

## **Advanced Thermal Processing Alternatives**

### **for Solid Waste Management**

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## ABSTRACT

The 1990's have seen a resurgence of interest in the development of new thermal processing alternatives for municipal solid waste (MSW). Sparked by increasingly stringent environmental regulations, much of this creative energy has been applied to technologies for the gasification of MSW: converting the solid, hard to handle material into a clean, medium- to high-Btu fuel gas. Other developers have focussed on full combustion technology but with a "twist" that lowers emissions or reduces cost.

A comprehensive study of these new technologies was recently completed under the sponsorship of the National Renewable Energy Laboratory of the U.S. Department of Energy<sup>1</sup>. The study characterized the state-of-the-art among emerging MSW thermal processing technologies that have reached the point of "incipient commercialization." More than 45 technologies now under development were screened to develop a short list of seven processes that have passed through the "idea" stage, laboratory and bench-scale testing, and have been prototyped at an MSW feed rate of at least several tons per hour. In-depth review of these seven included inspections of operating pilot or prototype units and a detailed analysis of technical, environmental and economic feasibility issues.

No attempt was made to select "the best" technology since "best" can only be defined in the context of the constraints, aspirations and circumstances of a specific, local situation. The basic flowsheet, heat and material balances and available environmental data were summarized to help the reader grasp the underlying technical concepts and their embodiment in hardware. Remaining development needs, as seen by the study team are presented. Economic analysis shows the general balance of capital and operating costs.

## INTRODUCTION

Several new or enhanced technologies that thermally process MSW are now well established. They include those that burn waste in the same physical form in which it is generated (grate-fired, mass burn incinerators) and those that first process the waste to a refuse derived fuel (RDF) and then burn the RDF (alone or with fossil fuels) using a spreader stoker grate. Mass burn and RDF combustion facilities are supplemented with elaborate back-end flue gas and residue treatment. Beyond these well-proven combustion processes, a new technology class has emerged: refuse gasification. Here, the organic fraction of MSW is heated to drive off a combustible gas with a substantial fuel value. The gas can be cleaned and burned in a gas engine or gas turbine to generate electricity. Alternatively, the gas is very usable as a boiler fuel either in thermal power plants or in industrial boilers. Emission data for combustors burning this gas generally show very low emission rates of dioxins, acid gases and other problematic pollutants. The processes studied in detail; identified with the name of the developer, are:

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

Of the seven emerging technologies discussed here, two (Energy Products of Idaho and Pedco Incorporated) use full combustion but in novel contexts. The other five processes (TPS Termiska AB, Proler International, Thermoselect Inc., Battelle, and ThermoChem Inc.) use gasification methods followed by fuel gas clean up. In niche market sectors and in the broader market, the five gasification technologies studied here are emerging as “commercially ready” alternatives.

The rate of penetration of the thermal processing market by new technologies will be paced by their environmental acceptability, their economic acceptability and their performance acceptability. From an environmental viewpoint, the seven technologies appear as a sound response to the regulatory challenges of the revised New Source Performance Standards (NSPS) and the Maximum Achievable Control Technology (MACT) rules<sup>2</sup>. Table 1 summarizes the process features and environmental characteristics of the seven processes.

Economics has always been a critical and probably pacing factor that affects the penetration of thermal processing technology in U.S. MSW practice. Table 2 summarizes preliminary economic data characterizing the seven processes. One must use caution in using these estimates since most of the processes are still evolving. Most of the processes have capital costs that are comparable to the \$121,000 per Mg/d (\$110,000 per t/d) typical of contemporary mass burn systems. The net operating cost, which is equivalent to the break-even tipping fee, for the gasification technologies are comparable to those for *owner-operated* mass burn facilities. The revenue stream from selling energy continues to be critical to overall economic acceptability.

The results are less clear concerning “performance.” Most of the processes studied (excepting Thermoselect) require an RDF feed. Landfills are still required for RDF residues and/or ash. Historically, most RDF facilities have incurred substantial post-construction rework, capital investment, down-rating of capacity etc. Most of the seven systems have significant development tasks ahead of them. Unfortunately, the catalyst of vigorous U.S. market activity is lacking to push this development and to foster risk-taking. Further, many systems are quite complex. This presents some problems in gaining acceptance by client communities, by regulatory authorities and from the financial and engineering entities involved in concept selection and project accomplishment.

## APPROACH TO THE ANALYSIS

Initially, more than 45 firms were identified as possible candidates. A two-stage screening process selected seven firms to be evaluated in detail. Data received from the 45 were analyzed to produce the recommendation for the list of seven firms as limited by available study funds. The scope of the detailed evaluation effort for the seven selected technologies was broad. Data for the detailed evaluation were obtained from the developers based on a faxed request, a detailed questionnaire, and extensive technical discussions before and after site inspection visits.

The evaluation included exploration of *technical issues* affecting the basic process feasibility, reliability, workers' safety, operability, and maintainability. Very important was the remaining degree of scale-up from the present level of development to commercially useful equipment. Also, operating experience was seen as critical.

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

*Business issues* revolved about the financial and work force resources of the firms to achieve commercial viability. The capital and operating costs of the system are important factors in the award of disposal contracts. To keep the focus on the thermal processing core of the processes, standardized costs were developed for the processing of MSW to an RDF. Also, cost curves were developed for conversion of the energy product of the processes (high pressure steam or a fuel gas) into electricity. The resulting technology cost information is then an economic picture of a generic plant that may not be optimal with standardized feedstock and energy conversion components. A serious buyer should contact the developer organizations to give them the opportunity to propose their costs for any specific situation.

## **TECHNOLOGY SUMMARIES**

### **1. Energy Products of Idaho (EPI)**

EPI is a limited partnership headquartered in Coeur d'Alene, Idaho. EPI's basic business is the design and fabrication of fluid bed combustion systems. Their corporate experience favors full combustion mode for their systems, they have pilot plant and commercial plant experience (three commercial systems) in a "starved air," gasification mode. Their most proven product, however, is the full combustion system. The EPI incineration system uses a bubbling-type fluid bed concept accepting a prepared 10 cm (4 in.) top size RDF (Figure 1). Within the bed, RDF particles are exposed to a vigorously turbulent, hot, oxidizing environment that promotes rapid drying, gasification, and char burnout. EPI proprietary design features in the bed provide continuous removal of oversized non-burnable materials. Hot gases from the bed are passed through a boiler to generate high pressure, superheated steam used to generate electricity or for process applications. A conventional dry scrubber-baghouse with carbon injection can achieve current air emission standards<sup>2</sup>.

EPI combustion technology is commercially available now. EPI has installed five furnaces in the U.S. with capacities of more than 55 Mg/d (60 t/d) burning an RDF fuel. They also designed and built three wood-fired, gasification-mode systems (1982-1985). They have acquired in-house operating experience with an RDF in their pilot plant gasifier, but by early 1997, they had no operating commercial-scale plants using RDF in the gasification mode.

Therefore, in matters of technical maturity and commercial verification, the full combustion mode EPI system is implementable with limited risk. The gasification mode requires additional testing, operating experience and design maturation and, thus, presents potential users with much greater risk.

### **2. TPS Termiska, AB**

TPS Termiska Processer (Thermal Processes), or TPS, is a small, independent Swedish company of about 50 employees working in the specialized field of energy and environmental process research and technology development. Their technology involves starved-air gasification of an RDF in a combined

bubbling and circulating type fluid bed (Figure 2). The lower, bubbling bed section provides the extended residence time for the burnout of massive or very wet feedstocks. As the particles shrink, they enter the circulating bed zone where gasification is completed and the ash is swept from the furnace. Following the gasification bed, TPS inserts a second circulating bed “cracker” unit. In the second bed, a ground magnesium-calcium carbonate (dolomite) is injected to catalyze the conversion of high molecular weight tarry gasification byproducts into low molecular weight, non-condensable compounds. Also, the alkalinity of the dolomite reduces acid gas concentrations. The TPS system produces medium heat content fuel gas.

The technology offered by TPS is presently close to commercial availability. In 1992, a commercial, two-bed unit was installed in Gréve-en-Chianti, Italy with a combined capability of 30 MW to gasify 100 percent pelletized RDF fuel or coarsely shredded wood or agricultural residues.

The manufacturing methods for the TPS-design gasifier systems, the long-term operability of their beds with acceptable management of bed solids, the projected emission control performance, the feeders, etc., have all been tested at Gréve in MSW-based RDF service. Therefore, it is believed that the TPS system should be implementable with only moderate technological risk.

### **3. Proler International Corporation**

The Proler SynGas Process is a patented technology to reform hydrocarbon-containing wastes into a gaseous product. It is represented by a 1.8 Mg/h ( 2 t/h) demonstration plant in Houston, Texas. The process was originally developed to gasify automobile shredder waste (ASR) but limited test results show its suitability to process MSW. Proler feeds preshredded material into a rotating, kiln-like reactor (Figure 3). In the proposed commercial process, the reactor is fired with the hot exhaust gases from a “Vitrifier” auxiliary unit that uses part of the product gas, carbon char and oxygen to melt the mineral residue. The overall process produces a medium heat content fuel gas that, after cleanup, is suitable for power generation or other fuel uses. The residue is discharged as what is stated to be a “commercially useful byproduct”.

Proler states that preliminary design work has been completed for a full-scale 865 Mg/d (960 t/d) commercial facility using MSW as feed stock and consisting of two process lines at 18 Mg/h (20 t/h) each. However, some technical issues require resolution before successful commercialization for MSW can be assured:

- The demonstration plant is now processing an RDF at a top size of 5.8 cm (2 in.). Proler expects the commercial plant to accept shredded material with a top size of 15.24 cm (6 in.) as a process change to achieve cost reduction in waste processing. This substitution may have adverse process impacts and has not yet been sufficiently tested to accept the change as acceptable.
- The demonstration plant has operated only on a limited basis with shredded MSW. An extended campaign of operation is essential to evaluate potential problems.
- The reliability and performance of the Vitrifier and the integration of this equipment with the existing gasifier have not yet been accomplished.

- The planned commercial size at (40 t/h) of MSW represents a scale-up of 5.5:1 on a per line basis over the demonstration plant. Experience with other MSW combustion and thermal process development shows that such a substantial step implies a high risk factor.

Further testing with MSW to resolve these issues seems desirable. Proler has an intent to continue their development efforts and to offer a comprehensive performance guarantee.

#### **4. Thermoselect Inc.**

The Thermoselect system processes co-mingled MSW into what are stated to be environmentally-safe products (Figure 4) that include reactor gas, vitrified solid granulates, elemental sulfur and sodium salts. No liquid effluents are discharged into the environment. The process is intended to reduce formation and emission of particulates and other pollutants.

Gasification is achieved at a high temperature. The mixture of solid refuse and char reaches a temperature of 800°C (1470°F) as it reaches the discharge end of a preprocessing section described by Thermoselect as the Degasification Channel. The products of gasification are then held in a reactor at a temperature of 1200°C (2192°F) for more than four seconds. Ash and metals fall out and are fused and granulated in a chamber called the “Homogenizer”. The reactor gas is quenched in a spray chamber to below 90°C (194°F). Data suggest that this combination of time and temperature destroys the complex organic compounds produced in the gasification process and yields a gaseous product (primarily CO, H<sub>2</sub>, CO<sub>2</sub> and steam) that has nearly reached chemical equilibrium. The raw gas is cleaned in a gas purification system that removes acid gases, hydrogen sulfide, particulate and volatile heavy metals. Air emissions result from the combustion of the cleaned reactor gas in turbines, gas engines, boilers and other means for the generation of electric power or other useful energy forms.

The Thermoselect demonstration facility in Fondotoce, Italy consists of one process line with a nominal capacity of 4 Mg/h (4.4 t/h) or 100 Mg/d (106 t/d). The line at the pilot plant includes all of the process units (acid and alkaline scrubbers, a hydrogen sulfide removal scrubber, coke filters, etc.) that are envisioned for the full scale, commercial plant. Tests results show only minute traces of organic compounds in the cleaned reactor gas. No chlorinated aromatic hydrocarbons other than traces of polychlorinated dibenzo p-dioxin (PCDD) and polychlorinated dibenzo furan (PCDF) were detected.

This system should comply with U.S. environmental regulations. The demonstration plant is stated to have gone through 15,000 hours of operation and operates continuously for five days a week processing unshredded municipal and industrial wastes. The plant uses the product gas to drive an engine generator.

Major unresolved areas are:

- Optimization of energy use.
- Use of Thermoselect’s reactor gas in gas turbines is untested as of early 1996, but is not expected to be a problem.



- Waste heat recovery to improve overall plant thermal efficiency to include finding uses for low grade heat.
- Continuity and reliability of operation needs to be confirmed. The demonstration plant has only been operated on a five day per week cycle. Continuous, seven-day per week, around the clock operation is yet to be shown.
- Scale-up. The current demonstration plant is reported to have a “nominal capacity of 4 Mg/h (4.4 t/h)” but, experience to date shows that the unit appears to operate at an actual throughput of only 3.8 Mg/h (4.2 t/h). The “Standard Design” two-line capacity is 10 Mg/h (11 t/h) or 240 Mg/d (264 t/d). Therefore, the scale-up factor based on actual operational experience is about 2.7:1. The success of the planned commercial size facility is yet to be proven.

## 5. Battelle

The Battelle High Throughput Gasification System (BHTGS) uses indirect heating in a twin circulating fluidized bed (CFB) gasifier and combustor (Figure 5). RDF is gasified in a CFB using steam as the fluidizing medium to generate a medium heating value gas 18.6 to 22.4 MJ/Nm<sup>3</sup> (500 to 600 Btu/sft<sup>3</sup>) without oxygen. Residual char is consumed in an associated CFB combustor. A circulating sand phase exchanges heat between the separate reactors.

Battelle’s process development began in 1977. Detailed process development activities were begun in 1980 with the construction of Battelle’s process research units (PRUs). Experimental data have been generated in gasifiers of 15 cm (6 in.) diameter and 25 cm (10 in.) diameter with a throughput of 0.22 and 9.1 Mg/d (0.24 and 10 t/d) dry RDF, respectively. Data from these showed that extremely high throughput, more than 19.5 Mg/h-m<sup>2</sup> (4,000 lb/hr-ft<sup>2</sup>) could be achieved.

Tests showed the technical feasibility of the gasification process and provided the basis for detailed process conceptual design and economic projections to be generated. Testing was conducted in 1989 in a 25 cm (10 in.) internal diameter gasifier with a height of 6.9 m (22.7 ft) and a 1.0 m (40-in.) internal diameter combustor with a height of 3.5 m (11.5 ft). The throughput was 0.65 Mg/d (0.72 t/d). 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 recharges from wood for about 60 hours as an integrated gasifier-turbine system.

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

The BHTG process is said to produce gaseous emissions from the reactor complying with the EPA’s MACT standards and NSPS for municipal waste combustors (MWC)<sup>1</sup>. Wastewater from the process contains only trace quantities of organic materials. The outlet of a simple industrial treatment system at Battelle’s test site showed wastewater to be within the EPA’s drinking water standards.

Major unresolved development and demonstration needs include:

- Important process development issues relate to fuel preparation and reactor gas cleanup.

- The specific level of fuel preparation necessary for the process has yet to be determined. Data suggest that fine shredding of the feedstock will not be required. Feed size range will be dictated by the feed system requirements and the rate of gasification processes.
- Product gas cleanup developments include tar cracking and particulate removal.
- Much more operating time with refuse at PRU scale is necessary to confirm the preliminary results obtained during the 1989 study at Battelle.
- The overall design concept needs to be expanded from a development focused on gasifier technology to a full plant with all auxiliaries and subsystems.

## 6. Pedco Incorporated

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

The Pedco Rotary Cascading Bed Combustor (RCBC) is, in essence, a robust solid fuel burner and heat recovery system. It is not a gasifier. Beyond conventional solid fuels (such as coal or wood chips) it can burn prepared MSW. Pedco's basic business is involved with the design of industrial combustion systems for steam generation based on the RCBC concept.

The RCBC burner consists of a rotating, horizontal, cylindrical combustion chamber (Figure 6). A bundle of boiler tubes projects into one end of the chamber. The rotational speed of the chamber is high enough such that a substantial fraction of the bed material is continually airborne. This produces an environment similar to that of a fluid bed but, here, a mechanically fluidized bed. The hot falling solids cascade across the whole diameter so that the boiler tubes are submerged in hot fuel and bed material. The hot solids recycle preheats the combustion air and dries and ignites the incoming fuel.

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

Pedco prefers to provide their RCBC system as a factory assembled RCBC burner with a waste heat boiler configuration that is of a size where shipping by truck or rail is feasible. The design heat release rate of the Pedco basic RCBC system is approximately 233,000 MJ/h ( $100 \times 10^6$  Btu/h) corresponding to daily RDF rates of 168 Mg/d (185 t/d). Air pollution trains (besides 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 its in-bed limestone addition and consequent acid gas absorption eliminates the necessity for the spray dryer absorber used in many mass burn plants. Additional data are needed to confirm this position.

Pedco has yet to develop and adopt a front-end waste system to produce a sized RDF feed for the RCBC system. Pedco has only limited experience with an RDF and has not yet established a firm basis on



which to specify their optimum top size. Development of a generalized RDF flow sheet should not be problematic. One notes, however, that most RDF facilities have required extensive redesign and reconstruction effort to bring the RDF processing elements to an acceptable level of reliability and performance.

Major unresolved development and demonstration needs include:

- Pedco must select or develop a full system concept and associated detailed specifications starting with RDF receipt and processing and including electrical generation and residue handling.
- Continuity and reliability of operation of an RCBC system must be confirmed in RDF service. Problems associated with fouling and/or plugging of the ash handling chutes with wire and oversized non-combustible materials; fouling problems with boiler tubes; air emissions; and tube abrasion and corrosion problems must be assessed in continuous RDF service.
- Experience to date with the cluster of boiler tubes inserted into the RCBC device has been limited to low pressure, saturated steam. To maximize power production, higher pressures and superheated conditions are preferred. Higher skin temperatures on the tubes may affect erosion and corrosion sensitivity and should be evaluated before commitment to a full scale facility.

## **7. ThermoChem Incorporated**

The Manufacturing and Technology Conversion International, Inc. (MCTI) Steam Reforming Process is an indirectly heated fluidized bed reactor using steam as the fluidizing medium (Figure 7). Under license from MCTI, ThermoChem, Inc. (TC) have the exclusive rights to apply its Pulse-Enhanced™ heater and steam-reforming technology to a variety of applications.

Pulse Enhanced™ indirect heating technology combined with fluid-bed and steam-reforming provides a process for converting the organic material in an RDF to fuel gas while separating the inorganic without oxidation or melting. The key to the process is the array of Pulsed Enhanced™ heater tubes immersed in the fluidized bed. Gaseous fuel is burned in the tubes such as to create an oscillating pressure. The effect of the pulsing flow is to significantly enhance heat transfer between the combustion products and the tube wall. This greatly increases the efficiency of energy exchange between the fuel and the bed material. The organic waste fed to the fluid-bed steam reformer reacts with steam to produce a medium heat content fuel gas.

MCTI's development efforts began in 1984. Experimental data have been generated in different scale reactors from 9.1 to 2,722 kg/h (20 to 6,000 lb/h) using various biomass and waste feedstocks. A 13.6 Mg/d (15 t/d) demonstration unit was operated on rejects from a cardboard recycle paper mill in Ontario, California in 1991-1992. Later, this unit, moved to TC's test facility in Baltimore, processed coal, woodchips and straw.

Based on 6.8 kg/h (15 lb/h) pilot plant tests, the TC Process appears to comply with the EPA NSPS for MWC's. Tests suggest the residue meets EPA TCLP leachability criteria set for landfill disposal as a nonhazardous waste. Wastewater contains only trace amounts of organic materials.

Major unresolved development and demonstration needs include:

- TC must select or develop a full system concept and associated detailed specifications starting with RDF receipt and processing and including electrical generation and residue handling.
- Continuity and reliability of operation of a TC system must be confirmed in RDF service. Of particular concern are problems with tube corrosion, erosion, and plugging.
- Problems with the cyclone capturing particulate in the bed off-gas must be evaluated in RDF service. The cyclones are subject to pluggage as they are in conventional atmospheric fluid beds.
- Solids removal from the bed must be evaluated and robust, reliable solids handling systems must be developed and tested.
- Considerable demonstration work is needed to address remaining uncertainties regarding air emissions, residue quality, plugging of the spaces between the tubes with wire, metals, rocks, etc. These uncertainties translate into persistent risks that should be carefully considered before use.

## CONCLUSIONS

Intense developmental activity applicable to the thermal processing of MSW is underway in the U.S. and Europe. One can identify more than 45 distinct efforts at some stage of process development now. Most of the processes are based on MSW gasification (as opposed to full combustion). In part, the focus on gasification reflects the current stringent regulatory situation in both the U.S. and Europe regarding the control of air emissions. Thus, processes that allow clean-up of the reactor gases before its combustion offer potential economy since the volume flow treated is small. The cleaned fuel gases can then either be burned in gas engines or gas turbines to generate electricity or sold as a fuel in conventional boilers.

Although many of the 45 processes are still at the bench or laboratory scale, several have progressed to a pilot or semi-works level where the difficult problems of reliability, flexibility etc. appear. The seven processes selected for study are all very near to commercialization. One technology has been carried out in four, full-scale commercial facilities and another in a two-furnace commercial plant. That means that most processes still present some risk to a prospective owner. This risk could show itself as higher capital or operating costs, lower reliability or lower energy recovery efficiency than have been forecast at this time. The development record for new MSW processing technologies suggests that such problems are probable for some processes as they move into full scale commercialization.

Based on data from pilot facilities, each of these processes can probably achieve full compliance with the U.S. EPA Maximum Achievable Control Technology (MACT) standards and the New Source Performance Standards (NSPS) for Municipal Waste Combustors promulgated in final form in December 1995<sup>2</sup>. Only one process matches a technology group as used by the EPA in their standard setting. Many are gasifiers and not the full combustion systems referenced in the EPA standards. Therefore, knowing how the federal standards will be applied is uncertain. As with most permitting issues, the ultimate resolution of these questions must wait until actual permits have been submitted and final regulatory action is required.

The residues from the processes do not present problems in the Toxicity Characteristics Leaching Procedure (TCLP) leaching tests. The quantity of data in this area, however, is limited and experience in mass burn plants suggests that significant variation in TCLP results can be expected. Two of the processes (Thermoselect and Proler) include process steps where the residues are melted (vitrified). For these processes, the TCLP results are exceptionally low since the metals are bound in a glass structure and cannot be readily solubilized. Both firms believe that the vitrified residue granules may be marketable and, therefore, that their process will have a lower operating cost than is shown in Tables 2a,b. As yet, however, the value of the granules, if any, has not been established in the U.S. marketplace.

The overall conclusion that can be drawn is that competitive alternatives to conventional mass burn or refuse derived fuel (RDF) combustors exist. The alternatives may not offer exceptional economic advantages. Most of the processes studied present a much lower air emission profile than do conventional plants. This may merit investigation by communities or regional jurisdictions considering volume reduction technology where air emissions are of particular concern. One should note, however, that conventional mass burn technology can also meet the recently promulgated MACT and NSPS<sup>2</sup> emission requirements. The economic data in Table 2 is intended to provide perspective; not to be directly applicable to a specific situation. *To obtain fair, applicable economic data, cost issues should be addressed directly with the firms* (see Appendix A).

The preceding technical descriptions, many of the economic estimates and the prospective environmental performance would suggest that these new technologies define the future of WTE facilities. However, with the exception of EPI and, to a degree TPS, all of the processes have important development and/or demonstration steps between the present status and proven commercial availability. All except Thermoselect require processing of MSW to an RDF, possible but always problematical. Experience with Purox, Landgard, Torrax and many other processing technology developments in years past has shown that commercial and technical success does not come easily if at all. The unrelenting crucible of 24 hours a day, seven days a week operation in combination with the malevolent nature of refuse clearly presents a profound challenge to the process developer.

Also, most of the process developers suggest optimistic overall energy recovery levels. However, almost all lose energy in the RDF-making step. Some use a water quench to cool the synthesis gas, thus losing 400 to 600 Btu/lb MSW in sensible heat. Others achieve superior environmental characteristics at the price of greatly increased process complexity and higher capital and operating costs. Several firms are small and will suffer with the extended facility development schedules and under the draconian financing requirements of most U.S. system procurements.

Still, the adventure and excitement of technical innovation and the promise of successful commercial development spurs these firms forward. The professionalism, the high technical standards, and the business commitment in most of the seven development firms were impressive. Further, despite a weak U.S. market, most firms are aggressively seeking clients for that vital "first plant." I wish them well.

## ACKNOWLEDGEMENTS

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## CONCLUSIONS

## REFERENCES

1. Niessen, W., Marks, C., and Sommerlad, R., "Evaluation of Gasification and Novel Thermal Processes for the Treatment of Municipal Solid Waste," Contract YAR-5-15116-01 report to the National Renewable Energy Laboratory, July 1996.

2. Federal Register, December 19, 1995 - 40 CFR Part 60.

## Appendix A

### Offices of Development Firms

#### 1. Energy Products of Idaho (EPI) Ltd. Partnership

4006 Industrial Avenue  
Coeur d'Alene ID 83814  
Tel: (208) 765-1611  
Fax: (208) 765-0503

#### 2. TPS Termiska Processer AB

Studsvik, S-611 82  
Nyköping, Sweden  
Tel: 011-46-155-22-13-00  
Fax: 011-46-155-26-30-52

#### 3. Proler International

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

#### 4. Thermostelect Inc.

201 West Big Beaver Road ,Suite 230  
Troy, Michigan 48084  
Tel: (810) 689-3060  
Fax: (810) 689-2878

#### 5. Battelle

505 King Avenue  
Columbus, Ohio 43201  
Tel: (614) 424-4958  
Fax: (614) 424-3321

#### 6. Pedco Incorporated

214 East 9th Street  
Cincinnati, Ohio 45202  
Tel: (513) 361-8643  
Fax: (513) 351-8646

#### 7. ThermoChem, Inc.

10220-H Old Columbia Road  
Columbia, Maryland 21046  
Tel: (410) 312-6300  
Fax: (410) 312-6303



**Table 1 Environmental Comparison of Developing Technologies**

Process Name	Thermal Treatment Technology	Air Pollution Control	Water Pollution Control	Residue Treatment or Disposal
EPI, Inc.	Bubbling Fluid Bed Combustor	Lime Spray Dryer Absorber, Fabric Filter, Selective Noncatalytic Reduction, Activated Carbon Injection	None: Dry System.	Landfill
TPS Termiska AB	Circulating Fluid Bed Gasifier with Dolomite Cracker	Scrubbing of Fuel Gas to Remove Particulate Matter, Condensable Organics, and Acid Gasses, NO <sub>x</sub> <sup>1</sup>	Cleanup of Scrubber Liquor. Not specified. <sup>2</sup>	Landfill
Proler International	Rotary Reactor Gasifier and Cyclonic Ash Vitrifier	Fabric Filter, Wet Scrubber, NO <sub>x</sub> <sup>1</sup>	Cleanup of Scrubber Liquor. Not specified. <sup>2</sup>	Proposed Sale as Vitrified Aggregate; Otherwise landfill.
Thermoselect, Inc.	Raw Waste Gasifier	Acidic and Alkaline Scrubber, H <sub>2</sub> S Removal, Activated Coke, NO <sub>x</sub> <sup>1</sup>	pH Adjustment, Metal Precipitation, Filtration, Distillation.	Proposed Sale as Vitrified Aggregate; Otherwise Landfill.
Battelle	Circulating Fluid Bed Gasifier and Combustor	Wet Scrubber, NO <sub>x</sub> <sup>1</sup>	Cleanup of Scrubber Liquor. Not Specified. <sup>2</sup>	Landfill
Pedco Incorporated	Rotary Cascading Bed Combustor	Lime Spray Dryer/Absorber, Fabric Filter, Selective Noncatalytic Reduction, Activated Carbon Injection.	None. Dry System.	Landfill
ThermoChem	Pulse-Heated Circulating Fluid Bed Gasifier		Cleanup of Scrubber Liquor. Not specified. <sup>2</sup>	Landfill

Notes:

1. NO<sub>x</sub> control may be required for the gas engine or turbine combustor.
2. Details of treatment were no specified by the developer.

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**Table 2 Summary of Statistics for Developing Technologies (per ton quantities relate to raw MSW)**

Process	Product Energy Form	Plant Size Evaluated (Mg/d <sub>raw</sub> )	No. Burnaces	Capital Cost (\$000)	Process Capital (\$000)	Proprietary Capital (%)	Capital Cost (\$/Mg/d)	Energy Product (MJ/Mg) <sub>raw</sub>
EPI Inc.	Steam	780	2	79,415	28,015	35.3	101,800	12,918 <sub>net</sub>
TPS Termiska Processor AB	Gas	1600	2	170,675	58,875	33.3	106,700	7,602 <sub>net</sub>
Proler International Corp.	Gas	1247	2	153,625	57,625	37.5	123,200	11,385 <sub>net</sub>
Thermoselect Inc.	Gas	1440	6	236,790	192,790	81.4	164,400	7,404 <sub>net</sub>
Battelle	Gas	849	2	80,532	12,532	15.6	94,900	11,548 <sub>net</sub>
Pedco Incorporated	Steam	800	2	87,067	28,167	32.4	108,800	10,387 <sub>net</sub>
ThermoChem Inc.	Gas	849	1	91,733	20,983	22.9	108,800	7,857 <sub>net</sub>
Generic Mass Burn	Steam	1365	3	150,000	30,000	20.0	109,900	6,860 <sub>net</sub>

Process	Gross Operating Cost (\$/Mg)*	Prime Mover#	Gross Power (kWh/Mg)	Net Power (kWh/Mg)	Net Operating Cost (\$/Mg)†	Gross Heat Rate (MJ/kWh)§	Net Heat Rate (MJ/kWh)§
EPI Inc.	85.21	ST	1088	895	52.71	9.69	11.78
TPS Termiska Processor AB	71.84	GT/ST	1230	1024	38.91	8.57	10.29
Proler International Corp.	99.15	GT	1281	1091	59.47	8.23	9.67
Thermoselect Inc.	123.24	GT	1083	778	94.92	9.74	13.55
Battelle	79.37	GT	1001	871	47.63	10.53	12.11
Pedco Incorporated	78.87	ST	886	868	52.29	11.89	12.15
ThermoChem Inc.	81.17	GT	1149	1004	44.56	9.17	10.50
Generic Mass Burn	85.88	ST	633	578	63.11	18.35	20.10

\*Gross operating cost/ton raw refuse—total of capital charges, insurance, labor, maintenance, and supplies before energy credits.

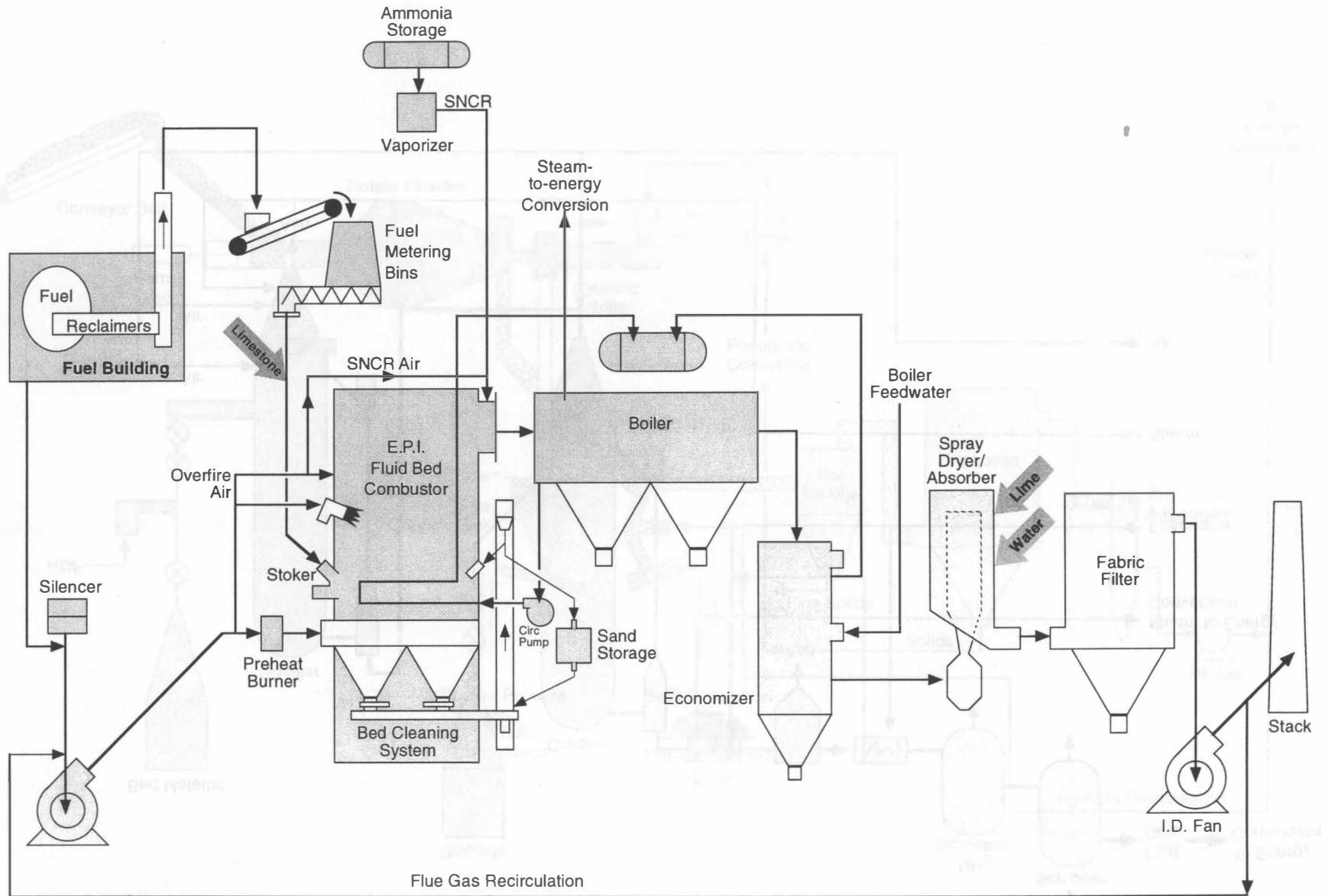
†Net operating cost/ton raw refuse—gross operating cost less energy credit.

§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.

# Prime Mover—ST=Steam Turbine,GT=Gas Turbine, Gt/St=Gas Turbine with heat recovery and additional generation using a steam turbine

Conversion factors: MG times 1.1 yields tons; kwh/MG times 0.826 yields kwh/ton; MJ times 1147.9 yields Btu.

Figure 1. Energy Products of Idaho Process Flowsheet



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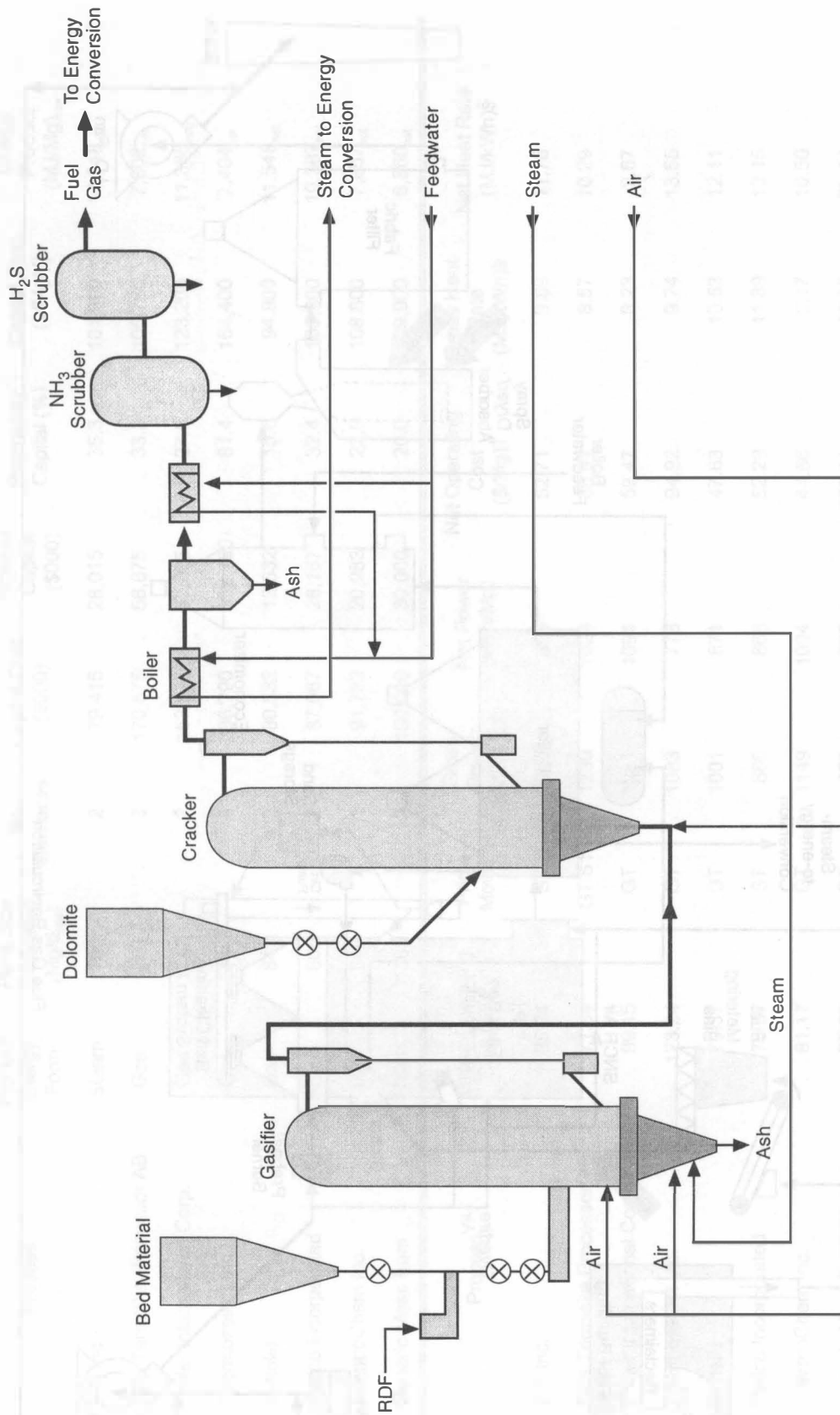


Figure 2. TPS Termiska Processor AB – Process Flowsheet

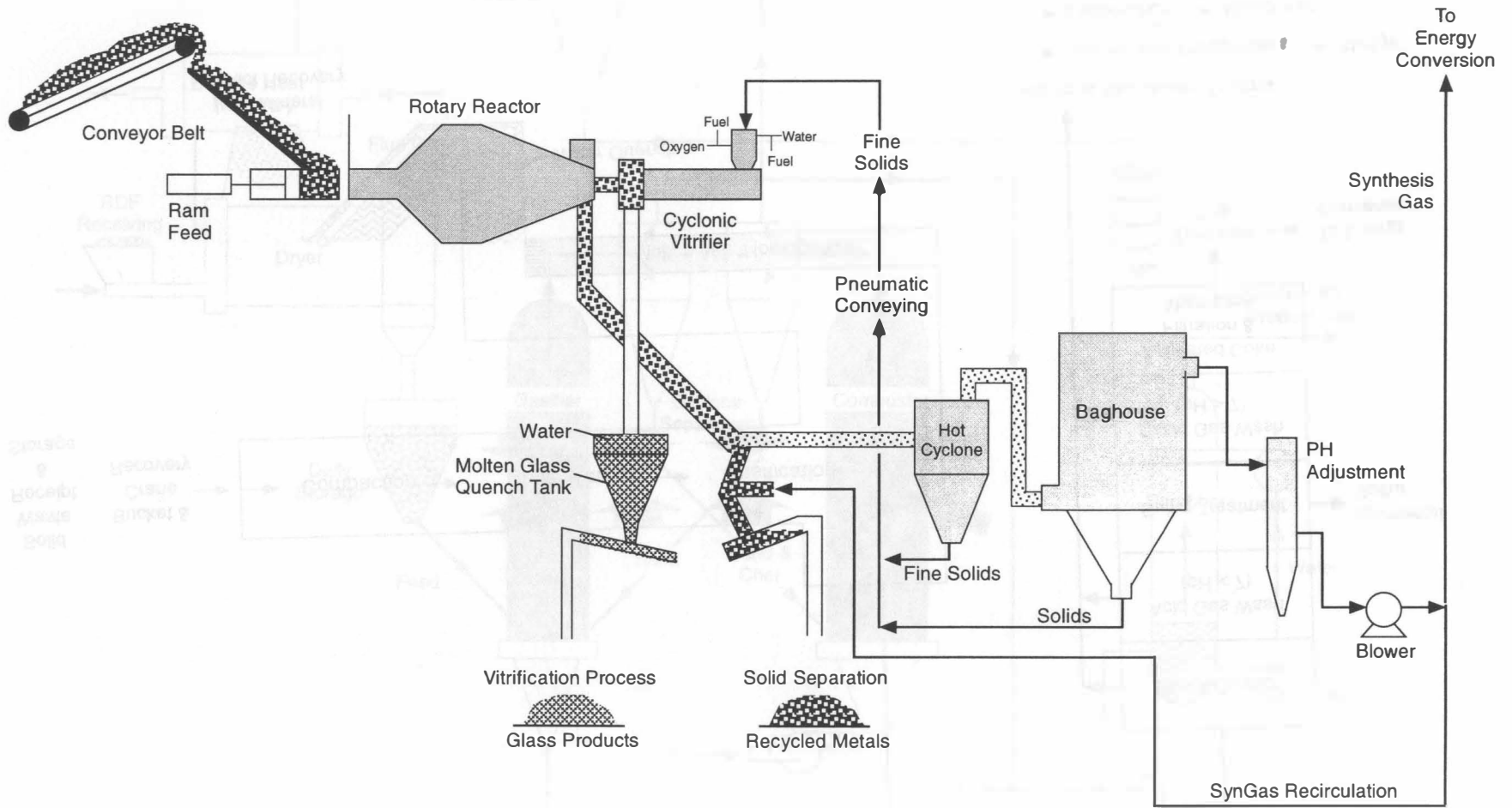
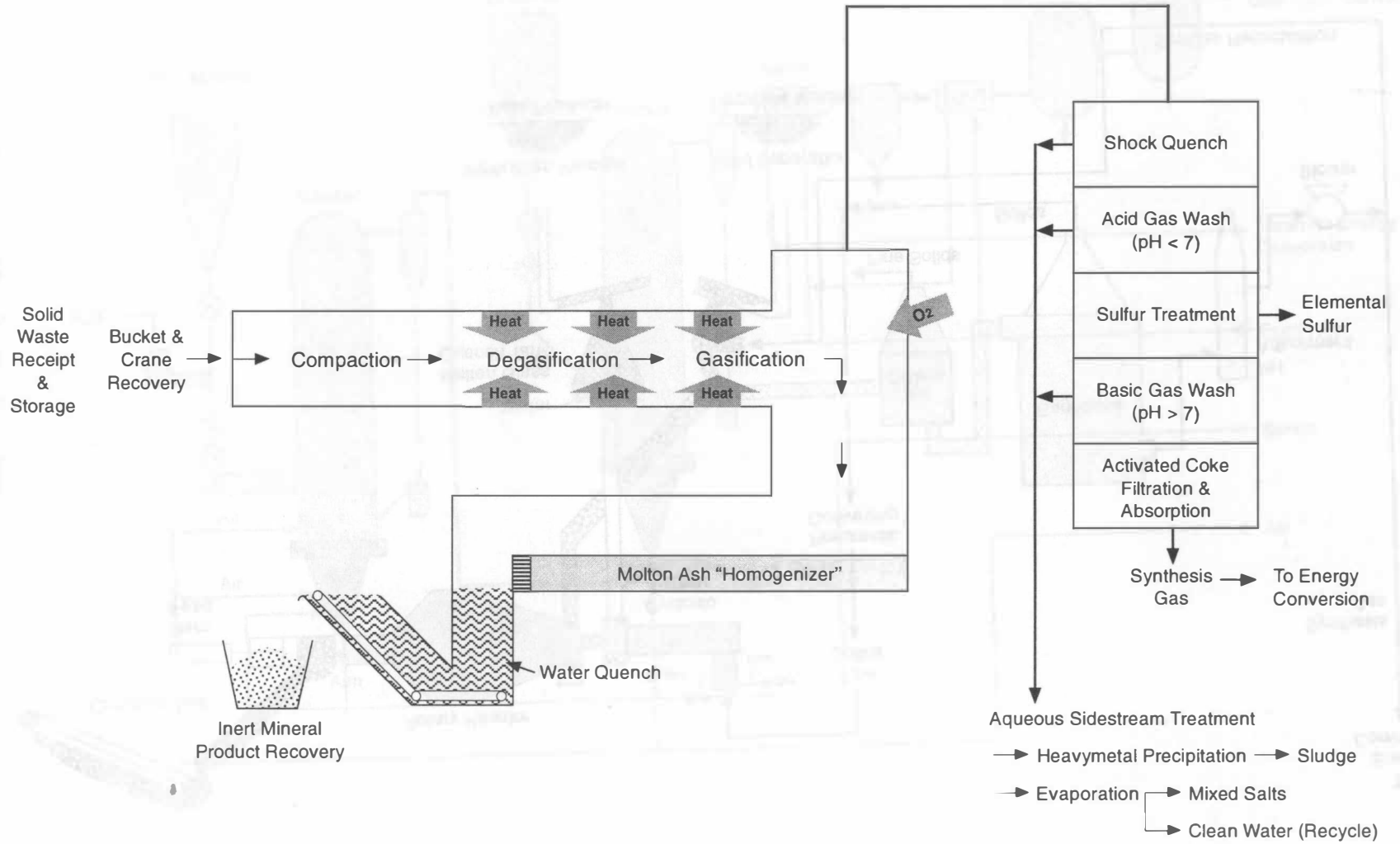


Figure 4. Thermoselect Process Flowsheet





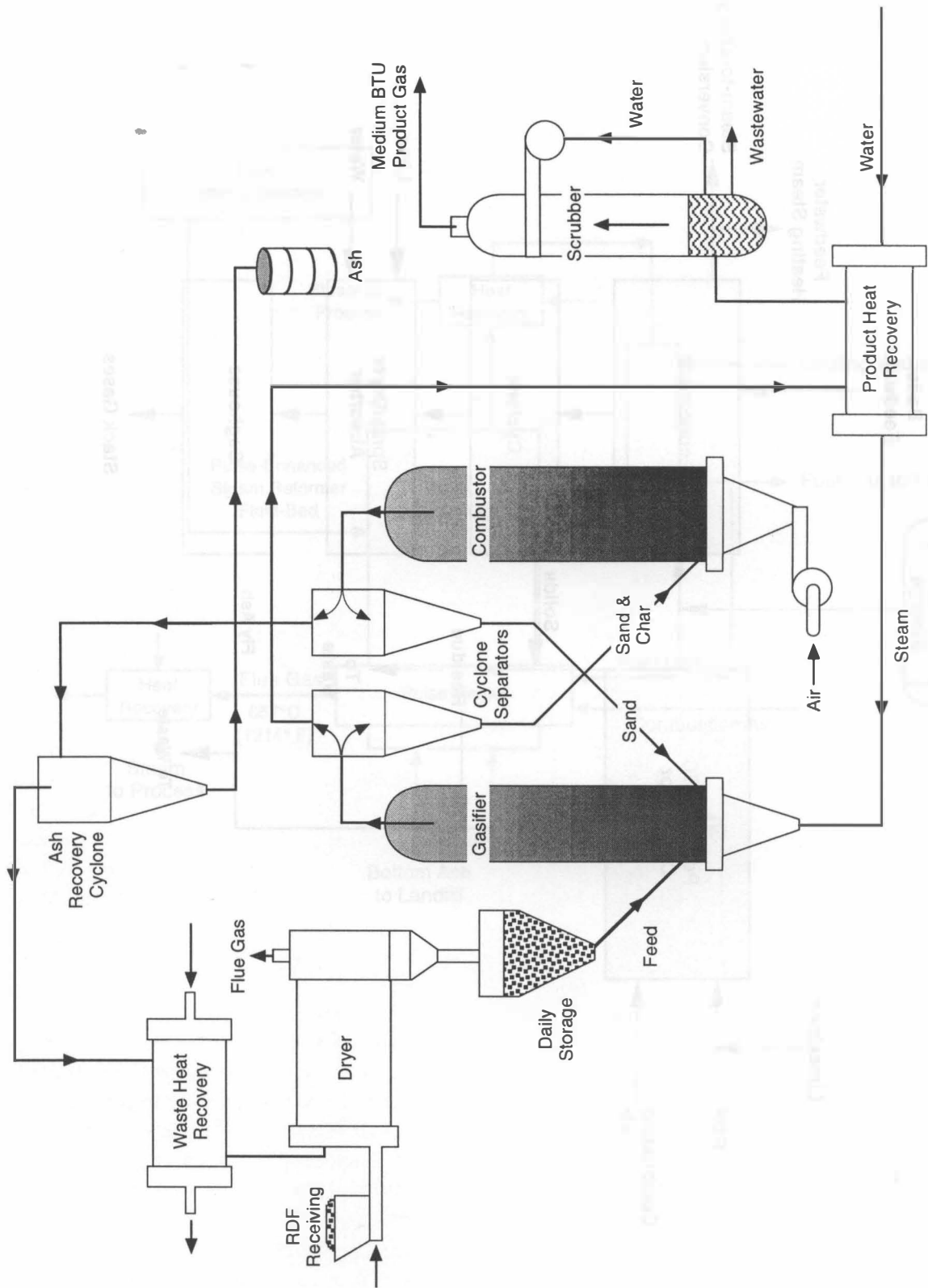


Figure 5. BHTGS Process Flowsheet

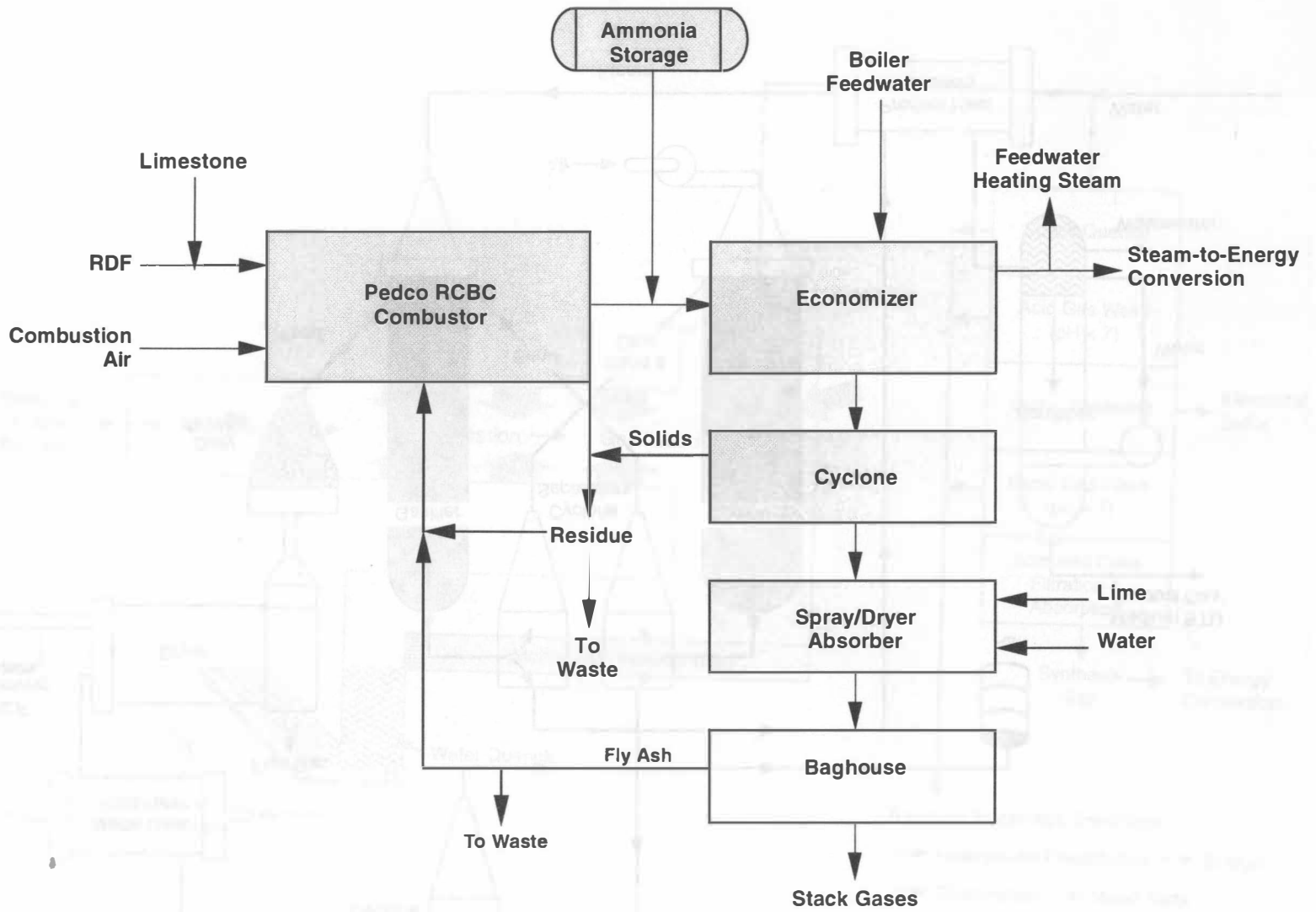


Figure 6. Pedco Process Flowsheet

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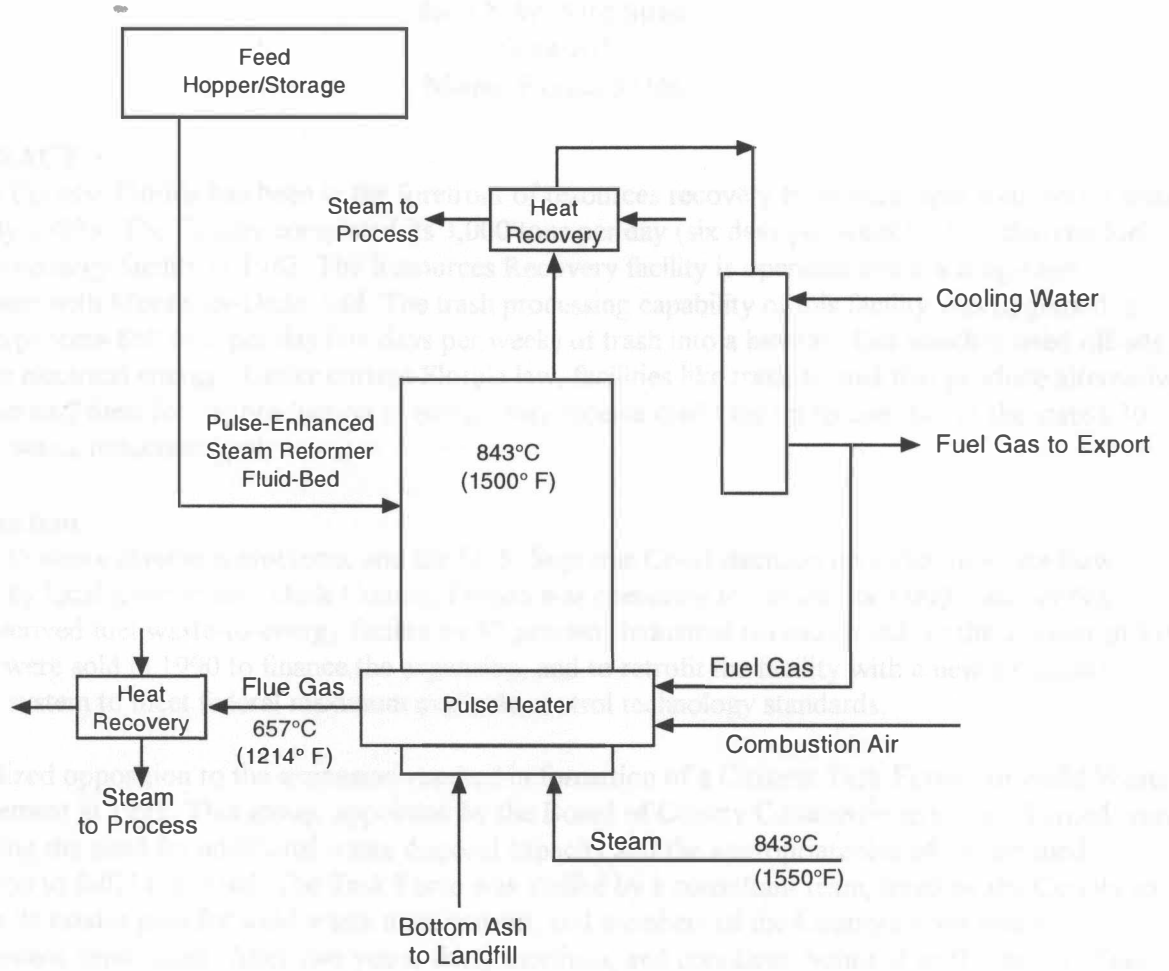


Figure 7. Thermochem's Process Flowsheet