design has been developed for a two-line nominal, 480-Mg/d (528-t/d) system housed in an attractive industrial building. Larger capacity systems are offered by adding multiples of the "standard" modules.

B. FINANCIAL AND BUSINESS ASPECTS

1. Projected Capital and Operating Costs

Capital and operating costs have been normalized to a common basis, according to the procedure described in the "Introduction." Capital costs for a six-line facility, including gas-turbine gas-engine electric power generation, are shown in Table 6.1. The developer points out that the installed costs will decrease as additional modules are added. The gas purification equipment, oxygen plant, power plant, and others will be shared by the process lines.

Yearly operating costs, estimated at $55.06 million (Table 6.2), cover a staff of 122 operators and administration personnel. With revenue from export power of over $12.6 million, net yearly owning and operating costs are about $42.41 million—equivalent to a break-even tipping fee of $94.92/Mg ($86.29/t). The developer believes that the granulated slag produced by the process should be considered a product that can be hauled away at no cost or sold. Thus the actual operating cost would be lower than shown in Table 6.2. However, the market for their slag has not yet been demonstrated in the United States.

2. Business Aspects

Thermoselect SA is a privately held Swiss company created to commercialize the Thermoselect process, for which over 31 patents have been issued. In January 1995 the German utility Badenwerke AG joined the company as a 25-percent owner. Thermoselect is not currently interested in selling the technology; they want to license it to plant owners. They are prepared to enter into the following arrangements:

- Provide a licensed facility to an owner on a turnkey basis
- Enter into a joint operating venture with an owner
- Work with a developer, community, finance group, or technology provider.

Table 6.1 Capital Cost: Thermoselect Six-Line Standard System

System:	1440 Mg/d (1584 t/d) MSW Six-Line Gasification System		
Air Pollution Control (APC):	Acidic and Alkaline Wet Scrubbers Hydrogen Sulfide Oxidation and Removal Acitivated Coke Filtration		
Process Water	Recovery Cleaning/Cooling Reuse		
Facility Capital Investment:			**Source**
Fuel Preparation:		None Required	
Process/Heat Recovery/ APC Train:			
Equipment	$ 145,300,000		Developer
CEM System	3,000,000		Developer
Process Core Cost	$148,300,000		CDM
Engineering & Contingency (30% of Process Core)	44,490,000		
Subtotal		$192,790,000	CDM
Electrical Generation (Two Gas Turbines and Steam Turbine System)		44,000,000	
Total		$236,790,000	
		per Mg/d MSW:	$164,400
		per t/d MSW:	$149,500

Table 6.2 Operating Costs for Six-Line Thermoselect System

Cost Element	No./Shift	Basis	Unit Cost	Annual Cost (000)	Source
Labor					
Superintendent	---	1	$45.00/h	$99	CDM
Clerk		1	$25.00/h	$55	CDM
Operator (Op.)	3	12	$32.00/h	$841	CDM
Auxiliary Op.	6	24	$30.00/h	$1,577	CDM
Feed System Op.	3	12	$30.00/h	$788	CDM
Plant Attendant	6	24	$25.00/h	$1,314	CDM
Elect./Inst Maintenance	6	24	$35.00/h	$1,840	CDM
Mechanical Maintenance	6	24	$35.00/h	$1,840	CDM
Nat. Gas (10^6 Btu/y)		496,500	$4.00/$10^6$ Btu	$1,986	Developer
Chemicals and Reactants			Allowance	$3,000	Developer
Oxygen (On-Site Plant)		N/A	$0	$0	Developer
Heavy Metal Sludge Disposal			Allowance	$150	Developer
Maintenance	$192,790,000		Allowance	3% of Capital	$5,784Devel
Insurance	$192,790,000	Allowance	1% of Capital	$1,928	Developer
Compliance Testing		Allowance		$300	Developer
Residue Landfill		124,500	$40/t	$4980	CDM
		Total Cost for Process Core		$26,480	
Contingency		10% of Process Core Cost		$2,648	CDM
Debt Service	$236,790,000		10.19% of Capital	$24,129	CDM Mt/y
Electric Gen. Operations.	N/A	390 x 10^6 Btu/h		$1,800	CDM
			Total Gross Cost	$55,057	
Electrical Revenue					
Gross Generation (MWh/y)	390 x 10^6 Btu/h	440,000			CDM
Internal Use (MWh/y)		(123,750)			Developer
Net to Export (MWh/y)		316,250	$0.04/kWh	($12,650)	
			Net Annual Cost	$42,407	
			Unit Cost $/t	$86.29	
			Unit Cost $/Mg	$94.92	

Thermoselect has stated that the proper funding and backing are in place for commercializing their process.

The addresses and communications numbers for Thermoselect as of late 1995 are:

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Plaza Pedrazzini,11
CH-6600 Locarno, Switzerland

Tel: 011-093-31.67.92
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C. IMPLEMENTATION FEASIBILITY

Development of this process is practically at the commercialization stage, as evidenced by the 100-Mg/d (106-t/d) demonstration facility in Italy. As of October 1995, several orders for full-scale standard plants had apparently been placed by European customers and were going though the permitting process.

The anticipated performance of Thermoselect technology relative to environmental emissions is expected to be very good. Stringent control and a high degree of detoxification of all effluent streams are consistent goals in the firm's development philosophy.

1. Current Status and Remaining Development Needs

According to Thermoselect, the demonstration plant has gone through 20,000 hours of operation and now operates continuously for 5 days a week, processing unshredded municipal and industrial wastes. The plant uses product gas to drive an engine generator and to heat the degasification channel. Since not all available gas is used, any excess is burned in a combustion chamber and discharged through the stack together with the products of combustion from the degasification chamber annulus.

Major unresolved areas appear to be:

- *Optimization of energy use:* An 1.8-MW engine being installed for further testing.
- *Use of reactor gas on gas turbines:* Being investigated.
- *Commercial plant design*: Replacement of natural gas with the reactor gas envisioned
- *Waste heat recovery from gas engine off-gases and process waters:* Planned for commercial systems to improve overall plant thermal efficiency.
- *Continuity and reliability of operation*: Demonstration plant has only been operated on a 5-day/ week cycle. Continuous round-the-clock operation is yet to be demonstrated. Experience in other development programs has shown the importance of demonstrating that the process can run successfully under the stresses and limitations of nonstop operation.

- *Scale-up*: Although the current demonstration plant is reported to have a "nominal capacity of 4 Mg/h" (4.4 t/h), experience to date shows that the unit appears to operate at an actual throughout of only 3.8 Mg/h (4.2 t/h). The Standard design (Table 6.3) has a line capacity of 10 Mg/h (11.0 t/h) per line; therefore it represents a scale-up factor over that indicated by Thermoselect of about 2.7:1 based on actual operating experience. The attainment of design capacity in scale-up situations is never certain because the relationships between the scale of operation (e.g., feed rate) and key process variables, such as the rate of heat transfer into the compressed "plug" of waste, are complex. Although the success of the planned commercial-size facility is yet to be proved, the extensive positive experience in the demonstration plant to date increases confidence in a successful outcome.

D. PROCESS DESCRIPTION

1. General Description

The Thermoselect system processes commingled MSW and "selected" industrial waste and converts them into what they state are environmentally safe products, including a cleaned product, vitrified solid granules, elemental sulfur, and sodium salts. No liquid effluents are discharged into the environment. Process water is treated and recycled. In addition, the process is intended to minimize both the formation and emission of particulates, nitrogen oxides, and other pollutants.

Gasification is achieved at a high temperature. The products of gasification are then held at high temperatures for more than 4 seconds—a relatively long residence time. Data indicate that this combination of time and temperature destroys the complex organic compounds produced in the gasification process and yields a product gas that, substantially, has reached chemical equilibrium. The raw gas is cleaned in an air pollution control/gas purification system, removing acid gases, hydrogen sulfide, particulates, and volatile heavy metals. Air emissions result solely from the combustion of the cleaned gas during the production of heat in boilers or other means for the generation of electric power.

The Thermoselect demonstration facility is located at Fondotoce, Italy, near Lago Maggiore, a picturesque tourist area in the southern foothills of the Alps. The plant was in normal operation during CDM's visit on October 8, 1995. The equipment, consisting of one process line with a nominal capacity of 4 Mg/h (4.4 t/h), is housed in an attractive low-level building with two relatively short stacks. Normal operation was in progress during the visit, with the delivery of municipal and bagged industrial wastes by truck. No odor or noise was observed either inside or outside the plant.

2. Process Description

a. Schematic and Flowsheet

Figure 6.1 is a schematic of the Thermoselect® gasification system; Figure 6.2 is a flowsheet showing the components of the process. The various stages of this process are described in the following subsections.

Table 6.3 Scale Up: Thermoselect Process

Category		Units	Prior Work		Fondotoce Facility	Standard Plant
Line	capacity	Mg/h.	1.00		3.8	10.00
	factor capacity				4.20	2.38
Press (Compactor)	maximum capacity	Mg/h	1.50		6.00	16.00
	capacity	kg/cycle	80.00		280.00	600.00
	cycles	1/h	12.50		15.00	16.67
Degassing Channel	length	m	20.00	13.00	13.00	14.00
	height	m	0.25	0.25	0.35	0.50
	width	m	0.90	0.90	1.50	1.80
	section area	m^2	0.23	0.23	0.53	0.90
	surface factor				2.33	1.71
	volume	m^3	4.50	2.93	6.83	12.60
	capacity	Mg	7.20	4.68	10.92	20.16
	residence time	h	7.20	4.68	2.60	2.02
High-Temperature Chamber	diameter lower section	m	2.10		2.10	2.60
	height solid bed	m	0.90		1.60	3.20
	volume lower section	m^3	3.12		5.54	16.99
	capacity lower section	Mg	6.23		11.08	33.97
	capacity factor				1.78	3.07
	energy input	MW			propor-tional	propor-tional
	residence time, top section	second	~2		>2.5	>2.5
Homogenization Chamber	length x width factor				~2.5	~2.5

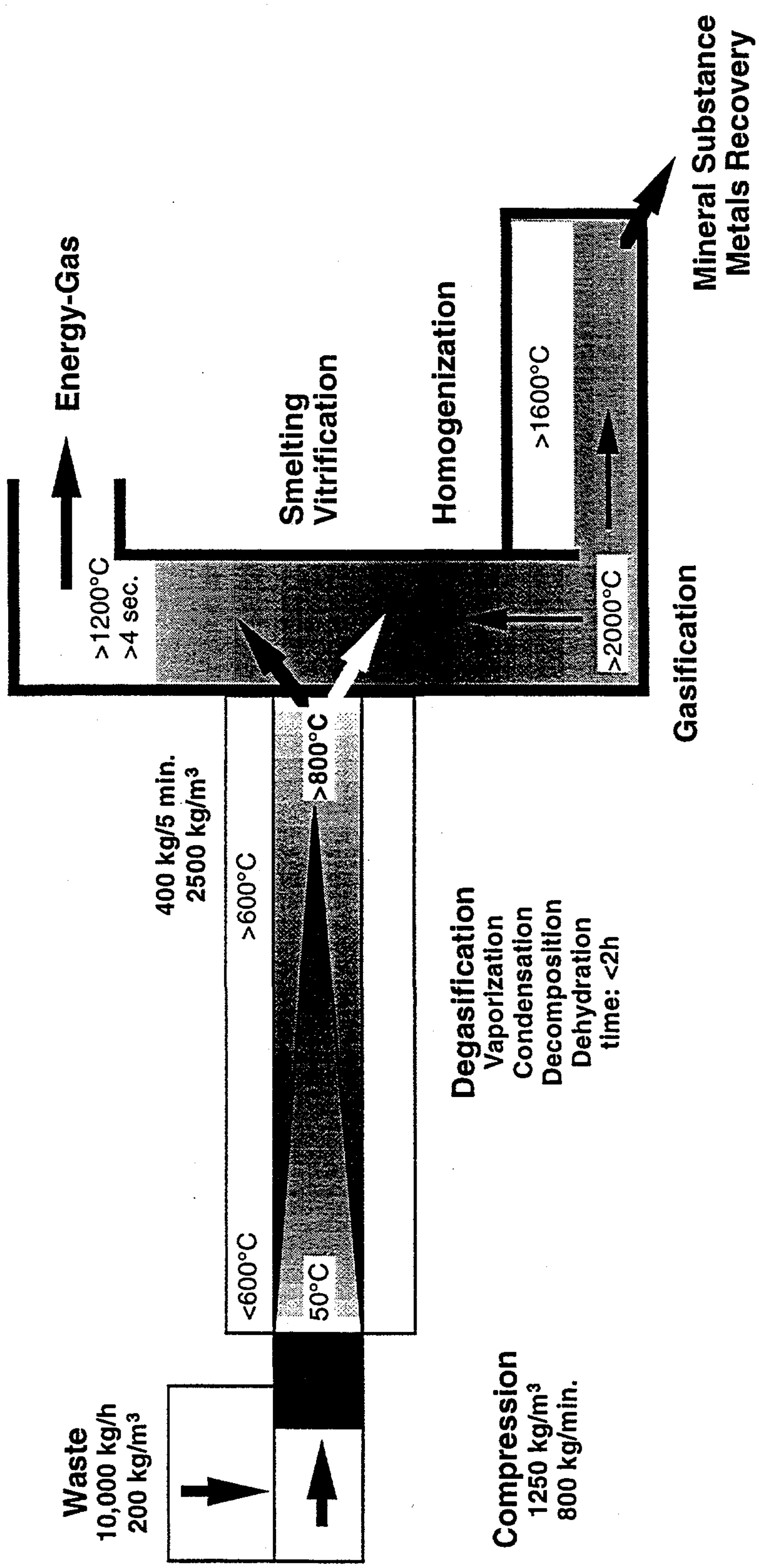

Figure 6-1
Thermoselect Process
Energy and Raw Material Recovery

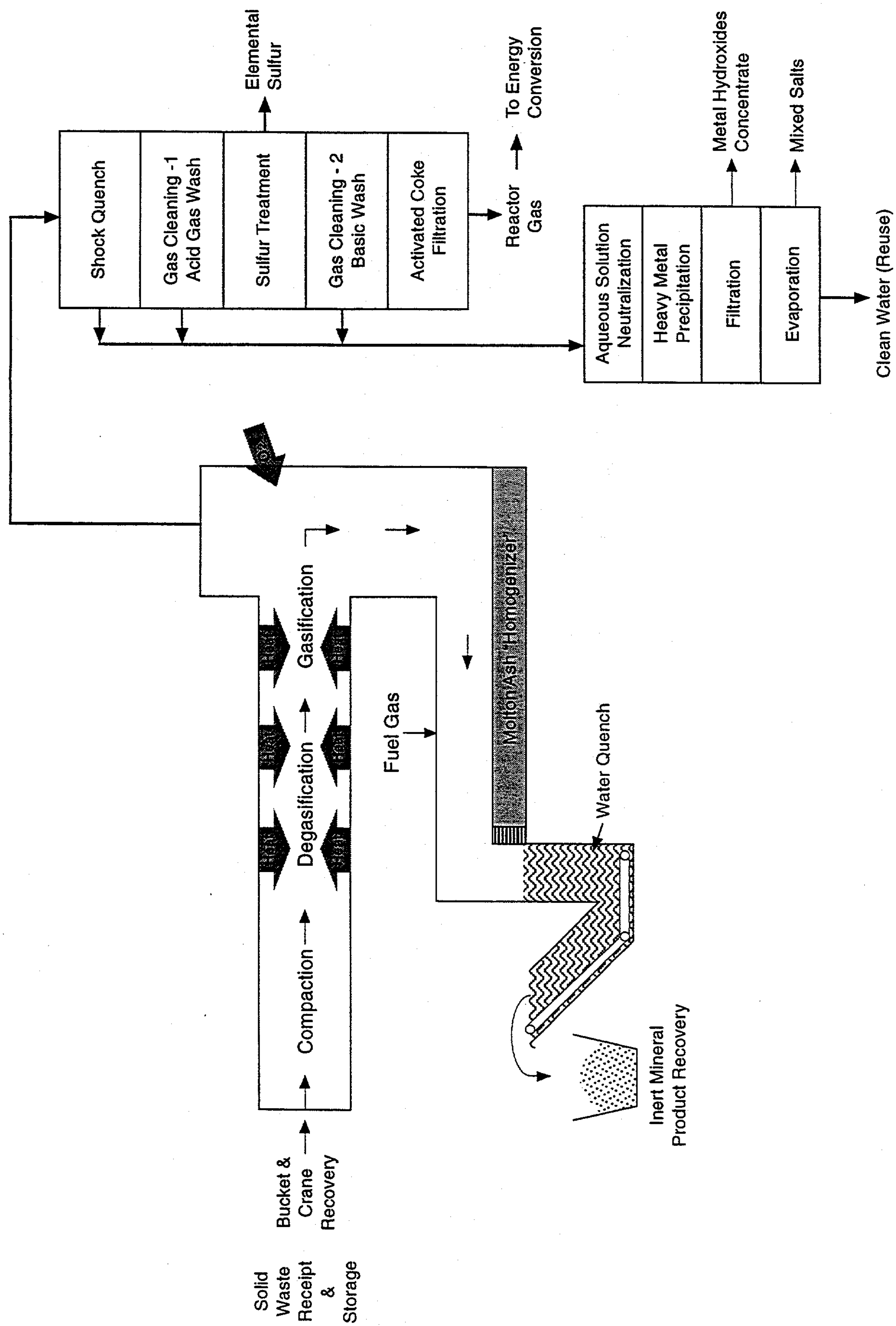

Figure 6-2
Thermoselect Process Flow Diagram

b. **Compaction**

An industrial scrap-metal compactor is used to pack commingled waste to less than 10 percent of its original volume, thereby removing the air contained in the original loose material. The raw waste is dropped by grapple from the waste pit into the housing of the compactor, which presses the loose material against a heavy metal gate to a density of 1.25 Mg/m^3 (78.5 lb/ft^3). As the process calls for feed, the gate opens, and the compactor moves the plug of waste though an unheated transition section into the degassing channel.

c. **Degassing/Pyrolysis of the Organic Fraction of the Waste**

The degassing channel containing compacted material is externally heated with a portion of the process generated gas to 600°C (1112°F). The reactor gas is burned with forced air in an annulus surrounding the degassing channel. As the compacted waste plug heats, volatile components (VOCs) contained in the waste vaporize and move the waste forward to the next stage. The heated vapors include the water common to solid wastes as steam. The waste plugs are pushed down the degassing channel; as they approach the transition to the next in-line state, they receive radiant heat from the next stage. The temperature in this area is 800°C (1472°F). At this transition point between the degassing channel and the next stage, identified as the high-temperature chamber (HTC), the waste plugs are much smaller because they have lost volatile components (water and VOC); the nonvolatile organic portion has been carbonized to a high degree, and the inorganic portion of the waste has remained virtually unaffected as part of the carbon matrix.

During this degassing stage, the conditions and ingredients that allow a water-gas reaction are present ($C + H_2O = CO + H_2$). Hydrogen and carbon monoxide thus move with the vaporized VOCs from the degassing channel into the upper section of the HTC, which is maintained at 1200°C (2192°F).

Upon reaching the transition point with the HTC, the carbon matrix breaks apart and falls into the lower section of the HTC. The travel time through the degassing channel is normally less than 2 hours.

d. **High-Temperature Gasification (maximum pressure: 1.3 atm)**

The matrix of carbon and inorganic material fills the lower section of the HTC, where oxygen is introduced. The reaction of oxygen with carbon produces a temperature of 2000°C (3632°F). This controlled exothermic temperature provides the heat necessary to melt the inorganic fractions—composed primarily of glass products and various metals—contained in the carbon matrix. In effect, this lower section performs as a smelter. The inorganic molten mass of mineral and liquid metals flows from the lower HTC into the homogenization stage, where it is prepared for removal from the process.

In the lower section of the HTC, the equilibrium reaction ($C + O_2 \rightarrow CO_2$) between carbon and oxygen produces the gas—carbon dioxide (CO_2). By shifting the equilibrium in the presence of CO_2 ($C + CO_2 \rightarrow 2\,CO$), a high-volume percentage of the energy carrier—carbon monoxide (CO)—is formed. Both these gases, the CO and a reduced volume of CO_2, flow to the upper section of the HTC, which is maintained at 1200°C (2192°F), and join the other gaseous products received from the degassing channel of the process.

In the upper chamber of the HTC, the addition of oxygen maintains the temperature at 1200°C (2192°F). This upper chamber is the collection point for all process gases. The temperature provided in this section through a proprietary oxygen introduction technique, combined with a residence period approaching 4 seconds and turbulence, is adequate to destroy the most complex organic compounds.

The resultant hot gases at 1200°C (2192°F) exit the HTC and are immediately water quenched in a spray chamber to below 70°C (158°F). Section g., Process By-Products, has a further discussion of the process.

e. Homogenization Chamber

The metal and mineral flow from the lower HTC enter this stage, where additional oxygen is introduced to react with any remaining carbon particles in the mineral/ metal melt flow. As all remaining carbon is depleted, additional heat is required to maintain the melt. Natural gas burners provide this heat at 23 kg/Mg (46.6 lb/t) or 31.15 m^3/Mg (1000 ft^3/t). The combined molten metal and mineral melt streams are quenched in a water bath. The vitrified mineral stream cools and forms a vitrified mineral granulate, and the metal mix freezes, forming metal alloy pellets, as the flow enters the water bath. The resultant mix of granulate and metal pellets is recovered using a drag chain conveyor. The developers have stated that the vitrified mineral granulate meets EPA Toxicity Characteristics Leaching Procedure (TCLP) standards, as shown in Table 6.4. Such compliance may make possible the use of this glass-like mineral product for:

- Raw material components for making clinker brick
- A cement substitute analogous to the use of anthracite fly ash
- A concrete additive
- A filler for bituminous mixtures
- A filler and antifrost layer in underground engineering
- Mineral fiber and heat insulation fibers
- Decorative pavers and blocks for the building industry.

The redox processes occurring above 1800°C (3272°F) reduce the metal oxides and cause typical alloy-forming metals such as nickel, chromium, and copper to pass into an iron-rich metal melt. Since this melt has a very low concentration of high-vapor-pressure components such as mercury, zinc, cadmium, lead, and arsenic, it can be used directly for metallurgical purposes.

Because of the severe duty imposed on the Homogenizer Section, it must be replaced periodically. The developer includes a "spare" Homogenizer in the basic plant capitalization to ensure that an exchange with a spare section can be performed with minimum line outage. The replacement period is 6 months, and Thermoselect has stated that cooling and removal of the spent unit, positioning of the refreshed unit, and restart can be accomplished over a weekend—a seemingly optimistic estimate.

f. Gas Cooling and Gas Separation from Process Water

The hot gases contained in the upper section of the HTC exit are rapidly water quenched to below 70°C (158°F). The reactor gases and sulfur gases (H_2S) are separated from the quench water and passed through successive scrubbers: acid wash at ~60°C (~140°F), desulfurization, and base wash at

Table 6.4 Vitreous Mineral Product: Elution Testing

Analysis	Result	Unit	EPA Regulatory Limit
Ignition	>200	°F	<140
Corrosivity	6.9	pH	<2, >12.5
As Cyanide	<0.10	mg/kg	variable
As Sulfide	<0.50	mg/kg	variable
Arsenic, TCLP	<0.40	mg/*l*	5.0
Barium, TCLP	0.07	mg/*l*	100.0
Cadmium, TCLP	<0.01	mg/*l*	1.0
Chromium, TCLP	0.04	mg/l	5.0
Copper, TCLP	0.11	mg/*l*	100.0
Lead, TCLP	<0.10	mg/*l*	5.0
Mercury, TCLP	<0.0025	mg/*l*	0.2
Selenium, TCLP	<1.0	mg/*l*	1.0
Silver, TCLP	0.03	mg/*l*	5.0
Zinc, TCLP	0.22	mg/*l*	500.0

40°C (104°F). They are cooled to 5°C (41°F) to remove water vapor and are then passed through a coke filter and warmed to ambient temperature before use.

When a waste feed containing 50% organic matter/ 25% organics/ 25% water at 10.4 MJ/kg (4472 Btu/lb) is processed, an 8.3-MJ/Nm^3 (224-Btu/ft^3) reactor gas with the following average composition results:

Average Reactor Gas Composition	Vol %
Carbon Monoxide (CO)	34 - 39
Hydrogen (H_2)	32 - 35
Carbon Dioxide (CO_2)	22 - 27
Nitrogen (N_2)	3 - 4
Methane (CH_4)	< 0.1
Other	< 0.6

These values appear close to those predicted by the assumption of thermodynamic equilibrium at 1200°C (2192°F), which suggests there is adequate retention time. The small amounts of methane, as well as larger proportions of CO, are indicative of the decomposition of higher-molecular-weight substances.

The cleaned reactor gas is an energy source for the production of electricity or as a fuel to a steam boiler. The energy conversion plant is included as part of the scope of supply by the developer. The reactor gas can also be a chemical feedstock for methanol or benzene formation.

Air emissions from all sources are significantly below EPA NSPS for large MSW combustors, as shown in Table 6.5.

The high-volume water quench of the hot process gases quickly lowers the temperature of the gases; the water serves as a sink for particulates, heavy metals, and water-soluble acid gases such as Cl_2 and F_2, which form HCl and HF respectively.

The sulfur-removal system converts hydrogen sulfide (H_2S) to sulfur using an iron III complex via a well-proven, proprietary process. The resultant iron III complex, proportionately formed, is regenerated in an adjoining stage using air oxygen. The removal of elemental sulfur (S), compared with the removal as gypsum ($CaSO_4$)—common to most thermal processes—reduces the sulfur solids end product by a factor of more than four.

g. Process By-Products

The processing-water solutions generated from the gas-cleaning sections are subject to conventional chemical material separation processes. After removal of the heavy metal hydroxides as a solid concentrate and other insoluble portions of the process water, the combined streams pass through a reverse osmosis membrane, removing much of the remaining salts (sodium chloride). This step is followed by evaporation of the water to remove any soluble residuals. The cleaned water is used in the process-water loops and cooling towers. Since the process recovers the water contained in the original waste input, there is additional water recovered as part of the process; it is sprayed on hybrid cooling towers and evaporated. No process water need be diverted to a sewer.

The following by-products are collected in addition to the product gas, vitrified mineral product, and metal alloy pellets:

- Industrial-grade sodium chloride (salt)
- Elemental sulfur
- Concentrate containing heavy metal hydroxides.

The metal and vitrified mineral granulates collected from the Homogenization Chamber can be density separated when in molten form, but they are more easily handled in granulate and metal-pellet form. These pellets can then be separated by a magnet into vitrified mineral product and metal alloy pellets. The metal pellets consist of iron alloy (>90%), with considerable amounts of copper (3 to 5%), nickel (0.6%), chromium (0.3%), tin (0.4%), and phosphorus (0.1%). Concentrations of heavy metals that find their way into these by-products are at acceptable levels.

Table 6.5 Comparison of Air Emissions

Component	Units	U.S. EPA*		Thermoselect†
HCl	ppm(v)	25.0	(or 95% removal)	0.5
SO_2	ppm(v)	30.0	(or 80% removal)	2.0
NO_x	ppm(v)			<80.0§
First Year		180.0		
Subsequent Years		150.0		
CO	ppm(v)	¶		30.0
Dust	mg/Nm^3	24.0		9.0
Cd and Tl	mg/Nm^3	0.020		<0.01
Hg	mg/Nm^3	0.08	(or 85% removal)	0.03
Pb**	mg/Nm^3	0.20		0.01
PCDD & PCDF				
Total	ng/Nm^3	13.0		
TEQ	ng/Nm^3	0.20		0.02

* Final U.S. EPA standards. NSPS for New MWCs: Federal Register, December 19, 1995 - 40 CFR Part 60

† Represents average daily values

§ This value is dependent on the method used to convert synthesis gas into an energy form.

¶ Depends on EPA interpretation of combustor class.

** Pb plus all remaining heavy metals: <0.07mg/Nm^3.

∑: Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V, Sn.

The residual aqueous solution from the wastewater purification system flows to a distillation tower to concentrate the residual sodium salt and recover high-quality water for recycle to the process. Thermoselect claims that the concentrate contains only minimal amounts of contaminants.

E. ENVIRONMENTAL ASPECTS

1. Process Emissions Characteristics

An extensive testing program was conducted between June and September 1994 by ten institutions from Germany, Switzerland, and Italy. Some of the participants were:

- RWTÜ-Essen
- TÜ Energy & Environment GMBH
- Badenwerke AG-Karlsruhe
- Filderstadt and Steiger Environmental Technology AG-Lista

Emissions data from the gases exhausted when heating the Degasification Channel (Table 6.5) indicate emissions well below the EPA NSPS for new MWCs.

Further, test results indicate less than 0.1% free oxygen in the gas and only minute traces of organic compounds. No chlorinated aromatic hydrocarbons, other than PCDD+PCDF, were detected. No aromatic amines, carbonyl-sulfide, carbon sulfide, or phosgene could be detected. The data indicate that this system will comply with US environmental regulations.

2. Aesthetics

The demonstration plant, as well as the standard plant design, includes an attractive low-rise architec- turally designed building that should blend in well in a commercial environment, such as a modern industrial park. What remains to be seen, however, is whether the short stacks presently included in the design will be acceptable to US regulatory agencies.

F. MATERIAL AND HEAT BALANCES

1. Mass Balance

The values of the mass and energy balances shown are derived from the experience and test data obtained at the demonstration facility. They have been recalculated for the six-gasifier representation of Thermoselect's standard 10-Mg/h (11-t/h) units.

The mass balance is presented in graphic form in Figure 6.3 at a total feed rate of 60 Mg/h (66 t/h). The balance shows the flow-through of materials, including the outflows of product gas and various by-products of the process. Although natural gas is presently used in the Homogenizer, Thermoselect anticipates that future commercial facilities will be able to use the product gas for this purpose.

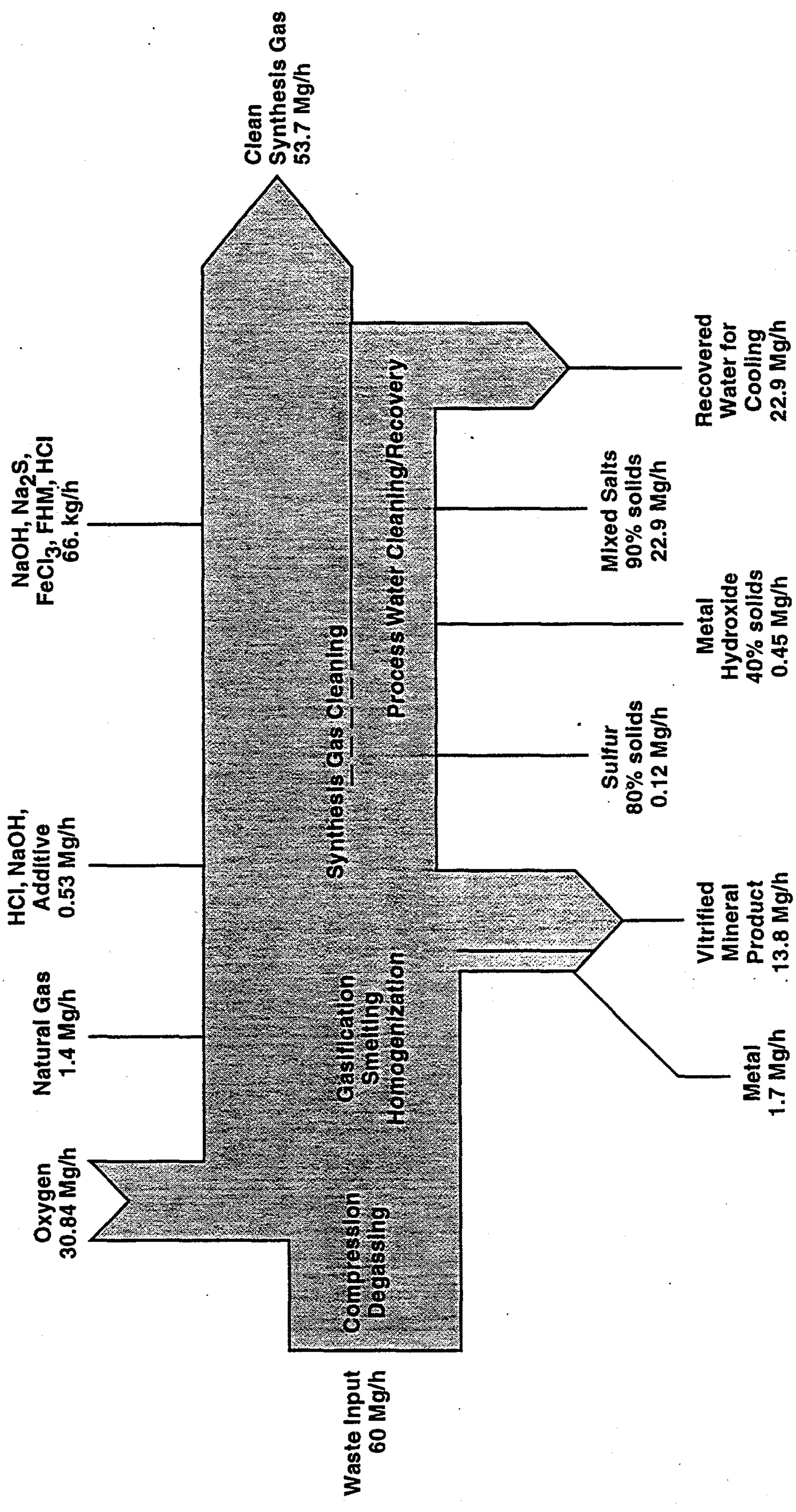

Figure 6-3
Thermoselect Mass Balance
(Six lines, 10 Mg/h/line: 450,000 Mg/y)

The process consumes oxygen at a rate of 0.514 Mg (1028 lb/t)/Mg (t) waste plus natural gas at 15.4 Nm^3/mg (1000 ft^3/t). The process produces about 830 Nm^3 (26,500 ft^3/t) /Mg(t) gas for each ton of waste. A six-unit facility is expected to produce the following quantities of by-products:

Metal	1.74 Mg/h	=	12,900 t/y
Vitrified granulates	13.8 Mg/h	=	102,000 t/y
Sulfur (80-percent solids)	120 kg/h	=	900 t/y
Mixed salts (90-percent solids)	0.72 Mg/h	=	5,400 t/y
Metal hydroxide (40-percent solids)	0.45 Mg/h	=	3,300 t/y

Thermoselect believes that a market exists for these products, with the exception of the hydroxide sludge, which may require monofill disposal as a hazardous waste. The metals can be comixed for use in metallurgical furnaces, and the mineral granulates can be raw material for the ceramics industry. Traces of heavy metals in the sludge are said to be securely bonded with mineralizing agents to ensure environmentally stable disposal. Sulfur and industrial mixed salts may find their natural market. However, in the economic analysis of the facility, no credits have been taken for such products. Thus the result of the analysis is conservative.

2. Energy Balance

Energy input of 173 MW (590 x 10^6 Btu/h) is supplied by the refuse, which has a heat value of 10.4 MJ/kg (4472 Btu/lb). An additional energy contribution of about 10 percent is made by natural gas. The energy balance (Figure 6.4) indicates a net thermal energy output in the product gas of 114.8 MW for the 60-Mg/h (61.4 t/h) system or 6900 MJ/Mg (5.9 x 10^6 Btu/t) after allowing for the heat energy absorbed in the Degasification channel. This gas is available for the production of energy.

Using the procedure for estimating energy conversion costs described in Section 2, the remaining clean gas generates 240,000 MW annually, or 530 kWh/Mg (484 kWh/t) of electrical energy in a gas engine/genererator. The developer's energy balance (Figure 6.4) indicates internal consumption of 16.6 MW or 123,750 MWh/y, leaving net exportable power at 116,250 MWh/y or 260 kWh/Mg (236 kW/t). The energy estimates are based on a conversion efficiency of 28 percent. The rejected heat from power generation is identified as recirculated "useful heat."

The six-line, 1440-Mg/d (1584-t/d) plant would have an installed electrical capacity of 32.2 MW, with a nominal 15.6 MW of export power. Although six, 2-MW spark-ignition gas-engine generators are assumed for the Standard Plant, the actual type of generation equipment is left to user preference. For a 32.2 MW plant, a gas turbine gas-to-electricity conversion strategy may be optimal. The gross heat rate for the facility, before use of internal power, is 18.5 MJ/kWh (17,500 Btu/kWh).

G. DEVELOPMENT HISTORY

The history of the Thermoselect demonstration plant is summarized in Table 6.6. As a demonstration facility for the process, downtimes were scheduled over the years for inspection, equipment modification, and permit application. The plant is presently being run continuously for 5 days a week, with the longest operating period of more than 36 weeks at 5 days a week.

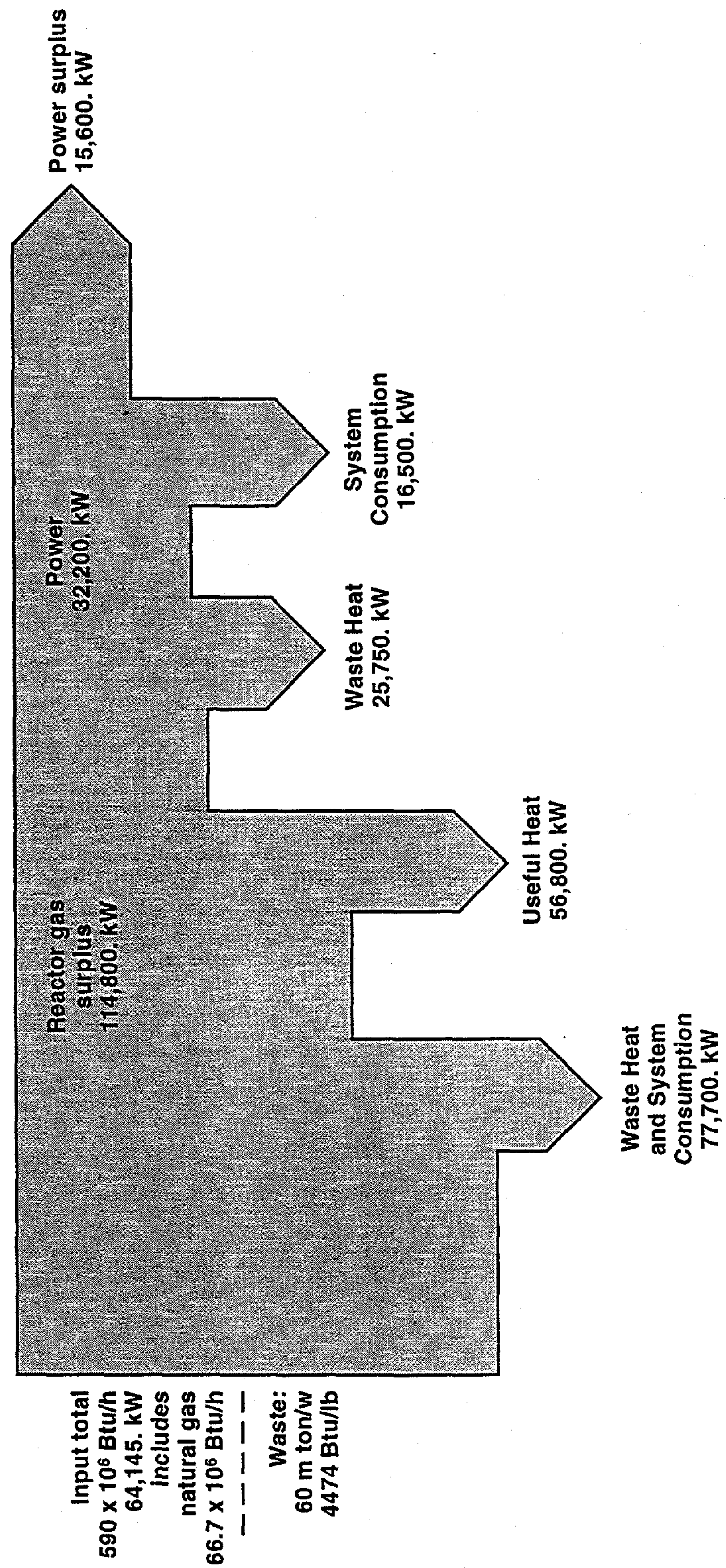

Figure 6-4
Thermoselct Energy Balance
(Six lines, 10 Mg/h/line: 450,000 metric ton/year)

Table 6.6 Sequence Steps in the Development of the Thermoselect Process

Time Frame	Duration	Status
1989	2 yrs	Study of the carbonized process vs. pressure, temperature, time, and waste properties: 10 kg/h (22 lb/h)
1991	1 yr	Development of the carbonization and degasification processes using 20-m long, 0.225 m^3 cross-sectional area; study of the gasification process and refractory lining behavior; development of a burner design ensuring both safety and a quick-change feature; material stability; measurement methods, and product quality: 1000 kg/h (2200 lb/h)
9/91	1 yr	Beginning of plant building construction.
3/92	7 months	Installation of major equipment completed.
10/92	0	Start-up of the complete demonstration plant after installation of an evaporator assembly. Includes trial period with tests of a 1.2-MW reactor gas engine. Plant operation licensed for a processing capacity of 4200 kg/h (9240 lb/h)
1/93	3 months	Beginning of an evaluation program by Italian, Swiss, and German experts.
4/93	6 months	Dismantling of major components and inspection by independent experts mandated to study the stability and dependability of processing assemblies after 4000 hours of operation.
11/93	13 months	End of a 12-month trial period including tests with a 1.2 MW reactor gas engine.
4/94	18 months	Permit received for the continuous operation of a complete disposal line (Fondotoce plant) at 100 Mg/d (110 t/d).
6/94	20 months	Comprehensive studies begin of the Fondotoce plant, including testing of all substance flows and the setting up of material and energy balances; waste throughput of up to 4.4 Mg/h (4.8 t/h) at waste calorific values of from 12 to 13 MJ/kg (5160 to 5590 Btu/lb).
9/94	2 yrs	Completion of testing and confirmation of the design for the standard plant.

* For start-up of demonstration plant

The table also shows the various upgrading steps undertaken during the history of this development; Figure 6.5 illustrates the dimensional changes (shown to scale) made when upgrading from laboratory scale to the proposed Standard Line.

The plant was subjected to thermal cycling during the early years to "identify stress areas." Engineering tear-down assessments was made in 1993 after 4000 hours. In December 1994, the plant was shut down after 7500 hours of operation for another assessment of the equipment. The evaluation did not show any unusual or unexpected wear or corrosion problems. Subsequently, the plant was restarted and, apart from weekend shutdowns, is now in continuous commercial operation. Certified TUV reports are available that summarized the findings for the 1994 shutdown.

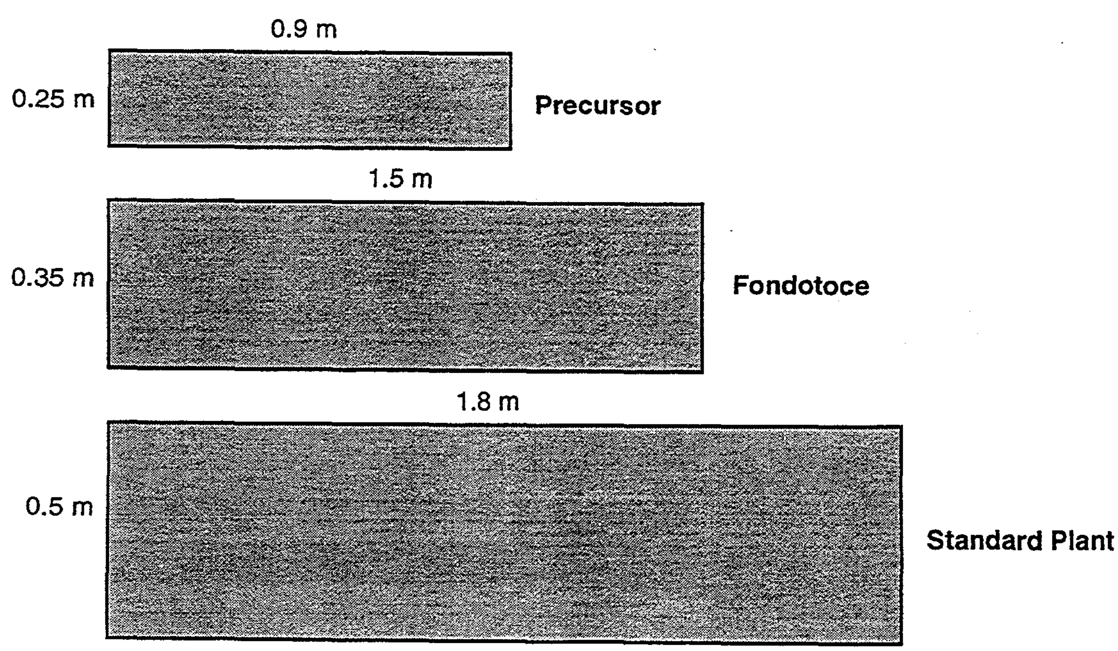

Figure 6-5
Degassing Channel
Cross-Sectional Area Comparison

H. INTERVIEWS

In the course of evaluating the Thermoselect technology, CDM engineers inspected the facilities in Fondotoce and met with staff from the U.S. operations. Those interviewed were:

- Fondotoce
  - — Dr. Jurgen Riegel, President
  - — Professor Dr. Rudi Stahlberg, Technical director
  - — Dr. Bernd Calaminus, Technical Associate, Chemical Engineer
  - — Dr. Uwe Feuerriegel, Technical Associate, Chemical Engineer
  - — Dr. Franz Steiger, Consulting Environmental Engineer
  - — Mr. Frederico Rei, Consulting Engineer
- U.S. Operations (Troy, Michigan)
  - — David Runyon, Executive Vice President
  - — Gayle E. Koch, Consultant

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5. R. Stahlberg, et al., "Part 3: Mass and Energy Balances of the Thermoselect Demonstration Plant," ASME ASTHMA Solid Waste Processing Division, 17th Biennial ASME National Solid Waste Processing Conference, Atlantic City, NJ, April 1996.

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Section 7

Battelle

A. Summary

The Battelle High Throughput Gasification System (BHTGS) is an indirectly heated, two-stage process that uses circulating fluidized bed (CFB) reactors. In a high-throughput gasifier, refuse-derived fuel (RDF) or other biomass feedstocks is gasified in a CFB to a medium-heating-value gas [18.6 to 22.4 Nm^3 (500 to 600 Btu/sft^3)], using steam without oxygen as the fluidizing medium. Residual char is consumed in an associated CFB combustor. A circulating-sand phase is the method for heat transfer between the separate reactors.

The BHTGS is said to produce gaseous emissions from the combustor that comply with EPA's New Source Performance Standards (NSPS) for Municipal Waste Combustors (MWCs). Wastewater from the process contains only trace quantities of organic materials. At Battelle's test site, the outlet of a simple, industrial treatment system—a sand filter followed by a simple charcoal filter—showed wastewater to be within EPA's drinking water standards.

Experimental data have been generated in Battelle's process research units (PRUs) in 1.5- and 2.5-dm (6- and 10-in) gasifiers with throughputs of 0.22- and 9.1-Mg/d (0.24- and 10-t/d) dry RDF respectively. Data from these units showed that extremely high throughputs, over 19.5 Mg/h•m^2 (1,400 lb/hr•ft^2), could be achieved. A wide range of feed materials, including RDF, has been tested in the system.

Battelle's development efforts began in 1977. Detailed process development activities were begun in 1980 with the construction of the PRU. These PRU investigations were conducted during the mid-1980s. The tests demonstrated the technical feasibility of the gasification process and provided the basis for generating a detailed process conceptual design. Based on this design, capital and operating costs estimates were also calculated. Testing of a highly prepared RDF was conducted in 1989 in a 2.5-dm (10-in.) ID, 6.9-m (22.7-ft)-high gasifier and a 1.0-m (40-in.), 3.5-m (11.5-ft)-high combustor. Throughput was 0.65 Mg/d (0.72 t/d).[1,2] The PRU has logged over 10,000 operating hours on a variety of feedstocks. The longest continuous operating run was approximately 100 hours at 9.1-Mg/d (10-t/d) dry RDF. A 200-kW gas turbine has been installed on the PRU and operated with wood for about 60 hours as an integrated gasifier/turbine system. The major issues requiring further work are feedstock preparation and gas cleanup.

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

B. FINANCIAL AND BUSINESS ASPECTS

1. Projected Capital and Operating Costs

Battelle has developed a process heat and material model to predict commercial-scale production with RDF as the feedstock. A copy of the computer printout for a 908-Mg/d (1000-t/d) dry RDF plant is shown in Figure 7.1. Battelle used this model to estimate the capital costs for a plant processing 908-Mg/d (1000-t/d) dry RDF. The cost of the gasifier plant was $19.2 million. The RDF Preparation Plant was estimated by Battelle at $25 million, based on published data for the National Ecology Plant in Baltimore, Maryland. The energy recovery was a combined cycle, and comparison with a conventional mass-burn waste-to-energy plant was quite favorable.[1] No estimates were made of operating and maintenance costs.

Even though the intent of this study was not to rank various technologies, a plant throughput at a lower rate was deemed more appropriate in this case. Battelle indicated the costs could be proportionate by ratio to the 0.6 power. This system and the ThermoChem system—another indirect system—are similar. Thus the ThermoChem referenced throughput of 479-Mg/d (528-t/d) dry RDF was assumed. This throughput converts to 595-Mg/d (655-t/d) wet RDF or 849-Mg/d (935-t/d) MSW. The original Battelle costing was done for a combined cycle. The same assumptions were made for this study, based on the fact that the BHTGS would be the same system, with a duty of 249,000 MJ/h (237 x 10^6 Btu/h). Capital costs are shown in Table 7.1.

2. Alternative Revenue Streams

In a study for DOE, K&M Engineering & Consulting Corporation designed an RDF plant that was connected to a gasifier plant. They analyzed resource recovery from the RDF preparation plant. The study also investigated various energy recovery systems.[3]

3. Business Aspects

Although Battelle has done only pilot plant testing with RDF, they have developed the gasifier system to the demonstration stage for wood chips. FERCO, Battelle's licensee, is commercializing Battelle's technology. FERCO chose not to participate in this study; they are actively pursuing the wood chip gasification market.

The main office address and communications numbers for Battelle, as of late 1995, are:

Battelle
505 King Avenue
Columbus, Ohio 43201

Tel: (614) 424-4958
Fax: (614) 424-3321

C. IMPLEMENTATION FEASIBILITY

Battelle's gasifier lends itself to a variety of applications—from gas distribution to energy recovery. In a recent study for DOE, K&M Engineering and Consulting Corporation analyzed implementation options. The energy recovery systems included combined cycle, Rankine cycle, methanol synthesis, and hot-water generation.[3] The BHTGS could be used for similar energy-recovery systems.

MASS AND ENERGY BALANCE SUMMARY FOR FOREST RESIDUE GASIFICATION MODEL

CASE #1	RDF
PLANT SIZE (t/d)	1000
DRY FEED RATE (lb/h)	83333.34
FEED MOISTURE CONTENT (%)	22.6
STEAM RATE (lb/h)	25983.59
PURGER GAS FEED (lb/h)	309.8
CARBON CONVERSION TO GAS (%)	63.2
PROD GAS RATE (sft³/h)	825507.5
ENERGY PRODUCT (10^6-Btu/d)	10773.3
PRODUCT HHV (Btu/h)	543.8
COLD GAS EFFICIENCY (%)	69.2
EXPORT ENERGY (10^6-Btu/h)	48.5
(lb/h STEAM @85% EFFICIENCY)	36115.2
TOTAL HEAT LOSS (10^6-Btu/h)	27.69
TOTAL PLANT,(% OF FEED HHV)	2.8
HEAT EXCHANGER (% OF FEED HHV)	1.6
GASIFIER INLET VELOCITY (ft/s)	10.17
COMBUSTOR GAS VELOCITY (ft/s)	17.9
GASIFIER TEMPERATURE (F)	1480.0
COMBUSTOR TEMPERATURE (F)	1780.0

COMBUSTION DATA

AIR REQ (lb/h)	183068.6
INLET AIR TEMP (F)	760
FLUE GAS RATE (sft³/h)	2427466.7
SAND RATE (lb/h-ft²) (GASIFIER)	34753

OVERALL ENERGY BALANCE (10^6-Btu/h)

	IN		OUT
WOOD	648.60	PROD GAS	590.18
STEAM	36.48	FLUE GAS	96.53
AIR	30.68	CONDENSIBLE	7.06
		DIRECT LOAD	20.85
TOTAL	715.74		714.63

HEAT LOSS SUMMARY

	10^6-Btu/h	%OF HHV
GASIFIER	1.382	0.21
COMBUSTOR	2.407	0.37
GASIFIER CYCLONES	0.403	0.06
COMBUSTOR CYCLONES	2.976	0.46
SURGE POTS	1.619	0.23
L VALVES	0.175	0.03
PIPING	8.986	1.30
SUM	17.846	2.75
(HEAT EXCHANGE)	9.846	1.52
TOTAL	27.692	4.27

ELEMENT BAL-GASIFIER (lb/h)

	IN	OUT
C	37891.67	37891.66
H	10441.91	10441.91
N	626.47	626.47
ASH	77135.23	77135.23
S	116.67	116.67
TOTAL	0.28	13382.28

VESSEL SIZES (ft)

	ID	OD	HEIGHT
GASIFIER	7.30	8.2	73.6
COMBUSTOR	12.50	13.6	73.6
GASIFIER CYCLONES	4.80	5.4	19.1
COMBUSTOR CYCLONES	9.80	9.4	35.2
SURGE POTS	11.70	12.8	23.3
L VALVES	1.40	2.1	15.0

DETAILED MASS AND ENERGY BALANCE

IN

IN	lb/h	10^6-Btu/h
WOOD	83333.3	648.6
MOISTURE	24109.5	0.0
STEAM	25983.6	36.5
NITROGEN	309.8	0.0
TOTAL	133820.3	685.1

CHAR

OUT	lb/h	10^6-Btu/h
C	13629.29	200.00
H	255.80	16.80
ASH	7125.00	3.20
TOTAL	21610.09	219.00

AIR REQUIREMENT

	lb mol/h	10^6-Btu/h
O_2	1326.8	6.63
N_2	6021.6	24.05
TOTAL	6348.3	30.68

NET PRODUCT GAS

GAS	lb mol/h	mol %	10^6-Btu/h
H_2	404.9	7.2	53.8
CO	909.0	16.2	120.2
CO_2	234.2	4.2	3.0
CH_4	362.6	6.5	145.0
C_2H_4	231.6	4.1	146.1
C_2H_6	13.3	0.2	9.3
H_2O	3439.8	61.2	110.6
N_2	22.4	0.4	0.2
TOTAL	5617.9	100.0	590.2

CONDENSIBLES

	lb/h	10^6-Btu/h
C	314.56	4.6
H	39.32	2.4
O	62.92	0.0
TOTAL	416.82	7.1

FLUE GAS

	lb mol/h	mol %	10^6-Btu/h
CO_2	1135.0	17.7	23.0
H_2O	127.9	2.0	4.5
O_2	119.8	1.0	1.6
N_2	5021.5	78.4	64.0
TOTAL	6404.9	100.0	93.1
ASH (lb/h)	7958.3		3.4
SUM (lb/h)	204688.7		96.5

Figure 7-1
Output of Computer Model for 1000 TPD RDF Gasification Plant

Table 7.1 Capital Cost: Battelle High Throughput Gasification System (BHTGS)

System:	849 Mg/d (935 t/d) MSW 595 Mg/d (655 t/d) RDF Circulating Fluidized Bed RDF Gasifier Heated by and Fluidized With Steam Combined With a Circulating Fluidized Bed Char and Sand Combustor Fluidized With Air		
Air Pollution Control (on Char/ Sand Bed Exhaust):	Mechanical Collectors Wet Scrubber		
Facility Capital Investment:			**Source**
Fuel Preparation:		$37,000,000	CDM
Process/Heat Recovery/ APC Train:			
Equipment (Installed)	$ 8,640,000		Developer
CEM System	1,000,000		Developer
Process Core Cost	$9,640,000		
Engineering & Contingency (30% of Process Core)	2,892,000		CDM
Subtotal		$12,532,000	
Electrical Generation (Combined-Cycle Gas Turbine)		31,000,000	CDM
Total		$80,532,000	
		per Mg/d MSW:	$94,900
		per t/d MSW:	$86,100

Battelle did not provide estimates of operating costs. The operating costs follow the guidelines mentioned previously for this study. The labor costs were based on the costs as generated for the ThermoChem system. The operating costs are shown in Table 7.2.

The wood-chip project in Burlington, Vermont, will be conducted in two phases. In the first phase, construction and operation of a 182-Mg/d (200-t/d) gasifier began at the site in 1995. The product gas will be burned in the existing boilers. In the second phase, a gas turbine will be installed to accept the product gas from the gasifier as part of a combined-cycle system planned for operation in 1997.[4,5]

1. Process Issues and Problem Areas

The primary process issue relates to fuel preparation. The specific level of fuel preparation necessary for the process has not yet been determined. In this case, preparation refers to the removal of low-melting-point inorganic materials, such as glass and aluminum, from the incoming waste. It does not encompass a requirement for fine shredding of the feedstock or for extensive preparation such as pelletizing. Feed size range will be dictated by the feed system requirements.

2. Operating Issues and Problem Areas

The primary operating issue when processing MSW in the system is ash agglomeration. The melting characteristics of the inorganic portion of the MSW feed material are directly related to the removal of glass and aluminum from that material.

3. Remaining Research and Development Needs

The primary research need is to determine the degree of preparation of the incoming MSW necessary for successful operation. A secondary need, but also important, is product gas cleanup (tar cracking and particulate removal). Additional operation at PRU scale is necessary to confirm the preliminary results obtained during the 1989 study at Battelle. Some preliminary data have been generated relative to the fate of chlorine in the process; these data should be confirmed before the design of a commercial facility.[7]

D. PROCESS DESCRIPTION

1. Overview

The BHTGS employs a CFB gasifier to provide high throughputs of biomass material. Heat necessary for the gasification reactions is provided from a stream of circulating sand which passes between the gasifier and an associated combustion reactor. The process is shown schematically in Figure 7.2. A small amount of char is produced as a result of the gasification reactions (typically 20 percent of the feed material). This char provides the fuel for reheating the circulating sand in the combustor. Like the gasifier, the combustor is a CFB reactor; it is also is capable of high throughputs.

Table 7.2 Operating Costs for Battelle Incineration System

Cost Element	No./Shift	Basis	Unit Cost	Annual Cost (000)	Source
Labor					
Superintendent	—	1	$45.00/h	$99	CDM
Operator (Op.)	1	4	$32.00/h	$280	CDM
Auxiliary Op.	1	4	$30.00/h	$263	CDM
Feed System Op.	1	4	$30.00/h	$263	CDM
Plant Attendant	1	4	$25.00/h	$219	CDM
Elect./Inst Maintenance	1	4	$35.00/h	$307	CDM
Mechanical Maintenance	1	4	$35.00/h	$307	CDM
Inert Gas (t/y)		609	$35/t	$21	Developer
Maintenance	$12,532,000	Allowance	3% of Capital	$376	CDM
Insurance	$12,532,000	Allowance	1% of Capital	$125	CDM
Compliance Testing		Allowance		$300	CDM
Residue Landfill		129,343	$40/t	$5,174	CDM
		Total Cost for Process Core		$7,734	
Contingency		10% of Process Core Cost		$773	CDM
Debt Service	$80,532,000		10.19% of Capital	$8,206	CDM
RDF Operations	N/A	290×10^6 t/y	$8.50/t	$2,465	CDM
Electric Gen. Operations	N/A	237×10^6 Btu/h		$1,700	CDM
			Total Gross Cost	$20,878	
Electrical Revenue					
Gross Generation (MWh/y)	237×10^6 Btu/h	240,000			CDM
RDF Power Use (MWh/y)		(7,250)			CDM
Internal Use (MWh/y)		(24,000)			CDM
Net to Export (MWh/y)		208,750	$0.04/kWh	($8,350)	
			Net Annual Cost	$12,528	
			Unit Cost $/Ton	$43.20	
			Unit Cost $/Mg	$47.63	

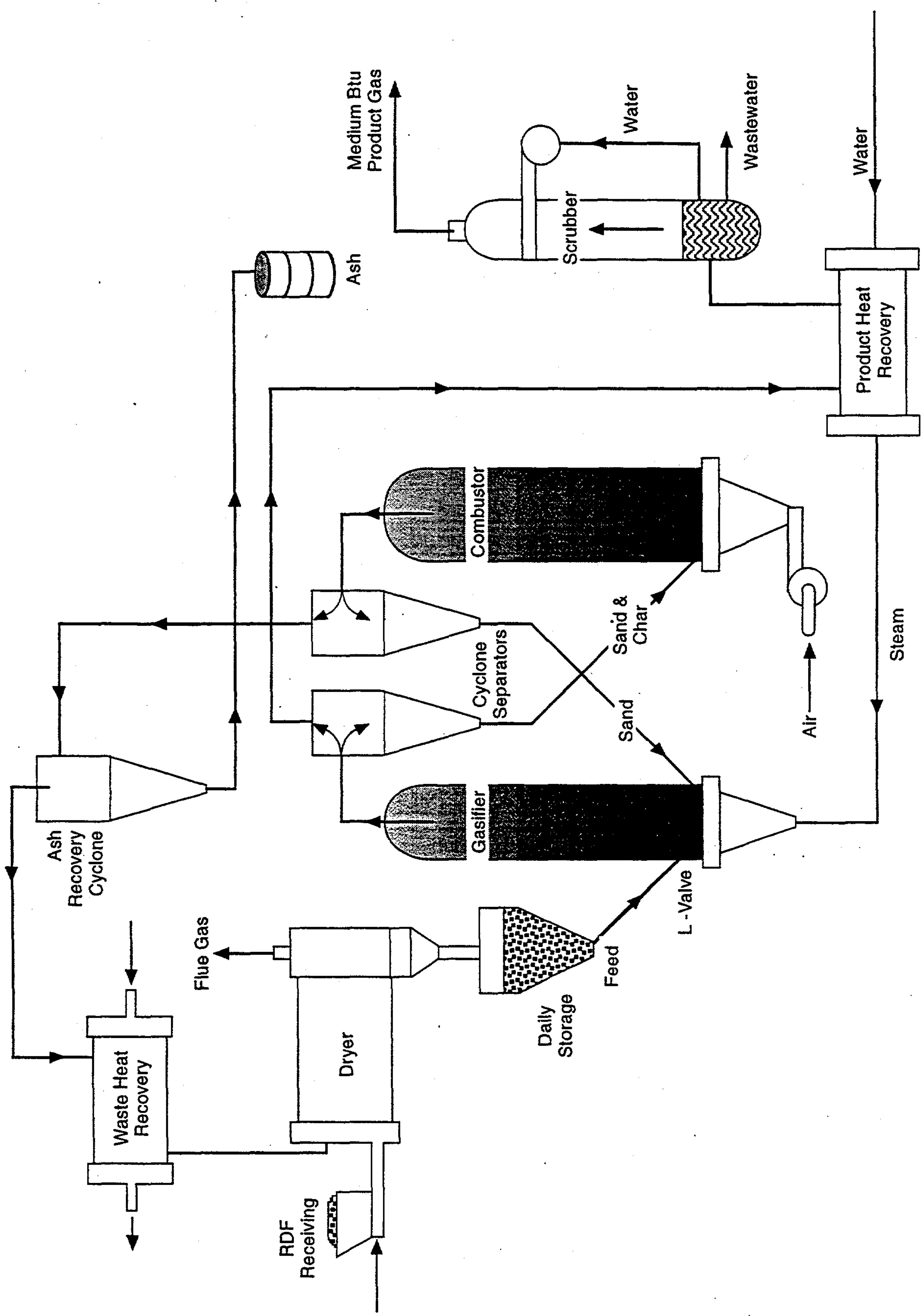

Figure 7-2
BHTG System

a. **Basic Concept**

The Battelle biomass gasification process produces a medium-Btu product gas without the need for an oxygen plant. The process schematic in Figure 7.2 shows the two reactors and their integration into the overall gasification process. This process uses two physically separate reactors:

- A gasification reactor in which the biomass is converted into a medium-heating-level gas and residual char
- A combustion reactor that burns the residual char to provide heat for gasification.

Heat transfer between the reactors is accomplished by circulating sand between the gasifier and the combustor.

The Battelle process provides a cooled, clean, 18.6- to 22.4-MJ/Nm^3 (500- to 600-Btu/sft^3) product gas. Waste heat in the flue gas from the combustor can be used to preheat incoming air and then to dry the incoming feedstock. Although these unit operations are not required, they provide a means of increasing product yield by returning waste heat to the process. The condensed, organic phase scrubbed from the product gas is separated from the water, in which it is insoluble, and injected into the combustor. As Figure 7.2 indicates, the products from the process are the cooled, cleaned product gas; ash; and treated wastewater.

Table 7.3 shows the chemical similarity of wood and RDF. Wood has been successfully tested and a commercial plant being constructed. The analysis shown is typical for RDF produced by National Ecology in Baltimore, Maryland. This same RDF was used during the Battelle PRU tests. The chemical similarity of the two materials suggested that RDF might behave in a similar manner to wood in the Battelle process. The PRU tests conducted in 1989 verified this expectation and demonstrated the potential of the process for providing an economical alternative to current RDF-based MSW systems.

The medium-heating-value gas generated can readily be used in conventional natural-gas-fired combustion equipment. Steam boilers, gas turbines, industrial heat treating furnaces, and process heaters are examples of potential users of the gas.

As Shown in Figure 7.2, fluidizing gases enter the gasifier at a level below the RDF feed entry port and an L-valve sand recycle entry. The sand, char, and product gas are conveyed from the top of the gasifier into the cyclone mounted atop the combustor; the cyclone disengages the sand and char and allows them to flow back into the combustor bed. After separation of the sand and char in the cyclone, the product gas passes through an additional cyclone, product heat recovery, and a scrubber.

The combustor, a bubbling fluidized bed with a refractory lining, is designed to minimize heat losses. Sand enters the combustor through a closed chute line from the gasifier cyclone. This line enters through the top of the combustor and extends downward into the fluidized bed. The sand bed is returned to the gasifier from the combustor by an L-valve. The L-valve provides the necessary seal between the combustor and gasifier environments.

Exhaust gases from the combustor pass through a cyclone separator, which discharges the fine, separated particles directly back into the fluidized bed. The flue gases then are further cleaned and cooled by a waste-heat recovery system and RDF dryer before being exhausted to the atmosphere.

Table 7.3 Comparison of Wood and RDF Analyses

Description	% Dry Basis	
	Wood	RDF
Proximate Analysis:		
Volatile Matter	83.89	77.76
Fixed Carbon	15.78	11.23
Ash	0.33	11.01
Total	100.00	100.00
Ultimate Analysis:		
C	52.37	47.31
H	6.04	6.16
O	41.30	45.71
N	0.02	0.68
S	0.25	0.14
Cl	0.02	---
Total	100.00	100.00
Heating Value, MJ/kg (Btu/lb) (dry)	9.22 (8739)	8.53 (8082)

b. **Commercial Plant**

Battelle estimated that a plant processing 1816-Mg/d (2000-t/d) dry RDF would require a gasifier 2.5 m (10 ft) in diameter, coupled to a combustor 5.4 m (17.7 ft) in diameter. A schematic of such a plant is shown in Figure 7.3.

E. ENVIRONMENTAL ASPECTS

1. Process Emission Characteristics

Low by-product production results in simple environmental systems. During the limited test program with RDF, lower concentrations of condensed organic materials were generated than in tests with wood. Battelle indicated a much more extensive evaluation would be necessary to confirm and quantify these results. Wastewater contained a mixture of hydrocarbons that were relatively insoluble in water, thus greatly simplifying projected wastewater cleanup requirements. Inorganics exit the BHTGS as part of the ash stream. Although sufficient RDF operating data have not been developed to provide complete mass-

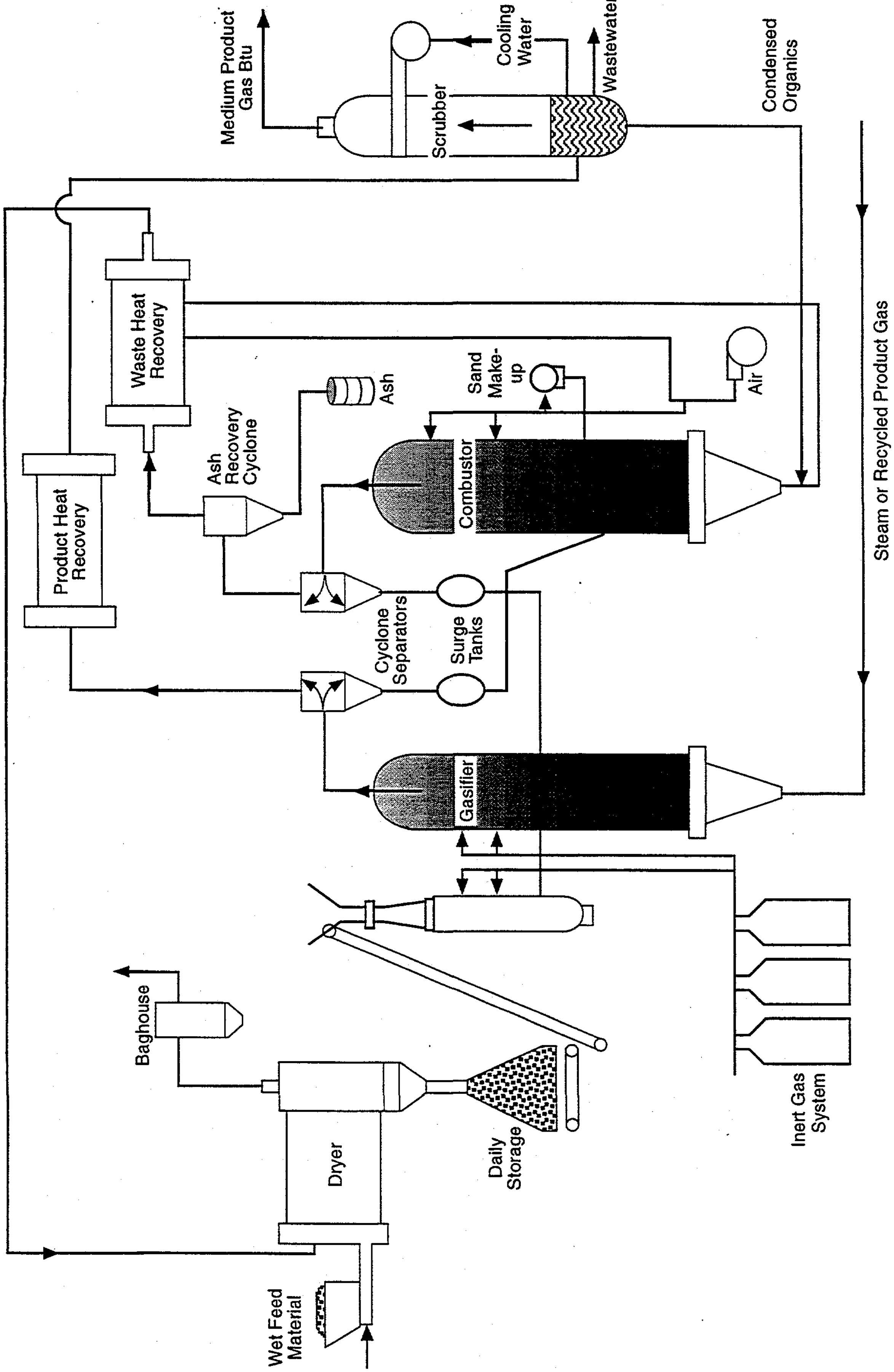

Figure 7-3
Schematic of Commercial Scale BHTGS Gasification System

balance results for all inorganic species, Battelle's experience with other forms of biomass suggests that inorganics tend to be removed from the combustor as fine fly-ash material.

Glass and aluminum, like other low-melting-point species, have the potential for causing operating difficulties if they become part of the circulating phase. The BHTGS, because of its CFB (entrained-flow through the reactors) tends to remove larger tramp material, such as glass and aluminum, from the bottom of the reactor.

The BHTGS includes a wet scrubber in the process loop. Battelle has suggested that this scrubber will significantly reduce the particulate matter concentration in the fuel gas stream, simplifying the end use of the gas for power-plant fuel applications. One concern, however, is whether the quality will be sufficient for use in gas engines and, particularly, gas turbines without secondary gas cleanup.

Chlorine was not measured during the RDF testing. However, subsequent proprietary Battelle data indicate that chlorine in the waste stream is converted completely to HCl in the gasifier and not to chlorinated organic materials such as dioxins and furans. There is a small concentration of HCl present in the gas, most of which is removed by the scrubber.[6]

2. Potential for Regulatory Compliance

The estimated emissions are expected to comply with EPA regulations for MSW incineration plants.

F. FLOWSHEET

1. Material Balances

Data generated during Battelle's test program were incorporated into a Battelle process heat and material balance model to predict commercial-scale production rates. Table 7.4 is a summary mass and energy balance based on the schematic flowsheet shown in Figure 7.4.

2. Heat Balance

The heat balance is shown in Table 7.4. The basis for the mass and energy balances is the computer model output shown in Figure 7.1. The cold-gas efficiency is 69.2 percent.

3. End Product

The results of testing with RDF are the end product data shown in Tables 7.5 and 7.6.

Table 7.4 BHTGS Mass and Energy Balance: Plant at 908 Mg/d (1000 t/d) dry RDF

Component	Stream No. 1	2	3	4	5	6	7
	RDF to Gasifier (lb/h)	Feed-water (lb/h)	Air to Combustor (lb/h)	Product Gas (lb/h)	Flue Gas (lb/h)	Ash (lb/h)	Waste-water/ Con-densibles (lb/h)
RDF (dry)	83,333						
H_2O(liquid)	24,194	25,984				15,684	22,178
Ash			144,617	22	5,022		
N_2			38,442	616	100,616		63
O_2					3,800		
CH_4				6,354			
C_2H_4				6,496			
C_2H_6				390			
CO				25,452			
CO_2				10,296	49,984		
H_2				810		267	39
H_2O(vapor)				61,920	2,286		
NH_3							
H_2S							
C						13,629	315
Subtotal, lb/h	107,836	25,984	183,059	112,334	196,726	29,580	22,595
Total, lb/h			316,879				316,879
Temperature, °F	70	120	70				
Duty, 10^6 Btu/h	649	36	31	592	93	3	7
Subtotal			716				693
Losses			0				21
Grand Total			716				716

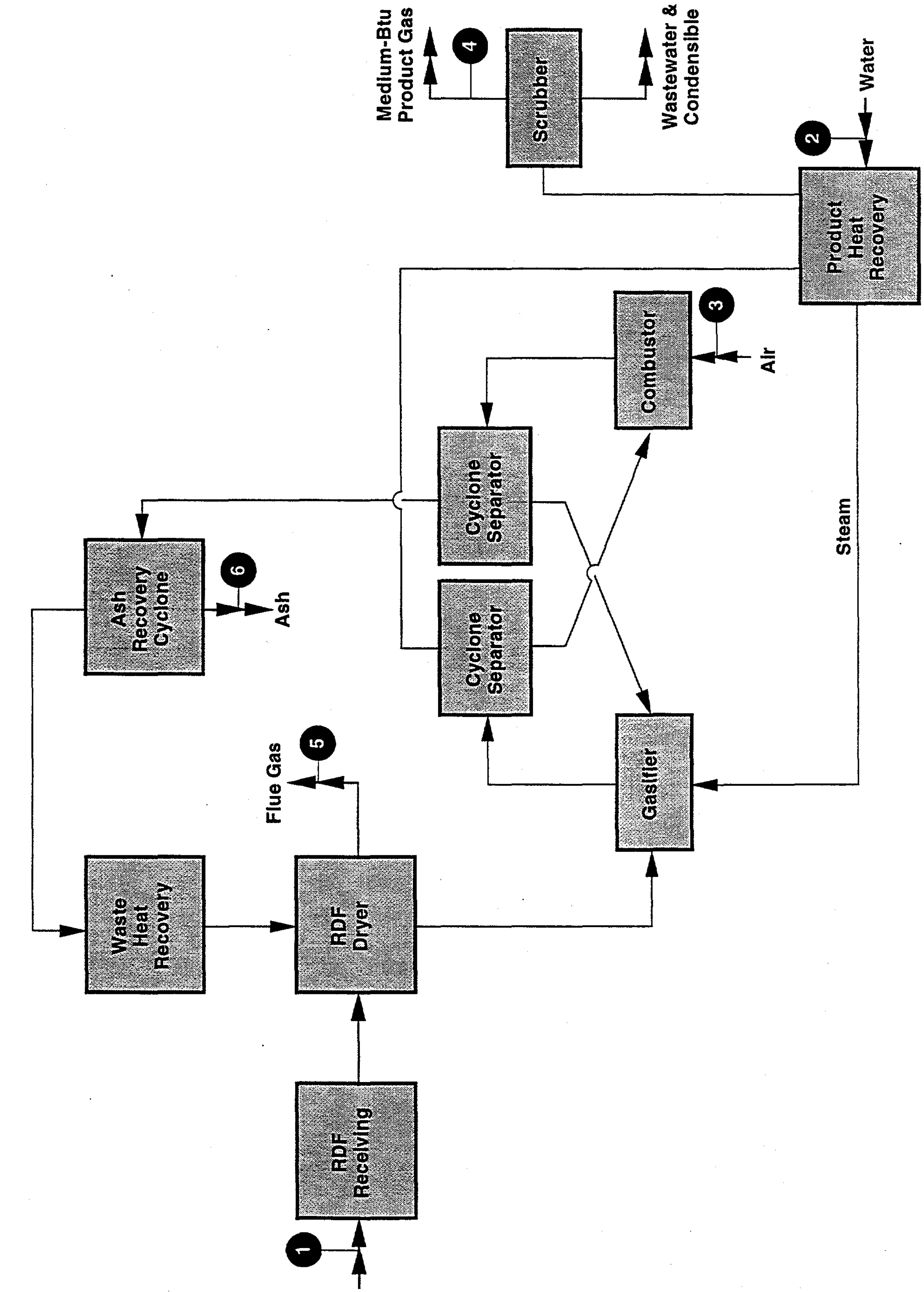

Figure 7-4
Battelle's System Schematic Flowsheet

Table 7.5 End Product Data

Gasifier Operating Temperature, °C (°F)	660-840 (1228-1544
Carbon Gasified, %	41-69
Product Gas Heating Value, J/Nm^3 (Btu/sft^3)	20.2-23.3 (541-627)
Product Gas Yield, sft^3/lb MAF Feed per RDF on MAF basis, Nm^3/kg (sft^3/lb)	0.43-0.75 (7-12)
Heating Value of Gas Produced, per RDF on MAF basis, MJ/kg (Btu/lb)	8.52-15.3 (3662-6578)

Table 7.6 Product Gas Composition (vol%)

H_2	15.7
CO_2	11.1
CO	43.9
CH_4	16.3
C_2H_4	11.2

4. Proposed Interface

Battelle has made studies that focus on power generation for a combined cycle using gas and steam turbines. According to Battelle's model, a 908-Mg/d (1000-t/d) dry RDF gasification plant will produce 947,000 MJ/h (898 x 10^6 Btu/h) medium product gas, and thus about 112 MW of power. A similar quantity of MSW in a mass-burn plant with a Rankine cycle will produce only 60 MW.

G. DEVELOPMENT HISTORY

1. Laboratory/Bench Studies

Development efforts on the BHTGS were begun in 1977. Initial tests were conducted in a 5-cm (2-in.) unit that could be used to screen different types of RDF.

2. **Pilot Plant Studies**

Detailed process development activities were begun in 1980 with the construction and start-up of a PRU at Battelle's West Jefferson Laboratory. The PRU was designed so that the inherently high reactivity of biomass feedstocks could be exploited. These PRU investigations, conducted during the mid-1980s, demonstrated the technical feasibility of the gasification process and provided the basis for generating a detailed process conceptual design.

Experimental data have been generated in Battelle's PRUs in 1.5-dm (6-in.) and 2.5-dm (10-in.) diameter gasifiers with throughputs of 0.22 and 9.1 Mg/d (0.24 and 10 t/d) dry RDF respectively. Data from these tests showed that extremely high throughputs—over 19.5 Mg/h•m^2 (4000 lb/hr•ft^2) could be achieved. A wide range of feed materials has been tested in the system including:

- RDF
- Hardwood and Softwood Chips
- Shredded Bark
- Sawdust
- Whole Tree Chips
- Shredded Stump Material

Testing in the PRU demonstrated the flexibility of the system to handle a variety of biomass forms with little or no preparation. This flexibility in feedstock acceptance was also apparent with the use of RDF as a feedstock for the process. The product gas heating value was consistent regardless of the moisture or ash content of the feed material tested.

3. **Semiworks Plant Studies**

None were planned or built.

4. **Current Status**

Using whole-tree wood chips, a commercial-scale demonstration is under way in Burlington, Vermont, at Burlington Electric's McNeil Generating Station.

H. INTERVIEWS

CDM engineers met with the Battelle Team involved with BHTGS development. Those interviewed were:

- Mark A. Paisley, P.E., Projects Manager
  Phone: (614) 424-4958
- Dr. Robert D. Giammar, Department Manager
  Process Engineering Department
  Phone: (614) 424-7701
  Fax: (614) 424-3321

I. REFERENCES

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4. M. A. Paisley and G. Farris, "Development and Commercialization of a Biomass Gasification/Power Generation System," Second Biomass Conference of the Americas, Portland, Oregon, August 21-24, 1995.

5. "Burlington Electric Plans Wood Gasification Project to Reduce Costs and to Meet Environmental Requirements," Battelle brochure, June 1995.

6. Letter from M. A. Paisley to R. E. Sommerlad, November 6, 1995.

7. Letter from M. A. Paisley to R.E. Sommerlad, December 11, 1995.

Section 8

Pedco Incorporated

A. SUMMARY

The Pedco Rotary Cascading Bed Combustor (RCBC) is, in essence, a robust solid-fuel burner and heat-recovery system. Among other solid fuels (coal and wood chips, for example), it can burn prepared municipal solid waste (MSW). Pedco's basic business is the design of combustion systems using the RCBC concept. Although their corporate experience favors applications providing steam for industry, they also have an interest in solid-waste management projects.

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

B. FINANCIAL AND BUSINESS ASPECTS

1. Projected Capital and Operating Cost

The projected capital investment for implementation of the RCBC technology is based on capital and operating cost estimates prepared by Pedco for a proposed plant to be located at a North American Rayon Corporation's production facility in Elizabethton, Tennessee. Pedco's detailed cost estimate was based on a development plan that began with two RCBC furnaces and provided for progressive expansion of RCBC capacity over time.

The plant concept evaluated during this project includes four RCBCs that receive 800-Mg/d (880-t/d) raw waste. This waste input results in 560-Mg/d (616 t/d) prepared RDF. At capacity, each of the boilers generates 22,100 kg/h (48,600 lb/h) steam. At peak load, the four boilers generate 24.8-MW electricity. The investment estimate uses the reference costs developed under this program for RDF preparation and energy conversion. Similar to recent experience in the permitting of new refuse-burning facilities, the Pedco boilers are equipped with spray/dryer absorbers (one absorber serving two Pedco boilers) and are equipped for carbon addition. Selective noncatalytic reduction (SNCR) in the boilers reduces NO_x. The capital cost of a complete Pedco system burning prepared, 5-cm (2-in.) top size, refuse-derived fuel (RDF) and generating electricity is shown in Table 8.1.

Table 8.2 presents operating cost estimates by Pedco for this plant. The costs incorporate estimates for RDF preparation and for energy conversion and revenues. For the energy generation calculations, the boilers were assumed to operate at 130-percent excess air (the average of Pedco's five pilot tests with RDF). Limestone, added as coarse, 1.0-cm (3/8- in.) screenings, corresponds to a Ca/(S+0.5Cl) molar ratio of

Table 8.1 Capital Cost: Pedco Thermal Processing System

System:	800 Mg/d (880 t/d) Raw Waste 560 Mg/d (616 t/d) RDF Four Rotary Cascading 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 Two Dry Scrubbers (HCl Control) Fabric Filter		
Facility Capital Investment:			**Source**
Fuel Preparation:		$41,400,000	CDM
Building		2,500,000	
Combustion/Heat Recovery/ APC Train:			CDM
Equipment			Developer
Boilers (4) with APC	16,934,000		Developer
Steam System	50,000		Developer
Solid Waste Feeder	637,000		Developer
Ash System	140,000		CDM
Spray Dryers (2)	1,906,000		
CEM System	2,000,000		
Combustion Core Cost	$21,667,000		CDM
Engineering & Contingency (30% of Combustion Core)	6,500,000		
Subtotal		$ 28,167,000	CDM
Electrical Generation (Steam Turbine)		15,000,000	
Total		$87,067,000	
		per Mg/d MSW:	$108,800
		per t/d MSW:	$98,900

Table 8.2 Operating Costs for Pedco Incineration 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.	1	4	\$30.00/h	\$263	CDM
Plant Attendant	2	8	\$25.00/h	\$438	CDM
Elect./Inst Maintenance	2	8	\$35.00/h	\$613	CDM
Mechanical Maintenance	1.5	6	\$35.00/h	\$460	CDM
Nat. Gas (10^6 Btu/y)		0	\$4.00/10^6 Btu	\$0	CDM
Lime (t/y)		1,510	\$85/t	\$128	CDM
Limestone Screenings (t/y)		3,020	\$9/t	\$27	CDM
Liq. NH_3 (t/y)		490	\$292/t	\$143	CDM
Carbon (t/y)		160	\$1,000/t	\$160	CDM
Maintenance- Supplies	\$28,167,000	Allowance	1.5% of Capital	\$423	CDM
Maintenance	\$28,167,000	Allowance	3% of Capital	\$845	CDM
Insurance	\$28,167,000	Allowance	1% of Capital	\$282	CDM
Compliance Testing		Allowance		\$300	CDM
Residue Landfill		118,300	\$40/t	\$4,732	CDM
		Total Cost for Combustion Core		\$9,736	
Contingency		10% of Combustion Core Cost		\$974	CDM
Debt Service	\$87,067,000		10.19% of Capital	\$8,872	CDM
RDF Operations	N/A	325 x 10^3 t/y	\$8.40/t	\$2,730	CDM
Electric Gen. Operations.	N/A	328 x 10^6 Btu/h		\$940	CDM
			Total Gross Cost	\$23,251.00	
Electrical Revenue					
Gross Generation (MWh/y	328 x 10^6 Btu/h	240,000			CDM
RDF Power Use (MWh/y)		(8,125)			CDM
Internal Use (MWh/y)		(36,000)			CDM
Net to Export (MWh/y)		195,875	\$0.04/kWh	(\$7,835)	
			Net Annual Cost	\$15,416	
			\$/t	\$47.43	
			\$/Mg	\$52.29	

1.75:1, matching Pedco pilot plant experience with acid gas control. On this basis, the net costs per ton of raw waste are $60.41/Mg ($54,921/t). No credits for recovered materials have been assumed.

2. Business Aspects

Pedco Incorporated (Pedco) has headquarters in Cincinnati, Ohio. Originally formed in 1967, Pedco has gone through several stages of organizational growth and subsidiary spin-off since. The present firm was organized in 1984 to pursue, among other interests, the development and commercialization of an innovative solid-fuel combustor. Pedco is an engineering firm with experience in the design, modification, construction, and operation of industrial plants. Following its 1984 reorganization, Pedco concentrated its entire effort on the development and commercialization of its proprietary technology: the Pedco Rotary Cascading Bed Combustion System (RCBC). The RCBC has been granted U.S. Patents 4,583,468 and 4,724,777; patents for the RCBC technology have also been issued elsewhere.

Pedco operates to supply the technology of RCBC systems based on their proprietary designs. Their responsibility generally focuses on fuel feeding; the rotating device including its internal boiler, air supply, ash recirculation, and other ash management systems; and the overall combustion control system. Their scope of supply includes all applicable process controls and systems for data collection and archiving. The boiler and all other aspects of energy recovery and conversion; air pollution control; the RDF preparation facilities; and the buildings, foundations, roads, and other civil works are normally designed and furnished by others.

As of late 1995, Pedco's address and communications numbers were:

Pedco Incorporated	Tel: (513) 361-8643
214 East Ninth Street, 2nd Floor	Fax: (513) 351-8646
Cincinnati, Ohio 45202	

C. IMPLEMENTATION FEASIBILITY

The technology offered by Pedco is presently short of confident, commercial availability for MSW management. Other than in a specialized hazardous-waste burning configuration, Pedco has installed only one RCBC furnace/boiler in the U.S. That unit, originally installed at the Hudepohl Brewery in Cincinnati, was subsequently upgraded and relocated to the North American Rayon Corporation plant in Elizabethton, Tennessee. The unit has a capacity of 4550 kg/h (10,000 lb/h) steam and is set up to burn a variety of fuels, including coal and coal-mine wastes, chopped tires, wood wastes, and an RDF fuel. The circumstances of the facility are such that it did not routinely practice 100-percent MSW-derived RDF firing. Pedco's total operating experience with RDF was only about 225 operating hours as of December 1995. They have explored coal and coal wastes much more thoroughly, with over 3500 operating hours for testing and design, in addition to time burning conventional fuels. Test burns of up to several hours in duration have also been made with a variety of industrial residues; shredded tires; and various solid, liquid, and sludge wastes.

Consequently, there is much to learn about a wide variety of process and operating features and problems in a "real" facility operating under inflexible requirements for process availability, operating costs, energy recovery etc. Thus the Pedco system, while attractive, presents a significant risk to prospective users. There are aspects of the process, such as boiler-tube bundle and internal ash chute plugging/fouling and corrosion/erosion throughout the system where the limited data and lack of sufficient operating experience present a prospective owner with considerable uncertainty. The lack of dioxin emissions data introduces another element of process uncertainty. Although the process does not appear to be especially problematic regarding dioxin generation, the high profile of this pollutant and its impact on the time and difficulty of facility permitting make such data omission an impediment to implementation.

The issue of risk is compounded by Pedco's present inability to fully guarantee the successful implementation of an RCBC system. Although this constraint may be relieved if a partner with substantial capital resources is found, it may present a problem to prospective owners.

1. Process Issues and Problem Areas

The primary process issue relates to the need for Pedco to develop and adopt a front-end waste-processing concept and, ultimately, a hardware system that can produce a 5-cm (2-in.) top-size RDF feed for the RCBC system. Development of an RDF flowsheet should not generally be a problem. However, at almost all RDF facilities, *extensive* redesign and reconstruction have been needed to bring the RDF processing elements of their system to an acceptable level of reliability and performance.

2. Operating Issues and Problem Areas

The primary Pedco need is to relate operating experience in all aspects of RDF burning to the RCBC system. Although the data and experience gathered to date appear to show very basic proof of principle, a firm offering a waste management concept must understand the design and operational issues of:

- Waste receipt
- RDF preparation and storage
- RDF recovery and firing
- Furnace behavior under long-term RDF firing conditions
- Ash characteristics and handling issues
- Associated air pollution control and residue-processing systems.

A few hours' operation of a robust combustor with RDF, however successful, does not constitute an adequate basis for facility design, process and emissions guarantees, air pollution and other permit submissions, and long-term operating contracts.

3. Remaining Research and Development (R&D) Needs

The primary R&D areas for Pedco include the following:

- *Operating time on RDF.* The development work to date has focused on the combustion of coal and coal-derived wastes. To gain acceptance of the process for solid-waste applications, there must be a greater level of experience in burning waste, including a more expansive data base on air emissions—especially for dioxins, CO, and acid gases. Additional data are also needed on residue quality, which includes the unburned carbon content in the ash. Data in these areas are needed both to assist in air pollution control concept selection and design and to facilitate permitting.

- *RCBC Performance on RDF.* The high degree of materials handling within the Pedco combustor and the frequently problematic history of materials handling for solid waste systems suggest that much more operating experience is needed to ensure compatibility of the basic RCBC concept with an RDF feed. Of particular importance are:

  — Fouling and plugging of the ash-handling chutes with wire and oversized noncombustibles

  — Similar fouling problems for the boiler tube bundle

  — Abrasion and corrosion problems.

  These problems could result in frequent equipment outages, affecting both plant throughput and electrical revenue, and in high maintenance expense.

- *Boiler Development.* Experience to date 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 greatly preferred. Higher skin temperatures on the tubes may affect their erosion and corrosion sensitivity and should be evaluated before commitment to a full-scale facility.

- *Other Issues.* The working environment of a solid-waste processing facility is very abusive and unfriendly. The material being handled and fired, the flue gases, the slags, the residue, and the plant air itself range from relatively benign to aggressively destructive. The development of a total facility concept that works with the reliability and availability sought by most municipal clients is neither trivial nor easy. There are hundreds of design decisions to be made relative to pumps, fans, vehicle tires, cranes, shredders, etc. Often such design decisions are blocked by the uncertain balance between cost and the desire to install high-quality, rugged, heavy-duty equipment that will confidently overcome the aggressive working environment. With only limited RDF and RDF-firing experience, many of these decisions may be wrong. If , after start-up, Pedco's cost for correcting the design is low, the consequences may not be great. If, however, the corrective actions are costly, the consequences could result in economic failure of the project. This risk is borne by the community.

D. PROCESS DESCRIPTION

The Pedco RCBC technology has been in use since 1981. In essence, the RCBC was designed to function as a robust, fuel-insensitive solid-fuel combustion system. An underlying marketing assumption by Pedco was that the burner would be mated to a waste-heat boiler serving industrial steam users. Alternatively, the RCBC burner could discharge into a boiler making superheated steam for electrical generation. As a fuel-flexible burner, the RCBC system is intended to burn coals, coal waste, wood, chipped tires, RDF, and a variety of other fuels having the common denominator of low cost. Figure 8.1 is a flowsheet of a typical Pedco steam generation operation.

The RCBC burner comprises a horizontal, cylindrical combustion chamber, as shown in Figure 8.2. A nonrotating bundle of boiler tubes projects into one end of the chamber, cantilevered from external supports. The rotating speed of the chamber is high enough to keep a substantial fraction of the bed material continually airborne, producing an environment similar to that of a fluid bed, but a mechanically fluidized

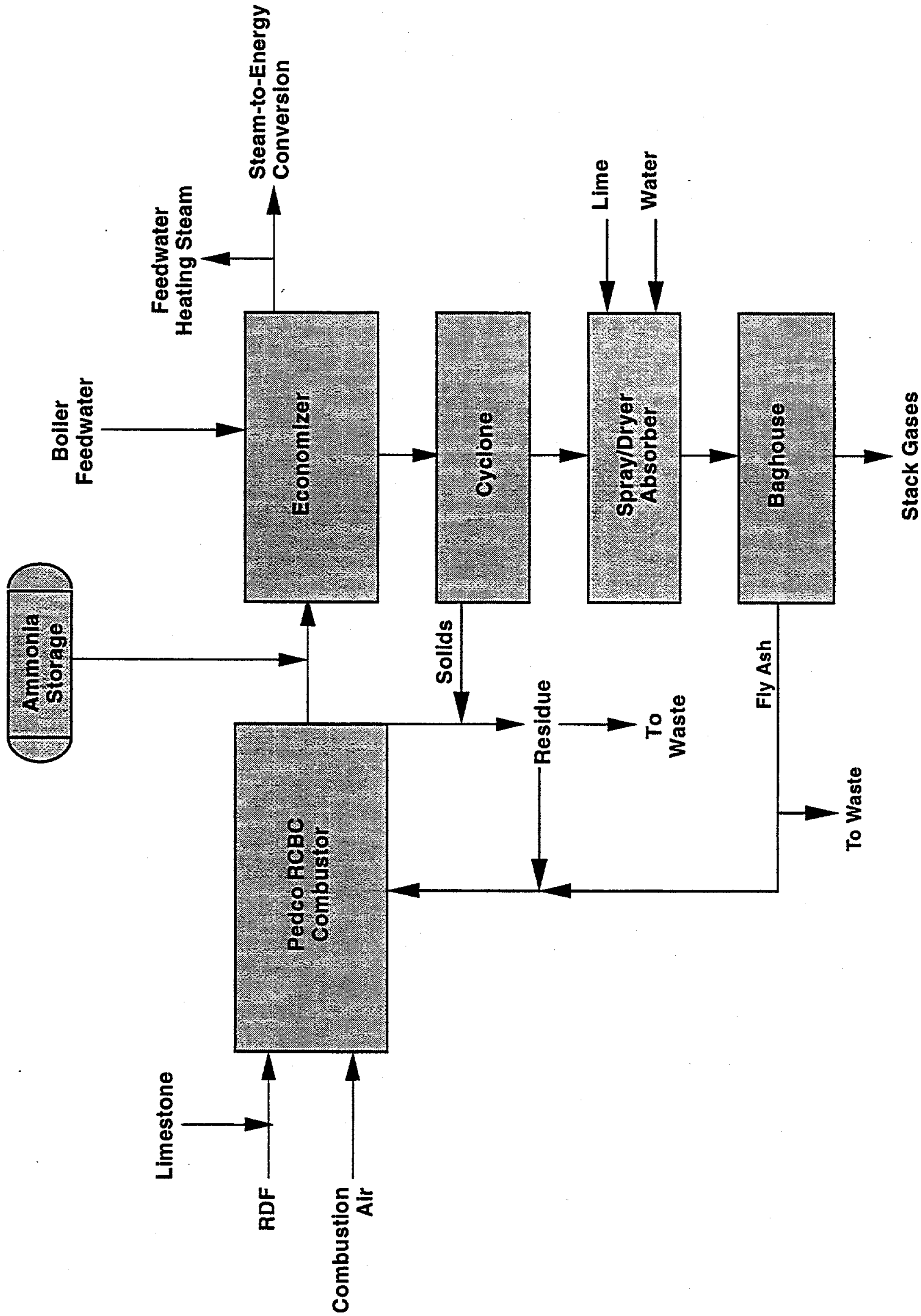

Figure 8-1
Pedco Process Schematic

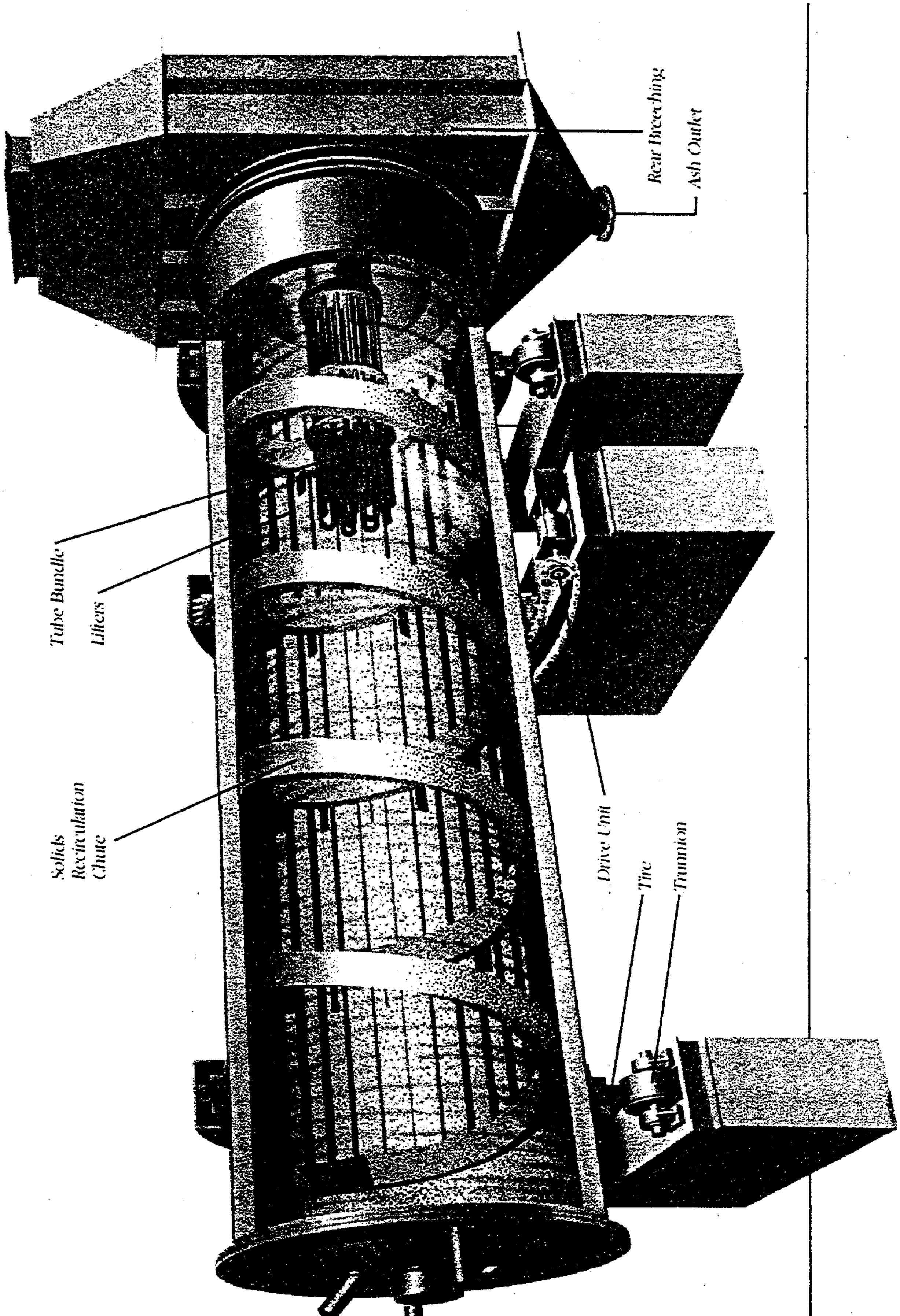

Figure 8-2
Pedco Rotary Cascading Bed Combustor

bed. The hot falling solids cascade across the whole diameter so that the boiler tubes are submerged in hot fuel and bed material. The bed material exchanges a portion of its heat to the boiler tubes and is then recycled to the feed end of the combustion chamber at a rate of 40 to 100 times the fuel feed rate. The hot solids recycle preheats and ignites the incoming fuel and the combustion air. This operating concept results in behavior much like a fluid bed—lower average temperatures than are seen in grate-burning systems and a high degree of temperature uniformity.

Pedco continues developing its RCBC technology at the North American Rayon Corporation facility in Elizabethton, Tennessee, in a system generating up to 4.55-Mg/h (10,000 lb/h) steam. The key elements of the system when burning MSW will have to include the RDF preparation system, the intermediate RDF storage system, the RDF reclaiming and feeding system, the RCBC burner and associated boiler, and the air pollution control system.

a. RDF Preparation

Although fuel preparation facilities are not normally supplied by Pedco, they have proposed an RDF preparation system consisting of a horizontal shaft hammermill or shear shredder-type primary shredding; secondary, hammermill shredding; magnetic separation; air classification; and disc screening of the fines for removal of glass and grit. The RDF feed specifications for the RCBC system may require a 5-cm (2-in.) top size. Additional test data are required to confirm the most acceptable top size.

b. Intermediate RDF Storage and Reclaiming

Generally, RDF processing facilities are operated only one or two shifts per day. Pedco is proposing 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 to minimize 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.

c. RCBC Burner and Boiler

The heart of the Pedco process is their RCBC burner and associated boiler. The system is "atmospheric," operating at a pressure only slightly below 1 atma. Limestone can be added to the bed as a means of absorbing SO_2 and HCl from the RDF or from coal or other "high-sulfur" fuels. The high solids recycle reduces the net unburned carbon losses and maintains the combustion zone temperature to only about 920 to 950°C (1600 to 1650°F). The RCBC can operate over a wide heat-release range. The "thermal inertia" of the large mass of recirculating ash acts as a thermal flywheel to stabilize bed temperature. Keeping a low mean temperature in the combustion chamber reduces thermal NO_x formation, minimizes the effects of high-temperature corrosion, and protects against bed agglomeration associated with local melting and "stickiness" of the ash particles.

The bed is fitted with a tube bundle cantilevered into the RCBC cavity on the discharge end. Using boiler water, the tube bundle is equipped for forced-flow cooling to maintain bed temperature in the target range. The hot, recirculating ash is an important means for energy transfer, exchanging heat between the combustion process and the boiler tube bundle. At the normal combustion zone temperature, SO_2 absorption is at its maximum, and NO_x generation is minimal. A feature of this temperature profile is that high-sulfur coals (4- to 6-percent sulfur) can be handled by the RCBC system without appreciable SO_2 emissions. The RCBC operates at from 100- to 120-percent excess air in refuse service, with typical RDF heat content and in-bed tubes for temperature control. This operation compares with the 90- to 110-percent excess air typical of mass-burning units.

In the 2.27-Mg/h (5000 lb/h) burner used at the Hudepohl Brewing Company, the system characteristics were:

- Internal Diameter — 1.66 m (5.5 ft)
- Length (Overall) — 7.57 m (25. ft)
- Maximum Temperature — 950°C (1650°F)
- Rotation (maximum) — 16 (23)rpm
- Heat-Transfer Area — 34.5 m^2 (375 ft^2)
- Steam Pressure — 1 MPa (150 lb/in^2)
- SO_2 Control — 90 percent (at Ca:S ratio of 1.2 for coals)
- Particulate Control Fabric Filter

Unlike the 1100°C (2000°F) combustion temperatures found in the diffusion flame above the bed in conventional mass-burn systems, RCBC bed combustion temperatures are relatively low. At these temperatures, furnace absorption of SO_2 and HCl is effective, and thermal NO_x generation is low.

One of the most important and proprietary features of the Pedco RCBC design is the bed ash management system. The system allows bed media to flow through a spiral chute buried in the refractory kiln liner and laid inside the outer shell. The solid bed material is collected by gravity as it flows into the chute at the discharge end of the chamber and is "pumped" by the kiln rotation to the feed end.

d. Air Pollution Control

In addition to the acid gas control achieved through in-bed lime addition, Pedco proposes to equip the combustion train with fabric filters for particulate reduction. Because of the low working temperatures, NO_x control may not be required. Carbon injection downstream of the boiler economizer can be provided for mercury control, although there is no operating experience available at Pedco to characterize the likely performance. Pedco could supply a conventional spray/ dryer absorber and fabric filter combination when there is a need for enhanced acid-gas and condensible-vapor removal.

e. Typical Plant Configurations and Performance

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 prospective Pedco "catalogue" RCBC system is approximately 233,000 MJ/h ($100x10^6$ Btu/h), corresponding to daily RDF rates of 168 Mg/d (185 t/d). Air pollution control efforts, beyond the addition of low-cost, coarse limestone screenings to the bed for acid gas control, would normally involve a fabric filter unit. Pedco believes that their in-bed limestone addition and consequent acid gas absorption eliminates the necessity for the spray/dryer absorber used in many mass-burn plants. However, there is a lack of data in refuse applications and the needed function of the spray dryer (with carbon addition). In order to cool the gases and achieve acceptable dioxin and mercury removal, a spray dryer unit servicing two Pedco furnaces has been incorporated into the flowsheets and economic analyses in this report.

E. ENVIRONMENTAL ASPECTS

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

a. Air Emissions

Data are available from the RDF tests for SO_2, NO_x opacity (continuous), and CO. No particulate or dioxin data were taken during these runs. The data in Table 8.3 describe tests during which RDF from three different sources was burned. In all cases, limestone was added for a portion of the test period to control SO_2 and HCl. The HCl stack emissions data are very limited. The project team reviewed only one set of data from three tests that used EPA Method 25. When burning the semidensified RDF from the Robertson County Recycling Center in Tennessee, the HCl concentration was reported to be less than 20 $\mu g/ft^3$.

b. Wastewater Emissions

Other than boiler and cooling tower blowdown streams, there are no wastewater streams from the Pedco process.

c. Residue Characteristics

Table 8.4 shows Toxicity Characteristics Leaching Procedure (TCLP) data for heavy metals in the Pedco fly ash. The tests were conducted by the Tennessee Technological University Water Center Laboratory in support of the Pedco semiworks testing program. These results would suggest that, for the waste material burned in the test, the ash does not trigger the metal limits corresponding to a "hazardous waste." Without additional data, it is impossible to extend this conclusion to ashes from other waste sources.

2. Potential for Regulatory Compliance

As described in the previous section on general process implementation, the Pedco system has only limited emissions and ash characteristics data. These data have been taken in the course of relatively short operating runs with RDF feeds. This limited data base can be expected to present some problems in preparing and defending permit submissions.

Ash inlet loading can be expected to be high, but not higher than fluid bed systems with very high particulate concentrations at the furnace outlet and those that meet code requirements. Acid gas control is, to a degree, effected by limestone addition to the bed. However, more data are needed to be confident that the regulatory limits can be met by this approach (without secondary control devices). NO_x is especially low for the Pedco RCBC. CO emissions patterns are not well characterized in Pedco's limited test data base for RDF combustion. Often, significant emissions of CO are observed; excursions of several thousand ppm, lasting several minutes, have been routinely observed.

Table 8.3 Measured Air Emissions from Pedco System

Pollutant	Measured Emissions Rate (lb/10^6 Btu)		
	Test T-11	Test T-16	Test T-22
Limestone Ca/S Ratio	3.7 - 4.3	2.35	None added
SO_2	0.07 - 0.98	0.08 - 0.71	0.02 - 0.03
NO_x	0.02 - 0.12	0.05 - 0.08	0.06 - 0.10
CO	0.10 - 0.12	0.42 - 0.66	0.22 - 1.09

Table 8.4 Measured TCLP Leaching Data (mg/*l*) for Pedco Fly Ash

Metal	Measured Value Test T-11	Measured Value Test T-16	Regulatory Limit
Arsenic	0.007	< 0.005	5.0
Barium	0.367	1.970	100.0
Cadmium	< 0.005	< 0.005	1.0
Chromium	< 0.005	< 0.005	5.0
Lead	0.010	< 0.005	5.0
Mercury	< 0.001	< 0.001	0.2
Selenium	< 0.005	< 0.005	1.0
Silver	< 0.005	< 0.005	5.0
pH, Lab	11.7	12.3	N/A

Emissions of dioxins and other organic species are uncertain. No emissions data for this pollutant sector are available. The low combustion temperature in the RCBC and the high degree of ash/carbon carryover would suggest that the uncontrolled emissions rates of these pollutants may be high. Current analysis of the dioxin emissions problem has suggested that dioxins are formed through chlorination reactions on graphitic carbon in fly ash. Data from Pedco show from 2.9- to 7.7-percent carbon in the ash. This result suggests that the potential for high dioxin formation exists. At present, however, there are no experimental data to either confirm or refute this hypothesis.

F. FLOWSHEET

1. Heat and Material Balances

Figure 8.3 presents the process flowsheet for a single Pedco furnace system burning 167Mg/d (184 t/d) RDF. This rate would correspond to a plant receiving approximately 240 Mg/d (262 t/d) raw waste. Material balances for this Pedco system are shown in Tables 8.5a and 8.5b, in metric and English units respectively. The balances represent the system from the feed system of prepared waste through the combustor, heat-recovery boiler, and air pollution control system to the steam header shown in Figure 8.3.

2. End Product (Fuel type and Characteristics)

The Pedco RCBC boiler system generates steam for process or electrical generation. Units can be constructed to generate either saturated or superheated steam.

3. Proposed Interface With Other Processes (Boiler, Methanol Plant, etc.)

The Pedco burner system is designed to be connected to a waste-heat boiler for the generation of steam. Although Pedco foresees opportunities in the application of their combustor to the supply of steam for industrial operations, electrical generation (a 100-percent reliable energy market) was assumed for the purposes of the NREL assignment.

G. DEVELOPMENT HISTORY

1. Laboratory/Bench Studies

The early work with the RCBC began in 1981. This initial phase of development involved use of a small incinerator to evaluate basic RCBC principles and, importantly, to collect data on the capture of sulfur dioxide and hydrochloric acid by adding limestone to the bed. The latter characteristic is particularly important if low-cost high-sulfur coals are used either as a supplemental fuel or as the main fuel in an industrial steam-raising operation.

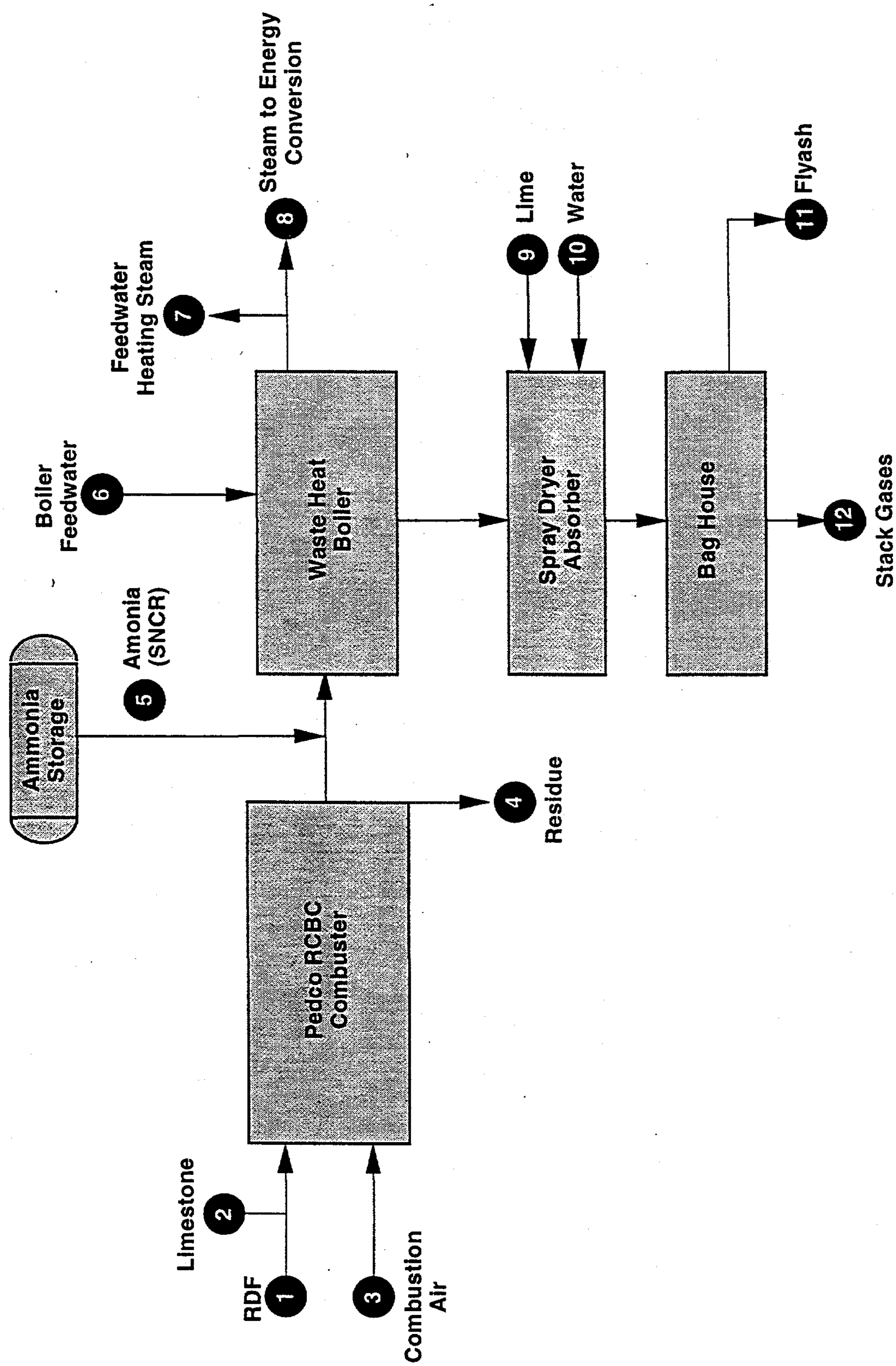

Figure 8-3
Pedco Process Flowsheet

Table 8.5a Material Balance for Pedco Furnace (Metric Units)

Location	Material	Characteristics	Mass Rate (kg/h)
1	RDF	Proximate Analysis: 83.55% Combustibles 9.12% Ash 7.33% Moisture 7.47 MJ/kg (dry basis)	6,955
2	Limestone Screenings	100% $CaCO_3$	64
3	Combustion Air	15°C	74,350
4	Residue	Dry weight	635
5	Ammonia	Anhydrous	13
6	Feedwater	115.5°C (saturated)	27,325
7	Feedwater Heating Steam	5.86 MPa/440°C	880
8	Product Steam	5.86 MPa/440°C	26,440
9	Lime	90% CaO	32
10	Water	Approximately 5% solids in feed slurry	1,225
11	Fly Ash	Dry weight Estimated as 10% of input ash + limestone, lime etc.	73
12	Stack Gas	143°C 1396 Nm^3	83,115

Table 8.5b Material Balance for Pedco Furnace (English Units)

Location	Material	Characteristics	Mass Rate (lb/h)
1	RDF	Proximate Analysis: 83.55% Combustible 9.12% Ash 7.33% Moisture 7,081 Btu/lb (dry basis)	15,300
2	Limestone Screenings	100% $CaCO_3$	142
3	Combustion Air	60 °F	163,569
4	Residue	Dry weight	1,397
5	Ammonia	Anhydrous	28
6	Feedwater	240°F (saturated)	60,114
7	Feedwater Heating Steam	850 lb/in^2/ 825°F	1,935
8	Product Steam	850 lb/in^2/825°F	58,178
9	Lime	90% CaO	71
10	Water	Approximately 2.6% solids in feed slurry	2,695
11	Fly Ash	Dry weight Estimated as 10% of input ash + limestone, lime etc.	160
12	Stack Gas	290°F 58,970 ft^3 (actual)	182,850

2. Pilot Plant Studies

The second phase of work began in 1985, when the Ohio Coal Development Office executed a co-operative grant with Pedco for the design, fabrication, installation, and testing of an RCBC combustor/boiler sized to generate 2.27 Mg/h (5000 lb/h) of 1 MPa (150 lb/in^2) steam. The system was located at the Hudepohl Brewing Company in Cincinnati, Ohio. The primary function of the boiler was the generation of process steam for use in the brewery. Thus the RCBC, operated by the regular Hudepohl boiler operators, functioned as a working boiler. It was serviced by the regular maintenance staff.

Hudepohl gave Pedco the freedom to burn test fuels, modify the system, and otherwise to explore the capabilities of the unit. Over the operating period from June 1986 through 1988, Pedco tested the unit with a wide variety of alternative fuels—alternative coals, wood waste, anthracite culm, shredded tires, and RDF, for example—although coal was the primary fuel. Over the period the unit was operated about 1400 hours.

The generally high level of success of the pilot testing led to the design and construction of a specialized RCBC system for burning hazardous wastes. The system has been operating since 1988. The unit is located in Texas and burns a variety of waste streams. The hazardous waste incineration unit is unique in both operating character and feed but, to the knowledge of the Pedco developers, is still in operation and is reported to have presented few operating problems.

3. Semiworks Plant Studies

When Hudepohl was acquired and their operations terminated, Pedco made arrangements to upgrade and relocate the boiler to the North American Rayon Corporation plant in Elizabethton, Tennessee. The upgrades increased the steam generation capacity of the system to 4.55 Mg/h (10,000 lb/h) and added a superheater with steam temperatures to 271°C (520°F). The physical dimensions of the combustor were unchanged, although the heat-transfer area was enlarged from 34.5 to 45.8 m^2 (376 to 500 ft^2) and the mean rotational speed was increased to 18 rpm. Once operational at North American Rayon, Pedco ran the facility from December 1990 through January 1992. They evaluated combustion and air emissions for several fuels; of importance was the RDF generated in the region. However, only about 160 hours of RDF operation were logged.

The series of tests showed the ability of the RCBC to burn a wide variety of wastes. The tests were of limited duration for any one fuel and in total; but within the test period, zero to very small degrees of erosion, corrosion, bed defluidization, or other problems were observed. Although the results were encouraging, long-term operation extending over several years and much more data on equipment performance may be needed to demonstrate, convincingly, that no problems exist that threaten the underlying technical acceptability of the process.

Pedco is attempting to secure financial support for a project to extend the development at the North American Rayon plant to include a facility with two, 27.3-Mg/h (60,000-lb/h) RCBC boilers. Boiler No. 1 would routinely be fired with RDF from Johnson City and Washington County, Tennessee. Boiler No. 2 would normally burn coal and other fossil- and waste-derived fuels. It would be equipped with RDF feeding systems, offering availability as a backup to Boiler No. 1. Pedco envisions that these boilers will have an internal diameter of 3.6 m (12 ft), be 12.11 m (40 ft) long, and have a heat-transfer area for the tube bundle of 220 m^2 (2400 ft^2). The rotation rate is expected to be 12 rpm. The steam pressure/temperature would be 5.86 MPa (850 lb/in^2)/440°C (825°F) to integrate with the North American Rayon steam system.

4. Current Status

Pedco claims that their testing program has adequately evaluated the major technical issues affecting the basic technical feasibility of their RCBC process. This may be true. However, the credibility of their process concept for MSW applications would be greatly enhanced if data were available from extended operating campaigns, where corrosion, erosion, plugging, wear, unexpected events, and other real-world process stresses had the opportunity to emerge and show their effects. The impact of such stresses can be significant. Untoward consequences can adversely affect on-time availability; increase maintenance expense and frequency; decrease power generation reliability, affecting the price that can be charged for the energy product; and engender other effects that erode the utility of the technology.

One can have confidence that these problem areas will be acceptable to an owner or will be tractable to modest engineering improvements or operating "work-arounds." However, the prospective owner of a new process that has had very limited operating experience must recognize that there is a risk that the process will fail to achieve its full potential. Total failure is unlikely, but additional capital investment for equipment modifications, higher maintenance costs, etc. may erode the economic and operational benefits that were expected.

H. INTERVIEWS

In the course of evaluating the Pedco technology, CDM engineers visited the Pedco Incorporated engineering offices in Cincinnati, Ohio. Those interviewed were:

- Mr. Gene McCracken, President
- Mr. William H. Long, Vice President
- Mr. Leland M. Reed, Ph.D., Vice President

Section 9

ThermoChem

A. SUMMARY

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 license from MTCI, ThermoChem, Inc. (TC) has the exclusive rights to apply its PulseEnhanced™ heater and steam-reforming technology to a variety of applications. These applications include industrial and municipal wastes and sludges—paper mill rejects, agricultural wastes, and refuse-derived fuels (RDF) and biomass fuels. The result is a clean, hydrogen-rich medium-heating-value, 13.9 to 16.7 MJ/Nm^3 (374 to 448 Btu/sft^3) gas. PulseEnhanced™ indirect heating combined with a fluid bed and steam reforming provides a process for converting organics to fuel gas while separating the inorganics without oxidation or melting. The heart of the process is the Pulsed Enhanced™ heater, which is immersed in the fluidized bed. This pulsed heater, with unique aerovalves, generates an oscillating flow in a bundle of heat-transfer tubes that pass through the fluidized bed gasifier. The pulsed combustion phenomenon results in turbulent mixing and significantly enhanced heat transfer between the gases in the tube and the RDF. Part of the product gas is used in the pulsed heater as the energy source. The exhaust from the heater never enters the fluid-bed steam reformer and does not dilute the product gas. The organic waste fed to the fluid-bed steam reformer reacts solely with the steam in a reducing atmosphere, producing the fuel gas.

Based on 6.8-kg/h (15-lb/h) pilot plant tests, the TC Process emits gaseous emissions from the combustor that are likely to comply with EPA's New Source Performance Standards (NSPS) for municipal waste combustors (MWCs). Using a gas cleanup system, the fuel gas is cleaned of acid gases that might be generated from impurities in the feed. The mineral matter contained in the feed collects in the fluid bed and drains from the bed. The residue meets EPA leachability criteria for landfill disposal as a nonhazardous waste. Wastewater contains only trace amounts of organic materials. Test data showed high steam-to-biomass ratios, especially with Municipal Solid Waste (MSW) and RDF. A wide range of materials has been tested in the pilot system.

MTCI's development efforts were started in 1984. Experimental data have been generated from different scales of reactors [9.1 to 2722 kg/h (20 to 6,000 lb/h)] using various biomass and waste feedstocks. In 1990 tests were conducted in an 20.32-cm (8-in.) reactor using RDF as the feed material at a throughput of 6.8 kg/h (15 lb/h).[1,2] In 1991and 1992, a 13.6-Mg/d (15-t/d) demonstration unit was operated using rejects from a cardboard recycle paper mill in Ontario, California. This same unit, relocated to TC's test facility in Baltimore, has since processed coal, wood chips, and straw.[1,2]

At a pulp mill in New Bern, North Carolina, MTCI and TC have built a five-heater fluid-bed steam reformer that can process 109 Mg/d (120 t/d) black liquor. A unit of similar size has been built in India to process organic solids from several food industries. Under the DOE Clean Coal Technology Program, TC received an an award for a 454-Mg/d (500-t/d) coal gasifier or 871-Mg/d (960-t/d) char production facility. Plans for a commercial plant to handle up to 528-Mg/d (655-t/d) RDF at a landfill site in South Carolina have reached the design stage.[3]

B. FINANCIAL AND BUSINESS ASPECTS

1. Projected Capital and Operating Costs

In a recent engineering study, TC developed several cases for an RDF gasifier and applied them to five options for energy recovery. The gasifier cases were for 227- and 595-Mg/d (250- and 655-t/d) RDF facilities; 300- and 726-Mg/d (330- and 800-t/d) MSW equivalents were based on TC's waste. The major components for the steam reformer consisted of:

- Fluidized bed reformer, including pulsed heaters to supply the heat required to dry the RDF
- Waste-heat recovery steam generator in the product gas stream to generate steam for fluidization
- Feedstock dryer using heat recovered from the product gas
- Quench system to cool the gas and remove entrained particulates
- Char handling system
- Steam superheater and an air heater installed on the pulse combustor flue gas

The dryer and air heater were not used in all configurations. Cases 1A, 1B, 2A, and 2B of the ThermoChem study were based on a steam reformer operated at 816°C (1500°F) and processing 227 Mg/d (250 t/d) wet RDF. At 649°C (1200°F), these reformers can process 595-Mg/d (655-t/d) wet RDF. Cases 3A and 3B were based on processing 595 Mg/d (655 t/d) at 816°C (1500°F). The Cases denoted "A" did not include a feed dryer or an air heater and, as a consequence, showed a lower cold-gas efficiency—54 percent vs. 65 percent of the RDF heat content appeared as fuel value in the product gas. The cold-gas efficiency is higher for the "B" Cases, where a feed dryer and air heater are used. The overall thermal efficiency is over 78 percent for the "A" Cases and about 87 percent for the "B" Cases. Associated plant capital and operating costs are given on pp. 45 through 57 of a K & M report.[3]

The reformer that included the dryer and air heater that processes 595 Mg/d (655 t/d) at 816°C (1500°F) processes 2.6 times the RDF as the lower-temperature, 649°C (1200°F) unit, and with a capital cost only about 40 percent greater. The costs for the dryer and air preheater are offset by decreased pulse heater costs. Cases 3A and 3B, the high-temperature, high-throughput [595 Mg/d (655 t/d)] scenarios at about $15.5 million, would cost about 35 percent more than the low-temperature, high-throughput case and about 90 percent more than the 231-Mg/d (255-t/d) high-temperature case.

The operating and maintenance costs are estimated to be $21.25/Mg ($19.32/t) RDF for Cases 1A and 1B, $10.95/Mg ($9.95/t) for Cases 2A and 2B, and $10.01/Mg ($9.10/t) for Cases 3A and 3B. Additional analyses were made for revenue from product gas alone at various gas prices. The cost analyses were also applied to various energy-recovery options.[3]

For this study, the project costing protocols described previously were applied. The throughput used was the same as in a recent TC study—479-Mg/d (528-t/d) dry RDF [595-Mg/d (655-t/d) wet RDF or 849-Mg/d (935-t/d) MSW]—for a combined-cycle gas turbine. A gasifier temperature of 816°C (1500°F) with a duty of 264,000 MJ/h (250 x 10^6 Btu/h) was assumed. The capital costs are shown in Table 9.1. Operating costs are shown in Table 9.2.

Table 9.1 Capital Cost: ThermoChem Steam Reforming Processing System

System:	849 Mg/d (935 t/d) 595 Mg/d (655 t/d) RDF Bubbling Fluid Bed Furnace Indirectly Heated by Using Steam as the Fluidizing Medium PulseEnhanced™ Heater		
Air Pollution Control (APC):	Wet Scrubber		
Facility Capital Investment:			**Source**
Fuel Preparation:		$37,000,000	CDM
Process/Heat Recovery/APC Train Equipment (Installed)	$15,141,000		Developer
CEM System	1,000,000		CDM
Process Core Cost	$16,141,000		
Engineering & Contingency (30% of Process Core)	4,842,000		CDM
Subtotal		20,983,000	
Electrical Generation (Steam Turbine)		33,750,000	CDM
Total		$91,733,000	
		per Mg/d MSW:	$108,000
		per t/d MSW:	$98,100

Table 9.2 Operating Costs for ThermoChem

Cost Element	No./Shift	Basis	Unit Cost	Annual Cost (000)	Source
Labor					
Superintendent	—	1	$45.00/h	$99	CDM
Operator (Op.)	1	4	$32.00/h	$280	CDM
Auxiliary Op.	1	4	$30.00/h	$263	CDM
Feed System Op.	1	4	$30.00/h	$263	CDM
Plant Attendant	1	4	$25.00/h	$219	CDM
Elect./Inst Maintenance	1	3	$35.00/h	$230	CDM
Mechanical Maintenance	1	3	$35.00/h	$230	CDM
Maint.- Supplies		Allowance		$52	Developer
Maintenance	$20,983	Allowance	3% of Capital	$629	CDM
Insurance	$20,983	Allowance	1% of Capital	$210	CDM
Compliance Testing		Allowance		$300	CDM
Residue Landfill		110,077	$40/t	$4,403	CDM
		Total Cost for Process Core		$7,079	
Contingency		10% of Process Core Cost		$708	CDM
Debt Service	$91,733		10.19% of Capital	$9,348	CDM
RDF Operations	N/A	290×10^3 t/y	$8.50/t	$2,465	CDM
Electric Gen. Operations.	N/A	264×10^6 Btu/h		$1,750	CDM
			Total Gross Cost	$21,350	
		Electrical Revenue			
Gross Generation (MWh/y)	264×10^6 Btu/h	275,500			CDM
RDF Power Use (MWh/y)		(7,250)			CDM
Internal Use (MWh/y)		(27,550)			
Net to Export (MWh/y)		240,700	$0.04/kWh	($9,628)	
			Net Annual Cost	$11,722	
			Unit Cost $/t	$40.42	
			Unit Cost $/Mg	$44.50	

2. **Alternative Revenue Streams**

As part of the study for DOE, K&M analyzed resource recovery from the RDF preparation plant. As mentioned previously, various energy recovery systems were also investigated.[3]

3. **Business Aspects**

Although TC has done only pilot plant testing with RDF, they have developed the gasifier system to the demonstration stage for sludge and black liquor.

The main address and communications numbers of the firm as of late 1995 are:

ThermoChem, Inc.
10220-H Old Columbia Road
Columbia, Maryland 21046

Tel: (410) 312-6300
Fax: (410) 312-6303

C. IMPLEMENTATION FEASIBILITY

TC's gasifier lends itself to a variety of applications, ranging from gas distribution to energy recovery. In a recent study for the Department of Energy (DOE), conducted in collaboration with K&M Engineering and Consulting Corporation, implementation options were analyzed. The energy-recovery systems included combined cycle, Rankine cycle, methanol synthesis, and hot water generation.[3]

As discussed in the sections that follow, it is clear that considerable demonstration work is needed to address remaining uncertainties regarding air emissions, residue quality, and tubesheet plugging with refuse-derived wire, metals, and rocks, for example. These uncertainties translate into risks for prospective owners.

1. **Process Issues and Problem Areas**

TC envisions no problem areas with RDF, and they dispute the potential for in-bed tube plugging and erosion/corrosion. However, experience in other RDF-based technologies strongly suggests that until full-scale trials over an extended period are complete, the risks and potential costs of these problems should not be ignored. Also, other development experiences suggest that there are issues with the engineering aspects of presorting and reliability of undensified RDF material-handling systems that must be learned and mastered by the developer. The cyclones are subject to plugging, just as they are in conventional atmospheric fluid beds.

2. **Operating Issues and Problem Areas**

Over 500 hours of operation on reject fiber and black liquor tends to give confidence to long-term operation. TC prefers sand to limestone as the bed material. However, they might consider limestone for chlorine sorption. TC believes all the technical problems can be solved, but they recognize that problems will become apparent when large-scale units become operational and that these problems can only be addressed in long-term operation.

3. Remaining Research and Development Needs

Many problems have been resolved. As with most fuel substitution technologies, commercialization is dependent on energy prices.

D. PROCESS DESCRIPTION

1. Overview

In the PulseEnhanced™ steam reformer, the organics react with steam, and the external heat is obtained by combustion of residual char from the reformer and part of the product fuel gas. The product gas from the indirectly heated processes does not contain combustion products or atmospheric nitrogen and is not as constrained with respect to potential end uses, such as for the production of methanol. Product gas quality from indirect systems is highly insensitive to feedstock moisture content, and this insensitivity provides a flexibility for the use of a broad range of high-moisture feedstocks for which predrying is impractical or uneconomical.

In the TC PulseEnhanced^{TC} steam reformer shown in Figure 9.1, a multiple-resonance tube-pulse combustor is employed. Using the resonance tubes as a firetube bundle raises the rate of heat transfer almost fivefold. Such high rates of heat transfer greatly improve energy efficiency and reduce the size of the reformer unit. These benefits significantly improve the economic competiveness of the process.

Combustion persists down the resonance tubes (firetubes) for a significant length in an environment of an oscillating flow field. Radiant heat transfer continues along the length of the firetube. Pulsing from pressure fluctuations is on the order of 175 to 180 dB in sound pressure level. This net pressure boost is employed to overcome pressure drop in the system. Pulse combustors also regulate their own air-fuel ratio within their range of firing without the need for extensive controls. Pulse-enhanced steam reformers have the potential for using different bed materials which can also act as catalysts and absorbents for the sulfur and chlorine species released in the process. In-situ capture of chlorine is expected to inhibit the production of dioxins and furans. Steam reforming occurs in an oxygen-free environment, which would preclude SO_X formation, with the H_2S formed easily and effectively scrubbed from the product gas.

The primary advantages of pulse combustion technology are:

- Enhanced heat-release rates and uniform temperature profile
- Enhanced heat transfer and reaction rates
- Combustion-air aspiration and flue-gas pressure boost
- Low capital, operating, and maintenance costs
- Modularity.[1]

A simplified process schematic is shown in Figure 9.2. Heat is recovered from the fuel gas, and then the gas cleaned in a scrubber. Part of the clean fuel gas is used in the pulse heater as the energy source. The exhaust from the pulsed heater never enters the fluid bed steam reformer and does not dilute the product gas. The pulsed heater is a low-emissions device with low NO_x emissions. The organic waste fed to the fluid bed reformer reacts solely with steam in a reducing atmosphere, producing hydrogen,

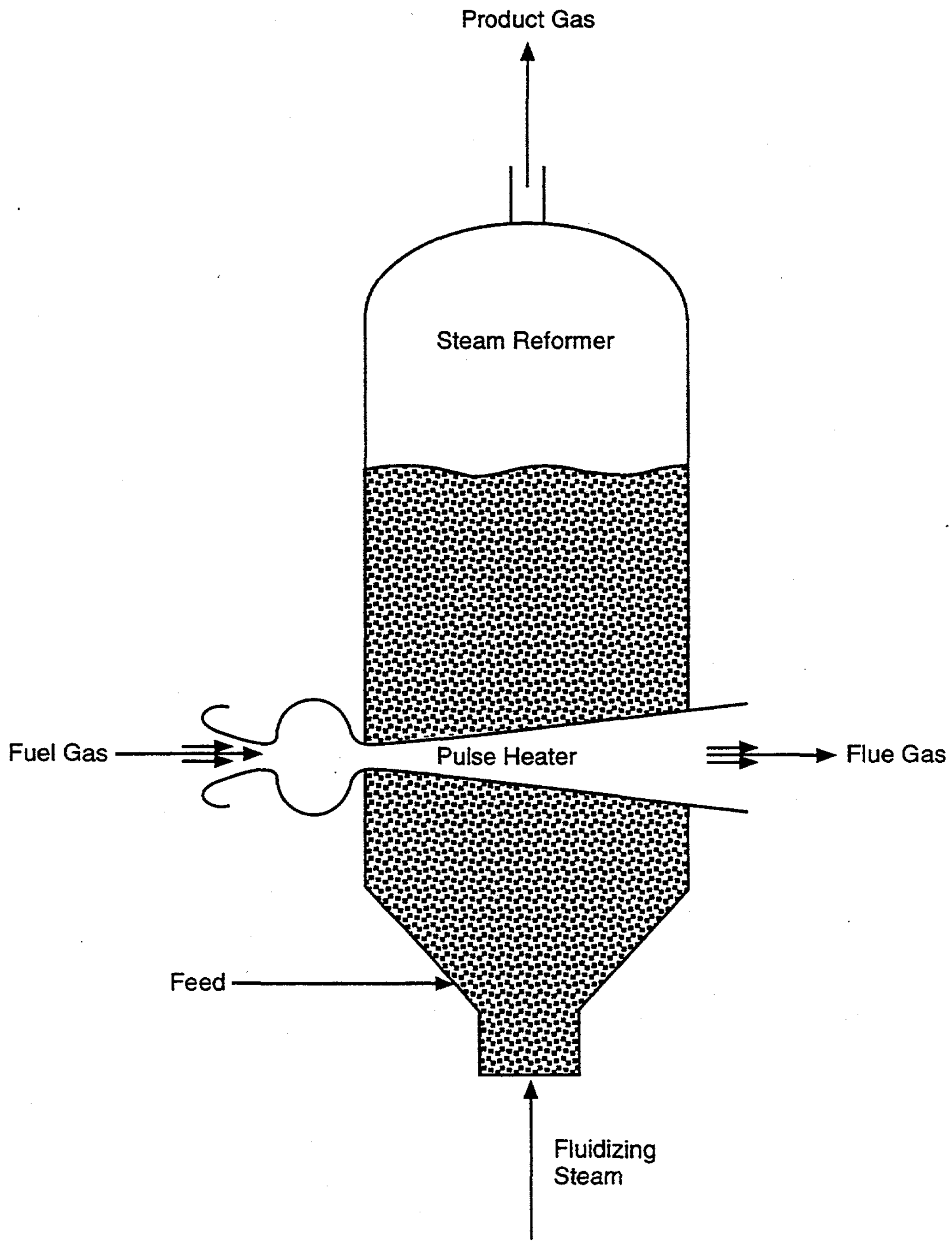

Figure 9-1
Thermochem Pulse Enhanced™
Steam Reformer Heater

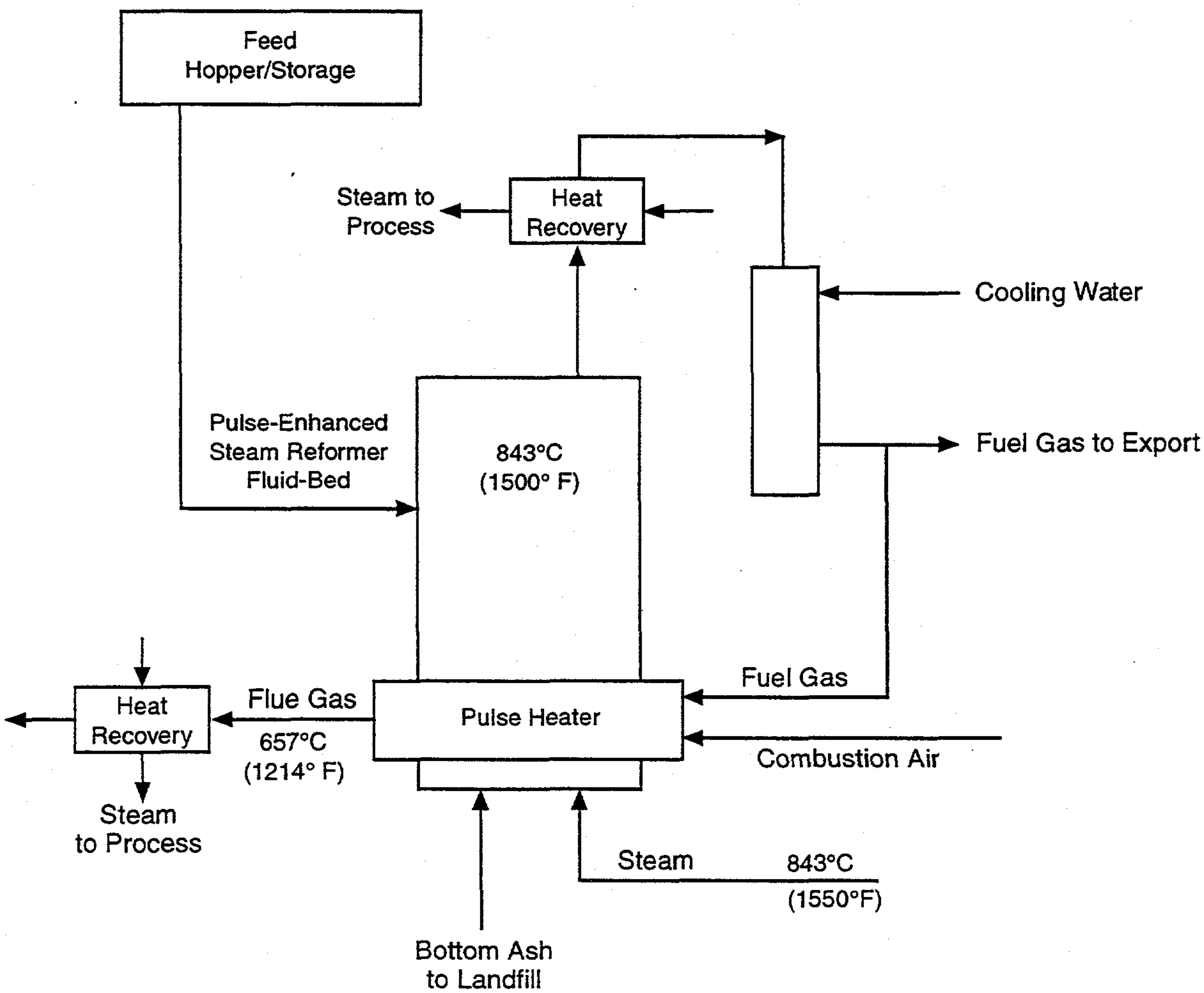

Figure 9-2
Thermochem's Pulse Enhanced™
Stream Reformer Simplified Schematic

carbon monoxide, carbon dioxide, and small amounts of light hydrocarbons. The product gas is cleaned of acid gases in the air pollution control (APC) system. The mineral matter contained in the feed collects in the fluid bed and is removed from the bed. The residue meets the leachability criteria set by EPA for disposal as a nonhazardous material. Two waste-heat-recovery boilers generate steam for the process by cooling the fuel gas and the flue gas.

Some systems have a dryer and an air heater. The dryer uses sensible heat from the fuel gas in between the boiler and scrubber. The air heater recovers sensible heat from the pulse heater flue gas.

The PulseEnhanced™ steam reformer is flexible and can trade off higher throughput by accepting a slightly higher char yield. In one design study, an increase of 162 percent in throughput resulted in a char residue that rose from 12 to 20 percent. The fluid bed can be operated at 816°C (1500°F). At this temperature, production of fuel gas is at its maximum and ash output is at its minimum. It can also be operated at a lower temperature, 649°C (1200°F), for example. At this temperature MSW (RDF) throughput is at its maximum, but more residue (char) is generated.

E. ENVIRONMENTAL ASPECTS

1. Process Emissions Characteristics

Indirectly fired systems have the advantage of minimizing product gas contamination as a result of the absence of combustion products in the product gas. Low temperatures and an oxygen-free reactor do not favor NO_x production. Likewise, low-temperature operation in the range of 600 to 810°C (1110 to 1490°F) results in low PCDD/PCDF in fly ash and flue gas. Operation at low temperature and an oxygen-deficient environment minimize the vaporization of toxic metals.

Limited Toxicity Characteristics Leaching Procedure (TCLP) leach testing indicated that the char is not hazardous, according to the TCLP threshold guidelines. Only barium and selenium were detected, but they were well below the allowable EPA maximum concentration of contaminants specifications, as shown in Table 9.3.[1]

Tests for polychlorinated dibenzo p-dioxin (PCDD) and polychlorinated dibenzo furan (PCDF) were conducted on RDF and char/ash samples. Both the feedstock and the char/ash contained very small amounts of dioxin and furan, as shown in Table 9.4.[2] These data suggest that the dioxin and furan compounds are substantially burned out. Such a conclusion is, however, very tentative. Data on actual flue gas discharge concentration are needed for comparison with EPA Maximum Achievable Control Technology (MACT) limits.

2. Potential for Regulatory Compliance

The estimated emissions are expected to be in compliance with regulations for MSW combustors. However, there are no data to support this expectation.

Table 9.3 ThermoChem TCLP Metal Concentrations From Cyclone Ash of RDF Test— November 7, 1990

Metal	Concentration (mg/l)		
	Detection Limit	Test Result	MCOC*
Arsenic	0.0125	ND†	5.0
Barium	0.1	1.3	100
Cadmium	0.1	ND	1.0
Chromium	0.1	ND	5.0
Lead	0.1	ND	5.0
Mercury	0.0025	ND	0.2
Selenium	0.0125	0.021	1.0
Silver	0.1	ND	5.0

*MCOC = Maximum Concentration of Contaminants †ND = Not detected, below detection limit.

Table 9.4 PCDD/PCDF Analysis of RDF Feedstock and Cyclone Ash in RDF Test (Concentration ng/g)—December 7, 1990

Component	RDF Feedstock		Cyclone Ash	
	Detection Limit	Concentration	Detection Limit	Concentration
Dioxins				
Total TCDD	0.56	ND	0.089	ND
Total PeCDD	0.76	ND	0.13	ND
Total HxCDD	0.11	ND	0.091	ND
Total HpCDD	Not Supplied	0.27	0.23	ND
Total OCDD	Not Supplied	1.7	0.21	ND
Furans				
Total TCDF	0.30	ND	0.29	ND
Total PeCDF	0.22	ND	0.13	ND
Total HxCDF	0.3	ND	0.20	ND
Total HpCDF	0.23	ND	0.21	ND
Total OCDF	0.48	ND	0.13	ND

F. FLOWSHEET

1. Material Balances

Data generated during TC's test program were incorporated into a process heat and material balance model to predict commercial-scale production rates. Table 9.5 is a summary mass and heat balance based on the schematic flowsheet shown in Figure 9.3.

2. Heat Balance

The mass and energy balance is summarized in Table 9.5 and presented in detail in Table 9.6. The basis for the mass and energy balances is TC's flowsheet shown in Figure 9.3. These results indicate that 72 percent of the refuse fuel energy has been converted to fuel value in the gas—a high cold-gas efficiency when compared with that from an air-blown gasifier.

Steam distribution to the base of the gasifier is accomplished by means of pipes (sparger tubes) discharge into the bed. Waste feedstock is introduced directly into the fluid bed using a water-cooled injection screw.

The hot product gases exit the gasifier to a recycle cyclone, where the entrained particulates are captured for return to the bed. A second cyclone, in series, removes much of the remaining particulates in the product gases.

The pulse combustor module, mounted at the base of the gasifier, has a normal firing rate of approximately 211 MJ/h (200,000 Btu/h). It is connected to two, independent firetubes immersed in the fluid bed. The firetubes indirectly transfer heat to the bed to support the endothermic gasification reactions, thus minimizing NO_x production. Likewise, low-temperature operation in the range of 600 to 810°C (1110 to 1490°F) results in low PCDD/PCDF in fly ash and flue gas. Operation at a low temperature and in an oxygen-deficient environment minimizes the vaporization of toxic metals.

3. End Product

Testing with RDF resulted in the end product data shown in Tables 9.7 and 9.8.[3]

4. Proposed Interface

In a recent study in collaboration with K&M Engineering and Consulting Corporation, TC conducted an assessment of the feasibility of an integrated facility combining MSW processing in the amount of 726 Mg/d (800 t/d), using the PulseEnhanced™ heater and steam-reforming technology with the following four options:[3]

- Combined-cycle plant for the production of electricity
- Boiler and steam turbine for the production of electricity
- Methanol production plant
- Hot water production for industrial use.

Table 9.5 Mass and Energy Balance Summary—595 Mg/d (665 t/d) RDF—High-Temperature Case

Stream	Incoming	From	Pressure (lb/in^2-g)	Tempera-ture (°F)	Mass Flow (10^3 lb/h)	Enthalpy (10^3 Btu/h)	Total Energy (10^3 Btu/h)
25	RDF	Feed Prep	0	77	54,583	0	356,734
5	Boiler Feedwater	Water Treatment	200	77	18,991	0	0
16	Combustion Air	Atmosphere	0	77	97,978	0	0
				Total	171,552	0	356,734
Stream	Outgoing	From	Pressure (lb/in^2-g)	Tempera-ture (°F)	Mass Flow (10^3 lb/h)	Enthalpy (10^3 Btu/h)	Total Energy (10^3 Btu/h)
8	Char to Disposal	Char Cooler	8	200	6,503	176	16,934
14	Water to Discharge		60	125	10,512	495	3,146
26	Hot Flue Gas	Air Heater	1	1184	116,168	50,801	50,801
20	Product Gas		3	125	37,997	7,075	264,071
				Total	171,180	60,519	334,952

Table 9.6 Mass and Energy Balance (655 t/d)

Component	Stream No./Description								
	1 RDF to Gasifier	2 Steam to Gasifier	3 Product Gas to Boiler	4 Product Gas to Dryer	5 Water to Boiler	6 Boiler Blowdown	7 Char to Cooler	8 Char to Disposal	9 Water to Cooler
CH_4			5,294	5,294					
CO			24,666	24,666					
CO_2			14,983	14,983					
H_2			2,395	2,395					
H_2O (vapor)		18,619	8,437	8,437					
NH_3			106	106					
H_2S			231	231					
C							1,189	1,189	
Ash	5,314						5,314	5,314	
MAF Feed	38,243								
H_2O (liquid)	440				18,991	372			25,414
N_2									
O_2									
SO_2									
CaO									
$CaCO_3$									
$CaSO_4$									
Total Mass, 10^3 lb/h	43,997	18,619	56,113	56,113	18,991	372	6,503	6,503	25,414
Temp. °F	220	1550	1550	947	77	375	1500	200	77
Energy, 10^3 Btu/h	356,734	0	382,673	382,673	0	0	16,758	16,758	0
Enthalpy, 10^3 Btu/h	1,434	33,362	48,435	31,800	0	113	2,036	176	0
Total Heat, 10^3 Btu/h	358,168	33,362	431,108	414,473	0	113	18,794	16,934	0
Pressure, lb/in^2-g	0	10	5	4	200	10	0	0	60

Table 9.6 (Cont) Mass and Energy Balance (655 t/d)

Component	Stream No./Description								
	10 Water to Discharge	11 Product Gas From Quench	12 Water to Quench	13 Water From Quench	14 Water to Discharge	15 Fuel Gas to Combustor	16 Air to Combustor	17 Flue Gas to Superheater	18 Steam to Superheater
CH_4		5,294				1,714			
CO		24,666				7,985			
CO_2		14,983				4,851		22,099	
H_2		2,395				775			
H_2O (vapor)		8,445				2,864		13,644	18,619
NH_3		0	6,646	6,752	106	0			
H_2S		2	14,380	14,609	229	1			
C									
Ash									
MAF Feed									
H_2O (liquid)	25,414		638,617	648,794	10,177				
N_2							75,157	75,157	
O_2							22,821	5,266	
SO_2								1	
CaO									
$CaCO_3$									
$CaSO_4$									
Total Mass, 10^3 lb/h	25,414	56,187	659,643	670,156	10,512	18,190	97,978	116,168	18,619
Temp. °F	150	125	95	125	125	125	400	1700	375
Energy, 10^3 Btu/h	0	380,022	166,354	169,005	2,651	123,026	0	0	0
Enthalpy, 10^3 Btu/h	1,860	10,462	11,627	31,532	495	3,387	7,714	69,755	22,123
Total Heat, 10^3 Btu/h	1,860	390,483	177,981	200,537	3,146	126,413	7,714	69,755	22,123
Pressure, lb/in^2-g	60	3	20	60	60	1	1	0.6	50

Table 9.6 (Cont) Mass and Energy Balance (655 t/d)

Component	Stream No./Description							
	19 Flue Gas to Air Heater	20 Product Gas to Export	21 Steam From Heat Recovery	22 Steam From Boiler	23 Steam From PC Cooler	24 Product Gas to Quench	25 RDF to Dryer	26 Flue Gas to Heat Recovery
CH_4		3,580				5,294		
CO		16,681				24,666		
CO_2	22,099	10,133				14,983		22,099
H_2		1,620				2,395		
H_2O (vapor)	13,644	5,982	18,619	13,906	4,713	19,023		13,644
NH_3		0				106		
H_2S		2				231		
C								
Ash							5,314	
MAF Feed							38,243	
H_2O (liquid)							11,026	
N_2	75,157					75,157		75,157
O_2	5,266					22,821		5,266
SO_2	1							1
CaO								
$CaCO_3$								
$CaSO_4$								
Total Mass, 10^3 lb/h	116,168	37,997	18,619	13,906	4,713	66,699	54,583	116,168
Temp. °F	1398	125	375	375	375	424	77	1184
Energy, 10^3 Btu/h	0	256,996	0	0	0	382,673	356,734	0
Enthalpy, 10^3 Btu/h	58,515	7,075	22,123	16,523	5,600	30,366	0	50,801
Total Heat, 10^3 Btu/h	58,515	264,071	22,123	16,523	35,600	413,039	356,734	50,081
Pressure, lb/in^2-g	0.2	3	200	200	200	3	4	0.2

Table 9.7 End-Product Data
[for operations at 798°C (1450°F)]

Carbon Gasified, %	83
Product Gas Heating Value, MJ/Nm³ (Btu/sft³)	15.6 (418)
Product Gas Yield, per RDF on MAF basis, Nm³/kg (sft³/lb)	1.24 (19.85)
Heating Value of Gas Produced, per RDF on MAF basis, MJ/kg (Btu/lb)	19.3 (8320

Table 9.8 Product Gas Composition

Compound	Vol%
H_2	45.4
CO_2	25.2
CO	14.5
CH_4	4.4
C_2H_4	0.6
C_2H_6	0
Other	9.9
Total	100.0

The primary objective of the TC study was to minimize the volume of waste that had to be send to a landfill, while incurring the lowest possible cost. The PulseEnhanced™ heater and steam-reforming technology was an alternative to the landfill option for the MSW and for currently available waste-to-energy systems. The results indicated that the combined cycle will produce about 278,000-MJ/h (264 x 10^6-Btu/h) medium-heating-value gas, generating about 36.5 MW. A similar quantity of RDF with a Rankine (steam only) cycle will generate 20.6 MW. In terms of the MSW characteristics used in TC's study, the combined-cycle energy conversion efficiency (heat rate) is 1206 kWh/Mg (1095 kWh/t). The Rankine cycle heat rate is 680 kWh/Mg (618 kWh/t) for 13.1 Mpa-g /510°C (1900 lb/in²-g/950°F) steam conditions. A mass-burn plant with a Rankine Cycle can achieve a heat rate of about 804 to 826 kWh/Mg (730 to 750 kWh/t).

G. DEVELOPMENTAL HISTORY

1. Laboratory/Bench Studies

MTCI (ThermoChem's licensor) operated a bench-scale gasification system at its former laboratory in Santa Fe Springs, California. The equipment is presently being relocated to TC's Baltimore laboratory. The 7-kg/h (15-lb/h) unit includes a gasifier, scrubber, filters, incinerator, and gas analysis instruments. The gasifier hot section consisted of the gasifier shell, steam-distributor nozzles, pulse-combustor module with integral immersed firetubes, recirculation cyclone, and polishing cyclone. The gasifier shell consists of a 10-cm (8-in.) lower portion and a 30-cm (12-in.) upper (freeboard) section. The expanded fluid bed height is approximately 1.8 m (6 ft). A schematic is shown in Figure 9.4.

2. Pilot Plant Studies

ThermoChem has several pilot units in the U.S. and abroad that have been used for sludges and black liquor:

- 11.3-kg/h (25-lb/h) small pilot plants in Santa Fe Springs, California (currently being moved to Baltimore, Maryland) and in Zaragosa, Spain

- 544-kg/h (1200-lb/h) process development units in Baltimore, Maryland, and in Erode, Tamil Nadu, India.

3. Semiworks Plant Studies

In New Bern, North Carolina, and in Pennadam, Tamil Nadu, India, 68-Mg/d (75-t/d) commercial feasibility demonstration units were operated. The former was used in a DOE Clean Coal Technology demonstration at a Weyerhaeuser plant to gasify black liquor. The plant is currently being relocated to another Weyerhaeuser plant.

4. Current Status

TC is focusing its efforts to the gasification of black liquor and sludges. A recent study with K&M Engineering and Consulting Corporation under DOE funding provided an opportunity to perform detailed technical and economic evaluations of gasifying RDF for several applications.[3] (Section 6 contains a discussion.)

Testing of RDF has been done on a 7-kg/h (15-lb/h) unit only.[3] Although they have achieved remarkable progress in scaling-up their system for black liquor, RDF is an extremely difficult material to handle and process. Scale-up from their pilot plant to larger size would be prudent before this system can be expected to be commercial.

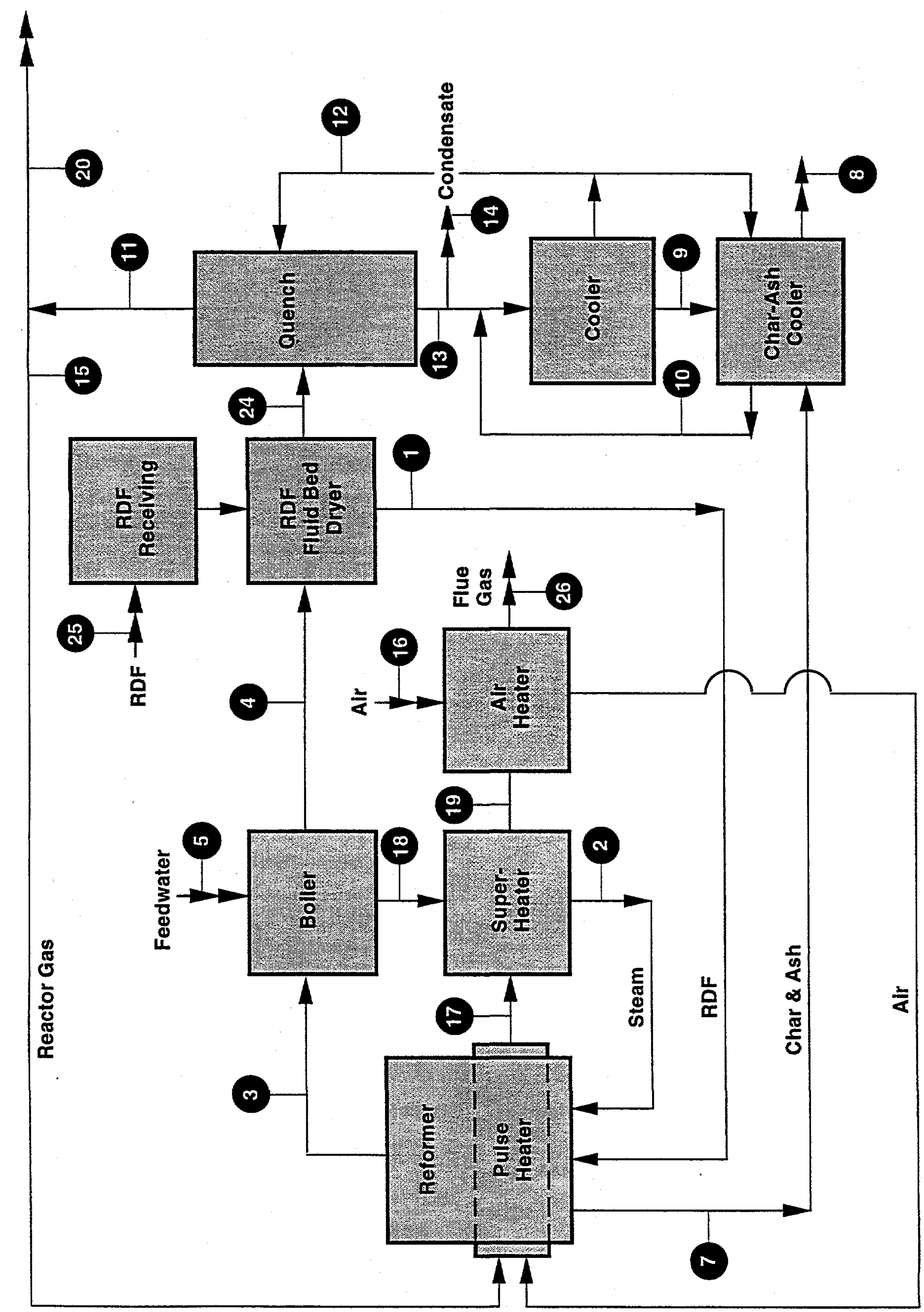

Figure 9-3
Thermochem System Schematic

H. INTERVIEWS

In the course of evaluating the TC technology, CDM engineers met with TC personnel in their Maryland offices. Those interviewed were:

- Gary Voelker, Chief Operating Officer
  Tel: (410) 312-6300
  Fax: (410) 312-6303

- William G. Steedman, Senior Systems Engineer

I. REFERENCES

1. "Steam Reforming of Municipal Wastewater Sludge, Phase 1 Final Report," prepared for the U.S. Environmental Protection Agency under EPA/SBIR Contract No. 68D00046 by Manufacturing and Technology Conversion International, Inc., 1990.

2. G. Voelker and K. Durai-Swamy, "MTCI Steam Reforming Process for Solid Waste Disposal - A New Technology," presented at the Solid Waste Management - Thermal Treatment & Waste-to-Energy Technologies, Washington, DC, April 18-21, 1995.

3. "Minimizing Landfilling Through Pulse Enhanced Steam Reforming of Municipal Solid Waste, Final Report," Prepared for the U.S. Department of Energy, Morgantown Energy Research Center, Contract DE-AC21-90MC27346 by K&M Engineering and Consulting Corporation, Washington, DC, September 1995.

Section 10

Refuse Gasification and Novel Thermal Processing Technologies in 1995 —A Summary Overview—

Refuse is a difficult fuel. The chemical, physical, and thermal properties of waste are heterogeneous and constantly changing. Compounding the effect of the variability is the fact that many refuse characteristics cause problems in high-temperature operation—ash fusion temperatures that are too low and heavy metal and chlorine concentrations that are too high, for example.

Yet with these problems comes an irrefutable fact—refuse is a material that cities and counties *must* manage. Unlike a fossil fuel that can be left in the ground if it commands no market, waste is generated daily in the course of human activity, and we must develop reliable methods for coping with it. Society has accepted the reality that the management of wastes is not free. So, again unlike the fossil fuels, sufficient value can be assigned to the disposal of wastes that one can consider subsidizing processes that accomplish the task or even substantially reduce the wastes themselves. Other than by supporting the goal of cost-effective disposal, most U.S. cities and towns also assign value to two other dimensions of waste management:

- Recovery of the greatest amount of *material* from waste (recycling) before destructive processing or disposal

- Recovery of useful *energy* from the waste.

The proper management of solid waste remains an important element of municipal sanitation and a major line item in municipal budgets. In years past, these realities, combined with energy conservation policies and anticipated increases in U.S. energy costs, created a significant opportunity for thermal processing and associated energy recovery from MSW. In recent years, however, several significant market developments have sharply curtailed the thermal processing market:

- Inability to ensure a reliable supply of waste
- Changing social attitudes
- Changing strategies for obtaining capital
- Lower prices for fossil-fuel prices and thus of energy revenue.

The supply problem is best comprehended from the view of a prospective owner. To ensure a successful endeavor, the owner of a capital-intensive waste management system must be able to support capital borrowing with firm, long-term contracts for waste disposal. More than one municipality or county is usually needed to secure such contracts, and wastes must be drawn from a relatively large area to take full advantage of the costly combustion facilities. The collection of waste has frequently been the purview of private-sector firms. And indeed, during the growth years of waste-to-energy technology, between 1970 and 1985, cities and counties directed these haulers to use a proposed waste management facility. For a time, this practice was acceptable, and it was supported by numerous State statutes, which aided in the formation of waste management districts and similar collectives. However, recent U.S. Supreme Court decisions have restricted the right of such districts to direct waste, calling the practice an unfair restraint of trade. Therefore, unless there is redress of the Court finding by act of the Federal Congress, the basic mechanism for raising capital for waste processing facilities will be greatly weakened or lost. Without such help, a prospective owner faces a greater financial risk during project development, and there is a concomitant effect on bonding costs to the communities and counties.

Environmental issues, especially air emissions, have also had an impact on municipal waste combustion. Initially, pressure focused on visible emissions—the smoking stacks from plants of the 1940s and 1950s were no longer acceptable. The Clean Air Act and its amendments drove the industry away from simple refractory enclosures to waterwall boiler designs. With cooled, air-tight waterwalls, low-excess-air operation was possible. The resultant decrease in flue gas volume made air pollution control economically feasible. This evolutionary change in equipment selection had the beneficial effect of bringing the technical sophistication and systems view of the commercial boiler and combustion industry into the MSW combustion market.

In 1977 the pollutant "dioxin" emerged as one new focus of concern. Dioxin has become the umbrella word for a mix of compounds that includes the several isomers and congeners of polychlorinated dibenzo-p-dioxin and polychlorinated dibenzofuran. Also in the spotlight are emissions of the acid gases [HCl, SO_2, and nitrogen oxides (NO_x)] and of the toxic elements (mercury, cadmium, lead, nickel, chromium, and arsenic, for example). Ash material has also been targeted. In the case of ash, interest has been directed toward both dioxin compounds and toxic elements. Although worry about the environment has not driven thermal processing programs out of business, it has resulted in significantly higher costs, more complex systems, and long delays in moving projects through the public review and regulatory-approval process.

The significance of these impediments to thermal processing is revealed by these observations:

- There have been few new starts of major WTE facilities in the U.S. for several years.
- Companies with owner/operator waste-to-energy plants are aggressively seeking new areas of business for the future.

Adding to these difficulties, there is a generally high level of stress within communities to keep expenditures as low as possible and to constrain borrowing. These cost-control measures are coupled with the "politically correct" pressures for recycling and cutting waste, which are at present dominant forces in the selection of new waste-management facilities in many areas of the U.S. However, these pressures and their consequences are most likely insufficient barriers to thermal processing as a viable option in solid waste management.

One has only to look to Europe, where waste-to-energy is in a commanding position and where environmental regulations are exceedingly strict. In Germany, France, and The Netherlands, recent legislation mandating the cessation of raw waste landfilling will further emphasize the role of thermal processing in solid waste management. Such market expansion in Europe will respond to air-pollution-based environmental concerns through shifts in basic thermal processing technology and the installation of enhanced "back-end control" devices. Although a duplication of this regulatory pattern in the U.S. is unlikely, there is activity in the U.S. Congress to address, and perhaps resolve, the supply reliability problem.

In response to the issues that have been raised, several new or enhanced technologies have emerged to thermally process solid wastes. The most common system is the mass-burn incinerator, which burns raw waste properties through the generation of a refuse-derived-fuel (RDF). A variation burns RDF, but it is combined with other fossil fuels to take advantage of existing combustion equipment, labor forces, energy-conversion systems, etc. One fact worth noting relates to RDF. If that fuel contributes less than 30 percent of the fuel weight input of an existing boiler, the federal air permit for that boiler is *not* affected.

Beyond these well-established combustion processes with energy recovery, a second class of technology has emerged—refuse gasification. Using this technology, usually after recycling and processing to an RDF, the organic fraction of MSW is heated with limited or no air. A gaseous stream with a substantial heat content is produced. This gas can then be cleaned of metals and other solids and of acidic gases, ammonia, hydrogen sulfide, and other contaminants and burned in a gas engine or gas turbine to generate electricity. Because the cleanup efforts focus on a relatively small gas stream rather than the much larger stream of flue gases from incineration systems, environmental emissions control is substantially less costly. Further, the ultimate combustion process takes place with relatively high-quality fuels rather than being mixed with MSW and its occasionally wet material, combustion-resistant constituents, etc.. Thus very low emission rates of dioxins, acid gases, and other problematic pollutants occur.

Of the seven emerging technologies studied, two—Energy Products of Idaho and Pedco International—use full combustion, but in novel contexts. The others—TPS Termiska AB, Proler International, Thermoselect Incorporated, Battelle, and ThermoChem Incorporated—use gasification methods followed by fuel gas cleanup and use.

The penetration of the thermal processing market by advanced technologies is paced by their environmental, economic, and performance acceptability. From an environmental viewpoint, the seven technologies represent an exceptionally sound response to the regulatory challenges of the revised New Source Performance Standards and the Maximum Achievable Control Technology rules of the U.S. EPA and the equally restrictive regulations within the European community.

Economics has always been a critical and probably pacing factor affecting the penetration of thermal processing technology into U.S. MSW practice. Tables 10.1a and 10.1b summarize the economic data collected and developed in this study. An "apples-to-apples" cost comparison among the seven technologies or between these technologies and conventional mass-burn technologies was not the objective, nor was it appropriate for this assignment. Costs should always be developed in a local context of capacity, construction cost, labor cost, energy revenues, etc. However, as the table shows, the capital costs of many of the processes are comparable to the $110,000 per Mg/d ($100,000 per t/d) typical of contemporary mass-burn systems—although some of the costs greatly exceed these norms. The proprietary portion of these new-technology plants ranges from a low of 25 percent to over 90 percent—a value generally higher than the 15 to 25 percent typical for mass-burn facilities. Most operating costs are quite comparable or slightly lower than are common for *owner-operated* mass-burn facilities. One should note that no profits and other charges and costs common to *vendor-operated* facilities were included in the economic analyses presented in this report. The net costs in Tables 10.1a and 10.1b, which may be regarded as the break-even tipping fee, vary widely; but as general numbers, they are mostly in the competitive area when compared with mass-burn plants.

Table 10.1a 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 ($/Mg)*	Gross Power (kWh/t)	Net Power (kWh/t)	Net Operating Cost ($/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 10.1b 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.

The results are less clear concerning "performance." Most of the processes, with the exception of EPI and Thermoselect, require an RDF feed. Landfills are still a necessity for inert materials that cannot be recycled and ash that cannot be used in construction. Historically, most RDF facilities have incurred substantial post-construction rework, capital investment, downrating of capacity, etc. Many of the systems studied have significant development tasks ahead of them. Unfortunately, the catalyst is lacking for the vigorous market activity needed to push this development and to foster risk-taking. Further, many of the systems are quite complex. This complexity presents some problems when attempting to gain acceptance from the client communities, regulatory authorities, and financial and engineering entities involved in concept selection and project implementation.

Finally, most of the processes are still in the developmental stage and have little continuous operating experience under commercial conditions. Thus some risk remains that process or equipment deficiencies or difficulties will appear . Those with knowledge of the waste-to-energy industry are very familiar with the development history of Purox, Landgard, Torrax, Black-Clawson, Melt-Zit, Ecologenics, and many other concepts, which were not successfully commercialized. In the aggressive working environment of waste-management facilities, risk has often meant significant, costly, and politically painful problems.

It would be premature to suggest that gasification technology is the thermal processing strategy of the future. Solid waste is a very difficult fuel. However, in both niche market sectors and the broader market, the gasification technologies studied, and some others, may well emerge as "commercially ready" alternatives, along with mass burning, RDF and fluidized bed technologies, which currently dominate the market.

It is noteworthy to comment that the project team was very impressed with the professionalism, the high technical standards, and the business commitment of most of the companies studied. Further, many of the developers have access to the capital resources that are so important to the challenges of technology demonstration and evolution. Such financial backing augurs well for the ability of many of these developers and others not studied in detail to further their developments and present to the marketplace convincing proof of the ability of their processes to meet the demands of MSW management.

Appendix A - List of Gasification and Thermal Process Firms & Processes

1. Lesley Manufacturing 1207 N 1800 Road Lawrence, Kansas 66049 *Les Blevins*	☐	(913) 842-1943 (913) 842-0341 (F)
2. Kvaerner EnviroPower, Inc. 10055 Red Run Boulevard Owings Mills, Maryland 21117 *Herbert J. Fruth*	☐	(410) 356-1111 (410) 356-1115 (F)Ext. 41
3. Global Energy USA 1500 Chiquita Center, 250 East Fifth Street Cincinnati, Ohio 45202 *Harry Graves, President and CEO*	☐	(513) 621-0077 alt. (513) 762-7817 (513) 621 5947 (F) alt. (513) 721-4628 (F)
4. Proler International Corp. 4265 San Felipe, Suite 900 Houston, Texas 77027 *Dennis L. Caputo, V.P.*	☐	(713) 963-5944 or (713) 627-3737 (713) 627-2737 (F)
5. Battelle Columbus 505 King Avenue Columbus, Ohio 43201-2693 *Mark Paisley*	☐	(614) 424-4958 (614) 424-3321 (F)
6. Themoselect, Inc. Columbia Center Suite 230 210 W. Big Beaver Road Troy, MI 48084 *David J. Runyon*	☐	(810) 689-3060 (810) 689-2878 (F)

7. Entropic Technologies 4660 South Hagadorn Road East Lansing, MI 48823 *Mark Battaglia*	☐	(517) 351-4901 (517) 351-9149 (F)
8.Pedco Incorporated 216 East 9th Street, 5th Floor Cincinati, Ohio 45202 *William H. Long*	☐	(513) 784-0033 (513) 241-7958 (F)
9. Thermogenics, Inc. 3620 Wyoming Blvd. NE - Suite 210 Alburquerque, New Mexico 87111 *Stephen Brand*	☐	(505) 298-4381 (505) 296-4860 (F)
10. Waste Conversion Systems 14590 East Freemont Ave Englewood, CO 80112 *Stan Abrams*	☐	(303) 690-8300 (303) 690-6336 (F)
11. Institute of Gas Technology 1700 South Mount Propect Road Des Plains, Illinios 60018-1804 *Ronald H. Carty*	☐	(708) 768-0591 (708) 768-0600 (F)
12. Bioenergy Development Corp. 220 W. 18th Street - 2nd floor New York, New York 10011 *Earl A. Rogers*	☐	(212) 865-2513 (212) 865-8713 (F)

13. Cratech, Inc. Route 5, 2303 North Second Tahoka, Texas 79373 *Joe D. Craig, President*	☐	(806) 327-5220 (806) 327-5570 (F)
14. Wright Malta Corporation Malta Test Station, Plains Road Ballston Spa, New York 12020 *J.A. Coffman*	☐	(518) 899-2227 (518) 899-4799 (F)
15. PRM Energy Systems, Inc. 504 Windamere Terrace Hot Springs, AR 71913 *Ron Bailey*	☐	(501) 767-2100 (501) 767-6968 (F)
16. Sur-Lite Corp. 8124 Allport Avenue Santa Fe Springs, CA 90670 *Deward Gjerde, General Manager*	☐	(310) 693-0796 (310) 693-7564 (F)
17. Morbark Industries 8507 South Winn Road Winn, MI 48896 *Run Demlow*	☐	(517) 866-2381 (800) 831-0041 (517) 866-2280 (F)
18. Ahlstrom - Pyropower (Proflow) 8925 Rehco Road San Diego, California 92121	☐	(619) 458-3000 (619) 457-1216 (F)

20. Procedyne ☐ (908) 249-8347
11 Industrial Drive (908) 249-7220 (F)
New Brunswick, NJ 08901

Thomas Parr, Manager Process Division

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21. Wayne Technology Corp. ☐ (803) 223-4964
625 East Durst Avenue (803) 229-4382 (F)
Greenwood, SC 29649

Gary Gunderson

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23. SRI International ☐ (415) 859-2430
333 Ravenswood Ave. (415) 859-3395 (F)
Menlo Park, CA 94025-3493

David Ross

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24. KFX Inc. ☐ (303) 293-2992
1999 Broadway Street, Suite 2505 (303) 293-8430 (F)
Denver, CO 80202

Theodore Venners

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25. Molten Metals Technology ☐ (617) 487-9700
51 Sawyer Road (617) 487-7870 (F)Ext. 7648
Waltham, Massachusetts 02154

Karen Colette

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26. Arizona State University ☐ (602) 965-0745
Center for Energy Research , Box 875806 (602) 965-2896 (F)
Tempe, Arizona 85257-5806

Dr. Tong

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27. University of Alabama R I Building , Room E33 Huntsville, Alabama 35899 *Dr. Brain Landrum*	☐	(205) 895-6154 (205) 890-7205 (F)
28. International Technologies, Inc. 1710 West Flecher Street Chicago, Illinios 60657 *Paul Baskis (Technical), Mike Fink (Business)*	☐	(312) 472-5006 (312) 472-7283 (F) (217) 892-8825
29. Destech Energy 2500 City West Blvd., Suite 150 Houston, Texas 77042 *Mark Roll*	☐	(713) 735-4000 (713) 735-4059 (F)
30. EnerTech Environmental, Inc. 430 Tenth Street N.W. Suite N-104 Atlanta, Georgia 30318 *Micheal Klosky*	☐	(404) 892-9440 (404) 892-8816 (F)
31. Energy Product of Idaho 8014 Germantown Road Philadelphia, PA 19118 *Joyce M. Ferris*	☐	(215) 248-5244 (215) 248-2381 (F)
32. Sofresid Paris, France *Goare Guer*	☐	011+33 1 4818-4160 011+33 1 4818-4497 (F)

33. Lurgi Energy Umwelt Gmbh. Lurgi Allee #5 Frankfort 60295 Germany *Johannes C. Loffler*	☐	011+49 69 5808 3468 011+49 69 5808 2757 (F)
34. Voest Alphine Turmstrasse #44 Linz, Austria extension *J. Lehner*	☐	011+43 732 6592 8625 011+43 732 6592 2884 (F) (They will ask for the fax and the "answer" is: 2884)
35. ThermoChem, Inc. 13080 Park Street Santa Fe Springs, CA 90670 *K. Durai-Swami SVP-Technology Applications*	☐	(310) 941-2375 (310) 941-2732 (F)
36. Comprehensive Resources Recovery & Reuse 628 Plymouth Foster City, CA 94404 *Micheal E. Cole*	☐	(415) 345-0502 (415) 369-4982 (F)
37. HydroMax 257 Water Street, Suite 2E New York, NY 10038 *Marc Kalish* (pron. kay-lish)	☐	(212) 385-7560 (212) 967-3018 (F)
38. Foster Wheeler Development Corp. 12 Peach Tree Hill Road Livingston, NJ 07039 *Ernest Daman*	☐	(201) 535-2332 (201) 535-2242 (F)

48.TPS Termiska Processor AB ☐ 011-46-155-22-1385
Studsvik AB S.611 82 011-46-155-26-3052 (F)
Nyköping, Sweden

Erik Rensfelt

---

50. Lawrence Livermore National Lab. ☐ (510) 423-7053
(510) 423-0618 (F)
Livermore, CA

Dr. Robert Schock *(working with Texaco/Montebello/Neil Richter*

Firms that could not be contracted or who indicated "no interest"(marked "X")

39. Southern Electric International ☐ (404) 261-4700
900 Ashwood Parway (404) 804-9610 (F)
Suite 500
Atlanta, Georgia 30338

William S. Bulpitt

---

19. Texaco, Inc., Montbello Research Lab☐ (310) 908-7238
329 North Durfee Ave. (310) 692-4625 (F)
El Monte, CA 91733 (310) 699-7408 (F-Backup)

Thomas Leininger

---

22. Interchem Environmental, Inc. ☐ (913) 599-0800
9135 Barton (913) 599-2923 (F)
Oveland Park, Kansas 66214

Lee Derr

---

40. Halcyon Associates

41. Kellog-Rust -Westinghouse

42. EDP

43. Xytell Bechtelle (713) 984-6700
1400 Brittmore Road
Houston, TX 77043

44. Conrad

45. GM/Lasco Steel

46. SRS

47. PUROX Contact made. Telephone shut off without forwarding address.

49. Ebara

Camp Dresser & McKee Inc.

10 Cambridge Center
Cambridge, MA 02142
(617) 252-8357
Fax: (617) 621-2565

FAX TRANSMISSION COVER SHEET

Date: *August 15, 1996*

To: *Thermal Processing Developer Mr*____________________

Re: *National Renewable Energy Laboratory (NERL) Assignment*

Sender: *Walter R. Niessen*

YOU SHOULD RECEIVE 3 PAGE(S), INCLUDING THIS COVER SHEET. IF YOU DO NOT RECEIVE ALL THE PAGES, PLEASE CALL (617) 252-8357.

On May 8, 1995 the National Renewable Energy Laboratory (NREL), an organization formed and reporting to the U.S. Department of Energy, awarded Camp Dresser & McKee Inc. (CDM) a contract to evaluate a limited number of thermal processing technologies that are (or could be) applicable to municipal solid waste (MSW). Although gasification-based processes have been highlighted by NREL, other advanced or novel thermal methods are of equal interest. We understand that your organization is involved in the development and commercialization of a technology in one of these categories. This letter invites you to consider participation in the NREL project.

The primary objective of the NREL work is to prepare an up-to-date, comprehensive and objective report on the selected processes. Each report will stand on its own: the project does not "pick a winner" or compare technologies. The scope of each report is quite broad and includes the presentation of facts, judgments and analytical results in the following areas:

- Technical - Flowsheets, heat & material balances, basic principle of operation
- Environmental - Air and water emissions, residue characteristics
- Business - Financial strength and resources
- Cost/Economics - As projected back to MSW waste management costs
- Operations - Reliability, flexibility, maintenance/operational features
- Implementation - Resources and strategy to move into commercialization phase

The activities during the first 30 days of our contract effort fall into two areas: (1) development of a comprehensive Work Plan and (2) selection of the candidates. The Work Plan is the blueprint for the report: what information will be sought? how will the information be analyzed and used? and in what form will the work product be presented. I mention this task to illustrate the fact that the detailed framing of our work is still evolving.

The second work area involves selecting the technologies to be evaluated. We have prepared a master list of over 40 candidates including what we trust are the correct addresses, the names of the most appropriate "contact persons", and the telephone/FAX numbers. This FAX marks our first formal contact with your firm. We ask you to fill out a return FAX (attached) to open the dialogue from your end. In the very near future (within a week or thereabouts) we plan to contact you directly by telephone. From these initial exchanges, we will collect sufficient information to produce a "short list" of approximately 20 technologies by May 25th. Following a second round of contacts in late May and early June, we will meet with NREL to select the final technologies that meet the project guidelines. That will mark the beginning of the in-depth data collection and analysis effort.

The ultimate report effort for the seven selected candidates will be comprehensive. It will include an inspection visit by CDM engineers to operating pilot plants or commercial facilities embodying the candidate technologies. Also, we anticipate in-depth discussions and exchanges of information and perspectives with appropriate technical, business and environmental specialists from the candidate firms. From these data and subsequent analysis, we will strive to produce a fair and insightful review of each technology and its potential applicability to MSW management problems. The proposed readership includes, importantly, potential "buyers" of systems as well as consultant organizations, academic researchers and governmental agency/laboratory staff professionals.

The CDM project team looks forward to contacting you within the next 10 days. Again, if you wish to consider participation in the project, please complete and return-FAX the message on the following page.

Very truly yours,
CAMP DRESSER & McKEE INC.

Walter R. Niessen - Principal Investigator
Investigation Team: Paul J. Stoller
Charles H. Marks
Robert E. Sommerlad

Enc/

Appendix B Fax Request for Basic Data

fax

To: Walter R. Niessen - Camp Dresser & McKee Inc.

Fax: (617) 621-2565

From: ____________________

Date: May ___, 1995

Pages: ______, including cover sheet.

- We are in receipt of your FAX message regarding the NREL project but have no interest in the project at this time. ☐

- Our firm may have an interest in participation. The correct and complete name of our firm is:
____

- The contact person you should talk to is:
____

- The street address (no Box numbers, please) is:
Street____________________________________
City__________________ State ______ Zip______________

- The best telephone/FAX number to use in the next 10 business days is:
Telephone (   )__________ , FAX (   )__________

- Message:
____
____
____
____
____

Appendix C. Preliminary Request for Data from Seven Processes

Dear Mr. _____________,

As the first step in our project for the National Renewable Energy Laboratory, Camp Dresser & McKee Inc. (CDM) has completed its preliminary screening of over 50 gasification and advanced thermal processing technologies applicable to municipal solid waste (MSW). As we have described to you and/or others in your firm, our project is intended to prepare a "state-of-the-art" report limited to a maximum of seven processes which best meet the following criterion:

o **State of Development** - Near to or just at the "commercial stage". All major process issues are to have been researched and resolved by the system provider. Tests should have been conducted at a scale of more than three tons per day and for a cumulative duration of more than 300 hours to demonstrate practical feasibility. At this point in our evaluation, it should appear that the process is technically feasible and potentially recommendable to communities desiring an advanced solid waste processing technology and prepared to accept some (but not excessive) technical risks.

o **Business Focus** - Clearly targeted on the processing of MSW. The candidate's policy in this matter should be visible both in their present business thrust and in the degree of focus on MSW issues in prior and on-going process development testing. Business planning should "fit" with the U.S. MSW marketplace as it is characterized by the type and quantity of available MSW, energy and materials markets and the nature of typical MSW management contractual agreements.

I am pleased to inform you that your firm and its waste processing process were selected as one of the seven processes to be evaluated. Specifically, I//Mr. Charles E. Marks/Mr. Robert E. Sommerlad will be the project leader for our review and evaluation or your process although others of our core team of senior specialists also will be involved. We expect to begin work in earnest over the next several weeks and have targeted the end of the year for completion of our work and submission of a draft report. In the interim, we hope to become much more familiar with your process and your status in implementation.

The ultimate objective of this project is to produce a public document in the form of a report that includes a comprehensive description of your process (and six others) together with the associated technical, environmental and financial characteristics. It is intended that our report will be made widely available to individuals, to consulting engineers, full-service MSW contractors, researchers and representatives from the various levels of government who have responsibility for solid waste management. Our present concept of our work product is best communicated by indicating the expected "Table of Contents" (see attached).

Specifically, we will seek the following information from you which we hope to replicate in our report:

- A relatively complete flowsheet showing all major items of process equipment;
- A complete heat and material balance tracking all significant mass and energy flows through the system;

- Any available air or water-borne emission data; and information on the economics (capital and operating costs, and any prospective revenue streams).
- General information (such as hours of operation, tons processed etc.) that characterizes the state of development and testing of the key technical features of the process.

We expect that the above information, specifically, will be made available to us free of constraints regarding disclosure to others. However, you may regard some of the details of your process, some of the equipment designs, aspects of operating techniques or conditions/set-points and other matters as proprietary or "company confidential". You will understand that once our report is printed, we lose any control on access and use of the information contained therein.

We recognize that this may produce a conundrum: how can we be exposed to enough information in enough depth to fully understand your process and its technical status while producing a report which protects your investment in technology development? On the other hand, we are **not** generating a "design manual" nor is our work "comparative" (each process chapter is free-standing). Our report need not include any subtleties of operating technique, set points, intricate discussions of control logic, details of materials of construction selections etc. (excepting, indirectly, as they relate to cost).

In view of these considerations we are willing, if requested, to execute a confidentiality agreement providing for the protection of your proprietary technology when explicitly marked as such, for a reasonable time period (e.g., 5 years) and subject to the conventional releases for information received from third parties or subsequently made public by you.

Please note that our contractual project manager and other members of the project "steering committee" (representing the National Renewable Energy Laboratory, the U.S. EPA, the U.S. Department of Energy and a representative of Southern California Edison) have a strong interest in fully understanding our work and the characteristics of your process. It is desirable if they can have access to as much as possible of the written data on your process without execution of a confidentiality agreement. Thus, please minimize the classification of data if it is not necessary to do so. If you believe it is critical, the steering committee members have indicated that they can execute such an agreement (although with difficulty).

Additionally, at the conclusion of our work when we have prepared a draft of the chapter of the final report relating to your process, we will submit a copy of the chapter for your review. We expect to allow two weeks for your review. At that time you can indicate those elements of the report where (if at all) you believe that proprietary information is revealed and we will edit/delete/mask same to our mutual agreement in the final text of the report. Also, if you disagree with our observations and conclusions or our editorial comments or critiques, you will have the opportunity to (briefly) provide a "rebuttal" which either will be inserted as a footnote or will be accepted and appropriate changes made. We reserve the right to limit the number and length of such commentaries.

We trust that this arrangement is satisfactory. If so, please provide a suitable confidentiality agreement (if one is necessary) which will be executed by me on behalf of the NREL project team. If you have remaining concerns or questions, please do not hesitate to call me at (617) 252-/8357/Mr. Marks at (617) 784-6374/Mr. Sommerlad at (908) 272-5667. We look forward to working with you and your associates over the next several months.

Very truly yours,
CAMP DRESSER & McKEE INC.

Walter R. Niessen, P.E.
Senior Vice President

Enc/

cc: C.H. Marks, R.E. Sommerlad, P.J. Stoller

Appendix D

WASTE GASIFICATION or NOVEL THERMAL PROCESSING FACILITIES

Please fill out if applicable. If quantitative answers are requested, please give ranges if appropriate. For our visit we will formulate more detailed questions based on your answers. Please note that the answers will be used for our report, which will be distributed.

1. BRIEF HISTORY

Since when has the plant been in operation (month/year)? ___/___

What is the current status of the plant?

___ demonstration/pilot ___ on-line ___ intermittent ___ shut down

___ commercial ___ on-line ___ intermittent ___ shut down

What is the longest continuous operating period _______ hrs, days?

What was the waste processing rate during that period?

average ______ (ton/day, tonnes/day)
maximum ______ (ton/hr, tonnes/hr)

Describe briefly the history of laboratory and pilot plant studies. If commercial, what has been the availability of the plant (operable hours per year/8760) since starting operation from year to year (if only shorter periods are applicable. Please indicate)?

1992___%

1993___%

1994___%

1995___%

What has been the <u>un</u>scheduled shut-down time of the plant so far?

1992 ___hrs ___%

1993 ___hrs ___%

1994 ___hrs ___%

1995 ___hrs ___%

Which are the reasons for the unscheduled shut-down time? Problems with any of the following system components (indicate relative importance):

__ fuel supply/preparation

__ gasifier

__ combustion

__ gas cleaning

__ electricity/heat generation

__ ______________

__ ______________

2. THE PROCESS

Please supply us with a process description and flowsheets of the process including temperatures, mass flows and energy flows, enabling us to present mass and energy balances.

Process Description attached? ___
Flowsheets attached? ___
Mass balances attached? ___
Energy balances attached? ___
Plant lay-out/plant dimension sheet attached? ___

What is the maximum capacity of one process-line of the present plant?

(tonnes of waste/day, tons/day)*

How many process lines have been installed for the present plant?

___ one
___ two

What is the thermal capacity (MW_{th}, Btu/hr) of one reactor?

minimum:________(MW_{th}, Btu/hr)

maximum________(MW_{th}, Btu/hr)

* indicate units as applicable

What elements of the system (from waste receipt to residue/flue gas treatment) are under test or remain to be tested/developed?

	element	under test	to be tested
1.	______	______	______
2.	______	______	______
3.	______	______	______
4.	______	______	______

3. WASTE FEED (WASTE) SPECIFICATIONS

Which type of waste is the plant designed for (specification concerns, type, components, composition)?

___ RDF (please specify): _____

___ selected types of waste (please specify) _____

___ all types of waste (please specify) _____

Which type of waste is used currently?

What is the waste configuration required?

___ pellets (cylindrical)
___ briquettes
___ bulky material
___ "fluff"

What is the type of the waste used currently?

What are the required dimensions of the waste?

What are the dimensions of the waste used currently?

Length ______ (mm) x diameter _____ (mm) x height _____ (mm)

Required bulk density (kg/m^{30}, lb/cft):

Bulk density of the used waste (kg/m^{30}, lb/cft):
What is the required/used waste composition?

	design	used
Proximate analyses	___-___	___-___

(wet basis, mass%)

- Moisture ___-___ ___-___
- Ash ___-___ ___-___
- Fixed Carbon ___-___ ___-___
- Volatile Matter ___-___ ___-___

Some components from the ultimate analysis (dry basis, mass%):

- S ___-___ ___-___
- Cl ___-___ ___-___

What is the required range of caloric value (LHV___ or HHV___) (MJ/kg Btu/lb)? ________________

What is the actual range caloric value (LHV___ or HHV___) of the waste (MJ/kg Btu/lb)? __________

What is the ash melting point/range (°C/°F)?____

Other aspects with respect to waste quality: ____

Can US waste (specifications attached) be processed in the plant?

___ Yes
___ No

If "Yes", is special pre-treatment required?

___ Yes
___ No

3a. AUXILIARY FUEL

Is auxiliary fuel/energy required?
___ Yes
___ No

If so, specify - type __________

quality __________ (Btu/cft, KWH per ton, MW_{th} per tonne)

4. PRODUCT/GAS SPECIFICATIONS

What is the raw gas composition at the reactor outlet (in volume%)?

		design	real values
-	H_2	___-___	___-___
-	CO	___-___	___-___
-	C_xH_y	___-___	___-___
-	CO_2	___-___	___-___
-	N_2	___-___	___-___
-	H_2O	___-___	___-___
-	Other	___-___	___-___

What is the specified concentration of the following components in the product gas at the mentioned locations in the process? (units?____________________ corrected to____________________)

		at the gasifier outlet		after gas cleaning	
		design	real	design	real
-	total dust	___-___	___-___	___-___	___-___
-	tar	___-___	___-___	___-___	___-___
-	HCl	___-___	___-___	___-___	___-___
-	H_2S	___-___	___-___	___-___	___-___
-	NH_3	___-___	___-___	___-___	___-___
-	K, Na, Ca salts	___-___	___-___	___-___	___-___
-	__________	___-___	___-___	___-___	___-___
-	__________	___-___	___-___	___-___	___-___

What is the specified dust particle size (μm) in the gas after the gas cleaning section? ____________
What is the specified calorific value (LHV___ or HHV___) of the product gas ($MJ/m_0 3$, Btu/cft)?
What is the specified enthalpy of the product gas (MJ/m_0^3, Btu/cft)?

pressure (bar absolute) ________

temperature (°F) ________

What is the production rate? ________(Nm^3/tonne, scft/ton)

5. OPTIMIZATION[1]

Can the process be optimized with respect to the energy efficiency?

___ Yes
___ No

How much improvement in efficiency do you expect?

___ Electric efficiency ___ %

___ Thermal efficiency ___ %

Can the process be optimized with respect to the emissions?

___ Yes
___ No

Is more energy needed to achieve minimum emissions?

___ Yes
___ No

Please fill out the minimum achievable emissions under "Environmental aspects".

6. SCALE-UP[2]

Where in the process are any limitations in scale-up?

___ In the reactor sections
___ In the process train after the reactor sections

What is the expected maximum capacity of one process-line?

____

With respect to the present plant configuration; concerns optimization by fine tuning etc.

Concerns future plants, which might differ from the present plant.

___ tonnes of waste/hr, ton/hr of waste

___ heat input (MW_{input}, Btu/hr)

7. ENVIRONMENTAL ASPECTS

What are the emissions (in mg/m_0^3, gr/cft dry flue gas at 11% O_2, 7% O_2) of the plant (if you have more data on realized emissions, please specify)?

		specified	realized	after optimization (expected)
total dust	___-___	___-___	___-___	
HCl	___-___	___-___	___-___	
fluorides	___-___	___-___	___-___	
CO		___-___	___-___	___-___
organic compounds (as C)	___-___	___-___	___-___	
sulphur oxides (as SO_x)	___-___	___-___	___-___	
nitrogen oxides (as NO_2)	___-___	___-___	___-___	
toxic metals Sb+Pb+Cr+Cu+Mn+V+Sn+As +Co+Ni+Se+Te		___-___	___-___	___-___
Cd		___-___	___-___	___-___
Hg		___-___	___-___	___-___
dioxins & furans (PCDDs and PCDFs in ng TEQ/m_0^3)	___-___	___-___	___-___	

What residue and effluent discharge streams are produced and in which quantities (in kg/tonne, l/tonne, lb/ton, gal/ton)? Please describe.

Heavy/toxic metals (mg/kg waste):	residue	effluent
- Pb	___-___	___-___

-	Cr	__-__	__-__
-	Cu	__-__	__-__
-	Zn	__-__	__-__
-	Ni	__-__	__-__
-	Cd	__-__	__-__
-	Hg	__-__	__-__

Please supply us with as much information concerning quantity and the characteristics (toxicity, leachability, configuration, composition) and the processing potential of the by-products as possible.

Information attached? ___ Yes
___ No

8 COMPLEXITY AND RELIABILITY

How many total employees are needed for running the plant? ____

How many annual manhours are needed for running the plant? ____ manhrs/yr

How many shifts are needed for operation? ____ shifts

How many maintenance (man)hours are needed for the plant annually? ____ manhrs/yr

Are there any fundamental problems in plant operation presently?

___ Yes
___ No

Are there any problems in plant operation which can be solved in a short term?

___ Yes
___ No

Is the process sensitive to corrosion/erosion?

___ Yes
___ No

Are special measures taken/required for safety? e.g. for reducing risk of fire, explosion, etc.?

___ Yes
___ No

What? ____

9. FINANCIAL ASPECTS

How many running hours are planned for commercial operation annually? ____ hrs

What is the planned availability of the plant annually? ____ %
What is the assessed technical lifetime of the complete plant? ____ years

What is the currency in which the amounts are presented?

- Italian Lire
- German Mark
- US Dollar
- Other: ________

Please present requested costs in present values:

What are the investment costs of:

- the complete plant: ___ capacity: ___ tonnes waste/hr
- the process line: ___ capacity: ___ tonnes waste/hr

What are the specific investment costs (per tonne waste) of:

- the complete plant (two lines): ___ capacity: ___ tonnes waste/hr
- the process line: ___ capacity: ___ tonnes waste/hr

Please fill in the following table:

Main component	invest. cost	technical lifetime of component	maintenance materials	maintenance personnel

	(___)	(yr)	(___/yr)	(manhrs/yr)
Preprocessing ______________	___	___		___
Feeding system	______________	___	___	___
Ash discharge system	______________	___	___	___
Reactor	______________	___	___	___
Flue gas treatment	______________	___	___	___
Product gas treatment	______________	___	___	___
Ash treatment ______________	___	___	___	
Water treatment	______________	___	___	___
Heat exchangers	______________	___	___	___
Power generation	______________	___	___	___

What is the accuracy of the afore mentioned investment costs?

- within 10%
- within 20%
- within 30%
- other limit: ___%

What are the local operatinging costs of the total plant?

Breakdown:		per year	per tonne waste
+	depreciation of investments	____________	____________

+/-	fuel costs	________	________
+	operation	________	________
+	maintenance	________	________
+	consumables	________	________
+/-	by-products	________	________
-	electricity/heat sold	________	________
+	other	________	________
	TOTAL COSTS		

Appendix D

WASTE GASIFICATION or NOVEL THERMAL PROCESSING FACILITIES

Please fill out if applicable. If quantitative answers are requested, please give ranges if appropriate. For our visit we will formulate more detailed questions based on your answers. Please note that the answers will be used for our report, which will be distributed.

1. BRIEF HISTORY

Since when has the plant been in operation (month/year)? ___/___

What is the current status of the plant?

___ demonstration/pilot ___ on-line ___ intermittent ___ shut down

___ commercial ___ on-line ___ intermittent ___ shut down

What is the longest continuous operating period _______ hrs, days?

What was the waste processing rate during that period?

average ______ (ton/day, tonnes/day)
maximum ______ (ton/hr, tonnes/hr)

Describe briefly the history of laboratory and pilot plant studies. If commercial, what has been the availability of the plant (operable hours per year/8760) since starting operation from year to year (if only shorter periods are applicable. Please indicate)?

1992___%

1993___%

1994___%

1995___%

What has been the <u>un</u>scheduled shut-down time of the plant so far?

1992 ___hrs ___%

1993 ___hrs ___%

1994 ___hrs ___%

1995 ___hrs ___%

Which are the reasons for the unscheduled shut-down time? Problems with any of the following system components (indicate relative importance):

__ fuel supply/preparation

__ gasifier

__ combustion

__ gas cleaning

__ electricity/heat generation

__ ________________

__ ________________

2. THE PROCESS

Please supply us with a process description and flowsheets of the process including temperatures, mass flows and energy flows, enabling us to present mass and energy balances.

Process Description attached?	___
Flowsheets attached?	___
Mass balances attached?	___
Energy balances attached?	___
Plant lay-out/plant dimension sheet attached?	___

What is the maximum capacity of one process-line of the present plant?

(tonnes of waste/day, tons/day)*

How many process lines have been installed for the present plant?

___ one
___ two

What is the thermal capacity (MW_{th}, Btu/hr) of one reactor?

minimum:________(MW_{th}, Btu/hr)

maximum________(MW_{th}, Btu/hr)

* indicate units as applicable

What elements of the system (from waste receipt to residue/flue gas treatment) are under test or remain to be tested/developed?

	element	under test	to be tested
1.	____________	________	________
2.	____________	________	________
3.	____________	________	________
4.	____________	________	________

3. WASTE FEED (WASTE) SPECIFICATIONS

Which type of waste is the plant designed for (specification concerns, type, components, composition)?

___ RDF (please specify): _____

___ selected types of waste (please specify) _____

___ all types of waste (please specify) _____

Which type of waste is used currently?

What is the waste configuration required?

___ pellets (cylindrical)
___ briquettes
___ bulky material
___ "fluff"

What is the type of the waste used currently?

What are the required dimensions of the waste?

What are the dimensions of the waste used currently?

Length ______ (mm) x diameter _____ (mm) x height _____ (mm)

Required bulk density (kg/m^{30}, lb/cft):

Bulk density of the used waste (kg/m^{30}, lb/cft):
What is the required/used waste composition?

	design	used
Proximate analyses	___-___	___-___

(wet basis, mass%)

- Moisture ___-___ ___-___
- Ash ___-___ ___-___
- Fixed Carbon ___-___ ___-___
- Volatile Matter ___-___ ___-___

Some components from the ultimate analysis (dry basis, mass%):

- S ___-___ ___-___
- Cl ___-___ ___-___

What is the required range of caloric value (LHV___ or HHV___) (MJ/kg Btu/lb)? _______________

What is the actual range caloric value (LHV___ or HHV___) of the waste (MJ/kg Btu/lb)? __________

What is the ash melting point/range (°C/°F)?____

Other aspects with respect to waste quality: ____

Can US waste (specifications attached) be processed in the plant?

___ Yes
___ No

If "Yes", is special pre-treatment required?

___ Yes
___ No

3a. AUXILIARY FUEL

Is auxiliary fuel/energy required?
___ Yes
___ No

If so, specify - type __________

quality __________ (Btu/cft, KWH per ton, MW_{th} per tonne)

4. PRODUCT/GAS SPECIFICATIONS

What is the raw gas composition at the reactor outlet (in volume%)?

		design	real values
-	H_2	___-___	___-___
-	CO	___-___	___-___
-	C_xH_y	___-___	___-___
-	CO_2	___-___	___-___
-	N_2	___-___	___-___
-	H_2O	___-___	___-___
-	Other	___-___	___-___

What is the specified concentration of the following components in the product gas at the mentioned locations in the process? (units?____________________ corrected to____________________)

		at the gasifier outlet		after gas cleaning	
		design	real	design	real
-	total dust	___-___	___-___	___-___	___-___
-	tar	___-___	___-___	___-___	___-___
-	HCl	___-___	___-___	___-___	___-___
-	H_2S	___-___	___-___	___-___	___-___
-	NH_3	___-___	___-___	___-___	___-___
-	K, Na, Ca salts	___-___	___-___	___-___	___-___
-	__________	___-___	___-___	___-___	___-___
-	__________	___-___	___-___	___-___	___-___

What is the specified dust particle size (μm) in the gas after the gas cleaning section? ______________
What is the specified calorific value (LHV___ or HHV___) of the product gas (MJ/$m_0$3, Btu/cft)?
What is the specified enthalpy of the product gas (MJ/m_0^3, Btu/cft)?

pressure (bar absolute) ________

temperature (°F) ________

What is the production rate? ________(Nm^3/tonne, scft/ton)

5. OPTIMIZATION[1]

Can the process be optimized with respect to the energy efficiency?

___ Yes
___ No

How much improvement in efficiency do you expect?

___ Electric efficiency ___ %

___ Thermal efficiency ___ %

Can the process be optimized with respect to the emissions?

___ Yes
___ No

Is more energy needed to achieve minimum emissions?

___ Yes
___ No

Please fill out the minimum achievable emissions under "Environmental aspects".

6. SCALE-UP[2]

Where in the process are any limitations in scale-up?

___ In the reactor sections
___ In the process train after the reactor sections

What is the expected maximum capacity of one process-line?

---

[1] With respect to the present plant configuration; concerns optimization by fine tuning etc.

[2] Concerns future plants, which might differ from the present plant.

___ tonnes of waste/hr, ton/hr of waste

___ heat input (MW_{input}, Btu/hr)

7. ENVIRONMENTAL ASPECTS

What are the emissions (in mg/m_0^3, gr/cft dry flue gas at 11% O_2, 7% O_2) of the plant (if you have more data on realized emissions, please specify)?

		specified	realized	after optimization (expected)
total dust	___-___	___-___	___-___	
HCl	___-___	___-___	___-___	
fluorides	___-___	___-___	___-___	
CO		___-___	___-___	___-___
organic compounds (as C)	___-___	___-___	___-___	
sulphur oxides (as SO_x)	___-___	___-___	___-___	
nitrogen oxides (as NO_2)	___-___	___-___	___-___	
toxic metals Sb+Pb+Cr+Cu+Mn+V+Sn+As +Co+Ni+Se+Te		___-___	___-___	___-___
Cd		___-___	___-___	___-___
Hg		___-___	___-___	___-___
dioxins & furans (PCDDs and PCDFs in ng TEQ/m_0^3)	___-___	___-___	___-___	

What residue and effluent discharge streams are produced and in which quantities (in kg/tonne, l/tonne, lb/ton, gal/ton)? Please describe.

Heavy/toxic metals (mg/kg waste):	residue	effluent
- Pb	___-___	___-___

- Cr ___-___ ___-___
- Cu ___-___ ___-___
- Zn ___-___ ___-___
- Ni ___-___ ___-___
- Cd ___-___ ___-___
- Hg ___-___ ___-___

Please supply us with as much information concerning quantity and the characteristics (toxicity, leachability, configuration, composition) and the processing potential of the by-products as possible.

Information attached? ___ Yes
___ No

8 COMPLEXITY AND RELIABILITY

How many total employees are needed for running the plant? ____

How many annual manhours are needed for running the plant? ____ manhrs/yr

How many shifts are needed for operation? ____ shifts

How many maintenance (man)hours are needed for the plant annually? ____ manhrs/yr

Are there any fundamental problems in plant operation presently?

___ Yes
___ No

Are there any problems in plant operation which can be solved in a short term?

___ Yes
___ No

Is the process sensitive to corrosion/erosion?

___ Yes
___ No

Are special measures taken/required for safety? e.g. for reducing risk of fire, explosion, etc.?

___ Yes
___ No

What? ____

9. FINANCIAL ASPECTS

How many running hours are planned for commercial operation annually? ____ hrs

What is the planned availability of the plant annually? ____ %
What is the assessed technical lifetime of the complete plant? ____ years

What is the currency in which the amounts are presented?

- Italian Lire
- German Mark
- US Dollar
- Other: ________

Please present requested costs in present values:

What are the investment costs of:

- the complete plant: ___ capacity: ___ tonnes waste/hr
- the process line: ___ capacity: ___ tonnes waste/hr

What are the specific investment costs (per tonne waste) of:

- the complete plant (two lines): ___ capacity: ___ tonnes waste/hr
- the process line: ___ capacity: ___ tonnes waste/hr

Please fill in the following table:

Main component	invest. cost	technical lifetime of component	maintenance materials	maintenance personnel

	(____)	(yr)	(___/yr)	(manhrs/yr)
Preprocessing ______________	____	____		____
Feeding system ______________		____	____	____
Ash discharge system ______________		____	____	____
Reactor ______________		____	____	____
Flue gas treatment ______________		____	____	____
Product gas treatment ______________		____	____	____
Ash treatment ______________	____	____	____	
Water treatment ______________		____	____	____
Heat exchangers ______________		____	____	____
Power generation ______________		____	____	____

What is the accuracy of the afore mentioned investment costs?

- within 10%
- within 20%
- within 30%
- other limit: ___%

What are the local operatinging costs of the total plant?

Breakdown:		per year	per tonne waste
+	depreciation of investments	____________	____________

+/-	fuel costs	______	______
+	operation	______	______
+	maintenance	______	______
+	consumables	______	______
+/-	by-products	______	______
-	electricity/heat sold	______	______
+	other	______	______
	TOTAL COSTS		

Appendix E
Conversion Factors, Conventions and Methodologies

1. Conversion Factors

From	To	Multiply by:
dscm	dscf	35.31
kcal/kg	Btu/lb	1.8
Mg/d	t/d	1.1023
MJ	Btu	948.6
MJ/kg	kcal/kg	238.9
MJ/scm	Btu/scf	26.8
MWh	MJ	3600.
meters	feet	3.281
Pascals	psia	6894.8

2. Conventions

a. Gas Characteristics

1. Unless noted otherwise, all gas heating values and pollutant concentrations are on a dry basis at 20 °C (68 °F) and 101.3 kPa (14.7 psi) at 7 percent O_2.

2. "Normal Conditions" (as in Nm^3)means 0.0°C, 101.3 kPa while "Standard Conditions" (as in sft^3) means 32.0 °F, 1.0 atmosphere.

b. System Configurations - The environmental controls installed for each technology are those selected by the developer firm as compatible with their conception of current environmental emission limits. Some firms exceed these limits as a matter of their internal policy. In some cases, the developer has not yet established a firm flowsheet for wastewater treatment. The energy efficiency for each technology is that inherent in the process. No attempt has been made to re-configure the flowsheet to optimize energy recovery beyond that proposed by the developers.

3. Conversion Methodology

a. To convert air emission concentration value X_1 reported at an oxygen concentration of Ψ_1 percent to its value X_2 at an oxygen concentration of Ψ_2 percent, use the following:

$$X_2 = X_1 \frac{(21.0 - \Psi_1)}{(21.0 - \Psi_2)}$$

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13. ABSTRACT (Maximum 200 words)
This report identifies seven developers whose gasification technologies can be used to treat the organic constituents of municipal solid waste: Energy Products of Idaho; TPS Termiska Processer AB; Proler International Corporation; Thermoselect Inc.; Batelle; Pedco Incorporated; and ThermoChem, Incorporated. Their processes recover heat directly, produce a fuel product, or produce a feedstock for chemical processes. The technologies are on the brink of commercial availaility. This report evaluates, for each technology, several kinds of issues. Technical consideratiuons were material balance, energy balance, plant thermal efficiency, and effect of feedstock contaminants. Environmental considerations were the regulatory context, and such things as composition, mass rate, and treatability of pollutants. Business issues were related to liklihood of commercialization. Finally, cost and economic issues such as capital and operating costs, and the refuse-derived fuel preparation and energy conversion costs, were considered. The final section of the report reviews and summarizes the information gathered during the study.

14. SUBJECT TERMS
municipal solid waste combustion; refuse gasification; refuse-derived fuel

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