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ENERGY RECOVERY FROM ARMY AMMUNITION PLANT SOLID WASTE BY PYROLYSIS

J. D. PINKERTON
R. F. TOBIAS
TRW DEFENSE AND SPACE SYSTEMS
REDONDO BEACH, CALIFORNIA

ROBERT SCOLA
ARRADCOM, PROJECT ENGINEER

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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WEAPON SYSTEMS LABORATORY
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Army Ammunition Plants (AAP's) dispose of large quantities of solid waste by incineration, open-air burning, and landfill. There is at present no attempt at energy recovery. The present study was conducted to determine the feasibility of adapting pyrolysis technology for energy recovery from these solid wastes.

20. ABSTRACT (continued)

Eight AAP's were surveyed to identify the types and amounts of solid waste generated. Candidate systems were evaluated to determine their suitability for this application. Safety considerations indicate that propellants, explosives and pyrotechnics (PEP) and PEP-contaminated waste with proper precautions could be handled safely by pyrolysis processes, but further work is needed to determine applicable size reduction techniques. It was determined that a 45.4 Mg/d (50 TPD) plant would be sufficient to handle the largest quantity of waste generated at any AAP. Capital cost were estimated at $4.1 million and annual cost at $623,100. Based on these costs it was concluded that pyrolysis is not economically feasible at this time even under mobilization conditions.

SUMMARY

This report presents the results of a study to determine the feasibility of adapting pyrolysis technology for energy recovery from solid waste generated at Army Ammunition Plants (AAP's). Restrictions on open burning of munition wastes and a desire to recover the energy in the waste in a useable form motivated this study.

Eight AAP's were surveyed to identify the types and amounts of solid wastes generated under current and mobilization production levels. Next, a survey and evaluation of candidate systems was conducted to determine those suitable for this application. Concurrently the safety aspects of the pyrolysis of propellants, explosives, and pyrotechnics (PEP) and PEP-contaminated waste was conducted. Safety considerations indicate that PEP and PEP-contaminated waste with proper precautions could be handled safely by pyrolysis processes, but further work is needed to determine applicable size reduction techniques.

Candidate pyrolysis systems were evaluated for: 1) the ability to process PEP-contaminated waste, 2) environmental acceptability, 3) pyrolysis oil yield, 4) technical maturity, 5) process economics and 6) lead time required to construct a plant. Five systems were initially identified as suitable. Two were found satisfactory in all categories except economics. A third system was attractive for this application but could not be considered fully acceptable because no cost data were available.

It was determined that a 45.4 Mg/d (50 TPD) plant would be satisfactory to handle the largest quantity of waste generated at any AAP. Such a plant, under mobilization production conditions, would be expected to produce approximately 9,000 barrels of oil annually. Capital costs were estimated at $4.1 million and total annual costs were estimated to be $623,100 per year. Even at full mobilization, and taking credit for not having to incinerate this waste, the economics reveal that this technology is not currently viable.

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INTRODUCTION

The objective of this contract was to determine the feasibility of adapting pyrolysis technology for energy recovery from solid wastes generated at Army Ammunition Plants.

For the past several years, the Army Armament Research and Development Command (ARRADCOM) has been engaged in various programs aimed at reducing fossil fuel consumption at AAP's. Energy conservation and alternate energy sources (nonfossil organic energy sources) have received the most attention. The driving force behind this activity was the oil embargo and subsequent radical oil price increases.

Army Ammunition Plants dispose of large quantities of explosives, explosive-contaminated waste and non-contaminated wastes either by open-air burning or incineration. Although it has been estimated that these wastes have a heating value of 23,200 KJ/kg (6000 Btu/lb), there is at present no attempt at energy recovery. In addition, the traditional open burning disposal of such wastes is now environmentally undersirable. Revocation of Part 76 of Title 40, Code of Federal Regulation (CFR) on 25 March 1975 rescinded a Federal exemption allowing open burning of munition wastes.

Many types of conversion processes are under development for converting waste materials to energy and at the same time serving as a satisfactory disposal method. Pyrolysis is one of the conversion processes which has received considerable attention in the last several years. It is one of the few processes which produces storable liquid fuel. In light of these advantages, ARRADCOM selected pyrolysis for investigation as a possible method of recovering energy from solid wastes generated at the AAP's.

The TRW program was organized into six separate parts:

1. AAP Waste Survey
2. Literature Survey of Pyrolysis Technology
3. Hazard Potential of Processing Munition Contaminated Wastes in Pyrolysis Plants
4. Evaluation of Candidate Systems
5. Cost for 5 TPD Pyrolysis Pilot Plant(s)
6. Economic Analysis of Pyrolysis Under Current and Mobilization Production Levels

This report summarizes the efforts, results, conclusions, and recommendations of the Program on Pyrolysis Adaptation for Energy Recovery at AAP's.

DISCUSSION

AAP WASTE SURVEY

Personnel at eight AAP's were contacted to obtain their latest available figures on current and mobilization production levels of solid wastes. The following AAP's were contacted:

Holston	Kingsport, Tennessee
Iowa	Burlington, Iowa
Joliet	Joliet, Illinois
Kansas	Parsons, Kansas
Lone Star	Texarkana, Texas
Louisiana	Shreveport, Louisiana
Radford	Radford, Virginia
Sunflower	Lawrence, Kansas

Basically the waste generated at these installations falls into three major categories:

1. Waste munitions containing propellants, explosives, and pyrotechnics (PEP)
2. PEP-contaminated waste
3. Non-contaminated waste

Waste PEP is generated from a number of sources (ref 1). Such wastes include munitions which have become obsolete, unserviceable, surplus, or unsafe. Also included are off-specification and scrap materials from primary production, loading, and rework. Production operations produce waste PEP from filling plant processing, cleanings from catch basin and sumps, materials from production jobs considered unsafe for storage or handling, and unserviceable, off-specification, and excess materials. Testing also produces waste PEP such as excess items from tests, misfires, and partially-consumed test items. Wastes are also created during research and development of new and more effective PEP. Of the many types of PEP that must be destroyed, Composition B, RDX, HMX, and TNT comprise the bulk of the amount burned. As a rule waste PEP's are destroyed by open burning.

The constituents that make up the quantities of PEP-contaminated waste are varied. A representative listing includes such items as lumber, wooden pallets, skids, cardboard boxes, plastic bags, miscellaneous maintenance materials (gaskets, hoses, rags, pump packing, gloves, plastic strappings, floor sweeping, and wood scraps), TNT liners, hoses, steel drums, aluminum insulation covering, and miscellaneous metal fittings. Open burning, landfill and incineration are all used for disposition of PEP contaminated wastes.

Non-contaminated waste is also very diverse. Included in this category are non-explosive refuse, fly ash, tar residue, and cinders. The tar fuel is used as boiler fuel and the remaining non-explosive refuse is disposed of either in refuse incinerators or landfill.

A summary of the survey is listed in Table 1. Current production figures are given in megagrams per year (Mg/yr) and a year's operation is considered to be 260 days. At the present time, there is no open pit burning of wastes at either Joliet or Louisiana AAP. Only small amounts of PEP waste are produced at these plants which is sold for reclamation of the nitrocellulose. The other wastes produced at these sites are either landfilled or baled and then sold. The table shows that Lone Star has a very high ratio of non-contaminated waste to PEP and PEP-contaminated wastes. The reason for this is that Lone Star is a Loading and Assembly Plant (LAP); PEP's are not manufactured there, but they are received from other AAP's and loaded into fuses, detonators, pellets, boosters, etc.

Table 1. Summary of Current Solid Waste Production at Eight AAP's

	Waste Category					
Installation	PEP Mg/yr	(TPY)	PEP-Contaminated Mg/yr	(TPY)	Non-Contaminated Mg/yr	(TPY)
Holston	71	(78)	250	(275)	386	(425)
Iowa	648	(715)	118	(130)	1040	(1142)
Joliet	Negligible		40	(44)	340	(375)
Kansas	—		18[a]	(20)[a]	403	(445)
Lone Star	1.2	(1.3)	4.7	(5.2)	944	(1040)
Louisiana	Negligible			[b]	567	(625)
Radford	407	(450)	227	(250)	1020	(1125)
Sunflower	—		126[a]	(139)[a]	52	(57)

[a] Total PEP and PEP-contaminated (very small quantities of PEP).

[b] Undetermined

The waste production rates depicted in Table 1 reflect a peacetime environment. During a mobilization period, waste production would be considerably increased. In general, the AAP's are currently running between 17% and 25% capacity. Holston and Sunflower are only running at about 10% capacity.

LITERATURE SURVEY OF PYROLYSIS TECHNOLOGY

The need for new sources of energy has stimulated research and development of processes for converting waste materials-silvicultural, agricultural, and urban waste - to energy. Pyrolysis is one of the processes which has recently received considerable attention as a means of both energy recovery and waste disposal. Pyrolysis itself is not a new process, as it has been practiced for centuries.

In pyrolysis the waste material is exposed to heat in an atmosphere deficient in oxygen. The organic material in the waste is thermally decomposed into a useable energy form. Gases, liquids, and carbonaceous char are all possible energy forms from pyrolysis. The form and characteristics of the fuel fraction depend on the operating characteristics of the particular system as well as on the waste being processed.

Several articles have been published recently which review pyrolysis technology (ref 2,3,4,5). Approximately 10 different pyrolysis waste-to-energy systems are now being demonstrated or are under development. Table 2 lists these systems.

In the present study, the preferred form of energy recovery from a pyrolysis unit is storable fuel, i.e., oil; therefore, the first five processes listed in Table 2 are candidate systems for evaluation in this study.

HAZARDS POTENTIAL OF PROCESSING MUNITIONS AND CONTAMINATED WASTES IN PYROLYSIS PLANTS

Safety aspects of various pyrolysis processes are discussed in this section. Several sources were used for this safety investigation. They included general references on explosives manufacture, transportation and handling, reports of results of experiments involving incineration and pyrolysis of PEP and PEP-contaminated wastes, and descriptions of the various pyrolysis processes.

Table 2. Waste-to-Energy Pyrolysis Systems

Company	System	Feed	Product	Status
1. Occidental Research	Flash Pyrolysis	Refuse, Wood waste	Oil, Low-Btu gas	181 Mg/d (200 TPD) Demo plant in El Cajon, California
2. Tech-Air Corporation Georgia Tech	Tech-Air Pyrolysis System	Wood waste, Refuse	Oil, Low-Btu gas, Char	45.4 Mg/d (50 TPD) Pilot plant in Cordele, Georgia
3. Enterprise	Enterprise Resource Recovery & Energy Conversion Process	Refuse	Oil, Hi-Btu gas	45.4 Mg/d (50 TPD) Pilot plant in South Gate, California
4. Wallace-Atkins	Wallace-Atkins Process	Refuse, Wood waste	Oil, Hi-Btu gas	45.4 Mg/d (50 TPD) Pilot plant in Baytown, Texas (under construction)
5. Redker-Young	Redker-Young System	Refuse, Wood waste	Oil, Hi-Btu gas	35.3 Mg/d (40 TPD) Pilot plant in Ingham County, Michigan
6. Envirochem	Landgard	Refuse	Low-Btu gas	907 Mg/d (1000 TPD) Commerical plant in Baltimore, Maryland (closed because of excessive emissions)
7. Union Carbide	Purox	Refuse	Mid-Btu gas	181 Mg/d (200 TPD) Pilot plant in South Charleston, West Virginia
8. Andco	Andco-Torrax	Refuse	Low-Btu gas	181 Mg/d (200 TPD) Commerical plants in Luxemburg & Belgium
9. Devco	—	Refuse	Low-Btu gas	6.3 Mg/d (7 TPD) Pilot plant in Queens, New York
10. Battelle Northwest	—	Refuse	Low-Btu gas	4.5 Mg/d (5 TPD) Pilot plant in Richland, Washington

At present PEP and PEP-contaminated wastes are disposed of by open pit burning or by burning in rotary furnaces, batch box, solid waste, and fluidized bed incinerators. These approaches have been shown to be safe for operating personnel when strict safety precautions are observed.

Recent work done at the Engineering Experiment Station at the Georgia Institute of Technology (ref 6) indicates that it is possible to pyrolyze organic wastes contaminated with 0.5, 1.0 and 2.0% TNT. No safety problems were encountered in this work. However, it should be noted that the TNT was applied to the waste after it had been ground. Thus no information was obtained on how contaminated waste could be ground. Grinding appears to be necessary for all pyrolysis units studied in this report.

Wet grinding of PEP for slurries, as is done in the present fluidized bed incinerators, and the wet grinding of the PEP-contaminated waste appear to be feasible ways around the detonation hazard associated with the grinding operation. The disadvantage is that the water would have to be removed in a dryer which would consume energy from the pyrolysis process.

In addition to the problem associated with grinding the wastes, two groups of hazards were also identified: those common to all industrial operations and those specific to pyrolyzing PEP-contaminated waste. The common hazards include the possibility of damage to equipment and injury to personnel arising from accidents occurring in the following situations:

1) Operation of motor vehicles.
2) Operation of mechanical equipment such as conveyors, hammer mills, etc.
3) Injuries resulting from falls, burns, electrical shocks, etc.

These injuries are common to normal industrial and chemical processing operations. The safety precautions and procedures to avoid or minimize these accidents are detailed in OSHA, state, and federal regulations, industrial regulations, and the uniform building codes. A detailed examination of the applicable codes and regulations will need to be carried out prior to construction of any selected pyrolyzing process. Technical Report 4586, Picatinny Arsenal, November 1973, (ref 7) provides a comprehensive overview of the design requirements for incinerators to combust explosive-contaminated waste and appears to be generally applicable to pyrolysis processes also.

The hazards associated with the pyrolysis process include fire, explosions, and escape of PEP dust into the atmosphere. A summary of these hazards is shown in Table 3, together with a block diagram of a generalized pyrolysis process. The process includes transportation of PEP-contaminated wastes to the pyrolysis site. This transportation would most likely be very similar to procedures now in use at several AAP's. Next, a sorting and metal removal step is shown, although such a step may not be necessary if careful control is exercised at the waste collection site. Size reduction and drying are determined by the process requirements and the moisture content of the waste. A process which requires no size reduction would be the most desirable from a safety point of view, since fires and explosion hazards are high in this type of operation. The final two unit operations consist of pyrolysis and char removal and disposal. The hazards here are primarily from explosions of bulk quantities of explosives.

Bulk quantities of explosives would have to be handled separately from contaminated waste. It would have to be wet ground and added to the waste in sufficiently dilute quantities so that explosive hazards are eliminated.

Table 3 groups the various unit operations with the type of hazard or malfunction and also presents the corrective or preventive action to be employed. The first hazard is fire, which could occur in any unit operation. Fires are not considered to be a hazard in the pyrolysis unit, since the oxygen supply can be controlled and thus excessively rapid oxidation of the nonexplosive materials can be controlled. Smoke

Table 3. Unit Operations and Associated Hazards

A) POSSIBLE PROCESS UNIT OPERATIONS

TRANSPORTATION → SORTING METAL REMOVAL → SIZE REDUCTION → DRYING → PYROLYSIS → CHAR REMOVAL

B) OPERATION HAZARDS

OPERATION	HAZARD OR MALFUNCTION	CORRECTIVE ACTION
DRYING, CRUSHING, CONVEYING, CHAR REMOVAL	FIRES	1. PROVIDE WATER SPRAY OR CO_2 FLOODING SYSTEM TO CONTROL FIRES IN WASTE. 2. PROVIDE SMOKE AND FLAME DETECTORS. 3. ISOLATE PLANT FOR SURROUNDING COMBUSTIBLE STRUCTURES AND REMOVE VEGETATION IN VICINITY.
PYROLYZERS, DRYING, CRUSHING, CONVEYERS	EXPLOSIONS DUE TO BULK QUANTITIES OF EXPLOSIVES IN SOLID WASTES	1. SEGREGATE WASTES AT POINT OF ORIGIN. 2. DESIGN REACTOR TO WITHSTAND OVERPRESSURES RESULTING FROM DETONATION EQUIVALENT TO 1% OF THE CHARGE BEING COMPOSED OF PEP. 3. DESIGN PRESSURE RELIEF DOORS FOR OVERPRESSURES EXCEEDING MAXIMUM DESIGN PRESSURE. 4. PLACE CONTROL CENTER A SAFE DISTANCE AWAY FROM THE REACTOR AND PROVIDE FOR REMOTE OPERATION OF THE REACTOR. 5. UTILIZE EXPLOSION-PROOF EQUIPMENT WHERE REQUIRED.
ALL	ESCAPE OF PEP DUST AND DECOMPOSITION VAPORS INTO ATMOSPHERE	1. USE CLOSED HOPPERS AND CONVEYORS. 2. PROVIDE POSITIVE VENTILATION OF CONVEYORS, ETC. COLLECT PARTICULATE MATTER IN BAG HOUSES OR OTHER GAS CLEANING EQUIPMENT. 3. SPRAY AND WASH DOWN THE EQUIPMENT AT SPECIFIED INTERVALS. 4. HAVE PERSONNEL WEAR PROTECTIVE CLOTHING AND BREATHING FILTERS WHILE LOADING OR OPENING THE SYSTEM. THOROUGHLY SHOWER AFTER EXPOSURE TO PEP DUST.

and flame detectors, a water spray and CO_2 extinguishing system, and separation of the pyrolysis process from adjacent combustible structures are the appropriate preventive measures.

Explosions of bulk quantities of explosives constitutes the most serious hazard. It should be possible to operate the unit remotely and thus eliminate any danger to personnel. During inspection and repair or maintenance operations, strict guidelines for handling explosive materials and the equipment will have to be established and followed.

The final hazard is the escape of PEP dust into the atmosphere and its subsequent inhalation or accumulation in the vicinity. Limitation of this hazard is perhaps the easiest, in that conveyors, hoppers, etc., can be closed, with ventilation and air filtration equipment controlling most fugitive particulate matter.

In summary, the major hazards to personnel and equipment resulting from pyrolysis of PEP-contaminated waste can be grouped into two categories:

1) Hazards common to all industrial operations such as personal injury resulting from falls, burns, shock, and contact with operating machinery. Control of these hazards and accident prevention is well established for industrial operations.

2) Hazards resulting from pyrolysis of waste material which contains explosives. These include fires, explosives, and escape of contaminants into the atmosphere. Proper design of equipment and adherence to safe operational procedures should minimize the danger to personnel of such hazards.

EVALUATION OF CANDIDATE SYSTEMS

The literature search involved in this study (see Table 2) revealed five pyrolysis systems which could be considered candidates for converting AAP solid wastes to oil. This section looks at each process individually and finally makes a relative comparison of the processes.

Occidental Research Corporation's Flash Pyrolysis System (ref 8)

History

In 1968, as an outgrowth of research on the conversion of coal to low-sulfur fuel oil, Occidental Research Corporation (formerly Garrett Research and Development Company) began studies on the conversion of the organic portion of municipal refuse to usable liquid fuel and the recovery of metals and glass. The decision was made in the early stages of development that the materials should be separated at high level of purity so that markets could be assured. This objective has apparently been met through several research and development programs.

Fundamentals of the conversion process were established with laboratory equipment capable of processing 1.4 kg/hr (3 lb/hr). Waste feed, in addition to municipal refuse, included bark, rice hulls, sewage sludge, animal manure, and rubber. This work was scaled up to a 3.6 Mg/d (4 TPD) pilot plant where the critical process variables were investigated, materials handling problems resolved, and sufficient product produced to establish its properties, including those as a fuel in burner test equipment. Information was obtained to serve as the basis for the design of a 181 Mg/d (200 TPD) plant at El Cajon, California. The plant has demonstrated that the process can satisfactorily make fuel. Most of the problems encountered during operation were of a mechanical nature. Bechtel, under contract to Occidental, is presently performing a complete economic analysis of the Flash Pyrolysis process.

Process Description

Figure 1 shows the process schematic of the Occidental resource recovery system, basically consisting of a front-end physical processing and materials separating section and a pyrolysis/purification section. The functions and operating characteristics of the equipment within these two sections are discussed separately below. It should be noted that the plant wastes should be free of glass, aluminum, and other metals; therefore, the front-end equipment could be reduced to eliminate the equipment used to separate these components out of the feed stock.

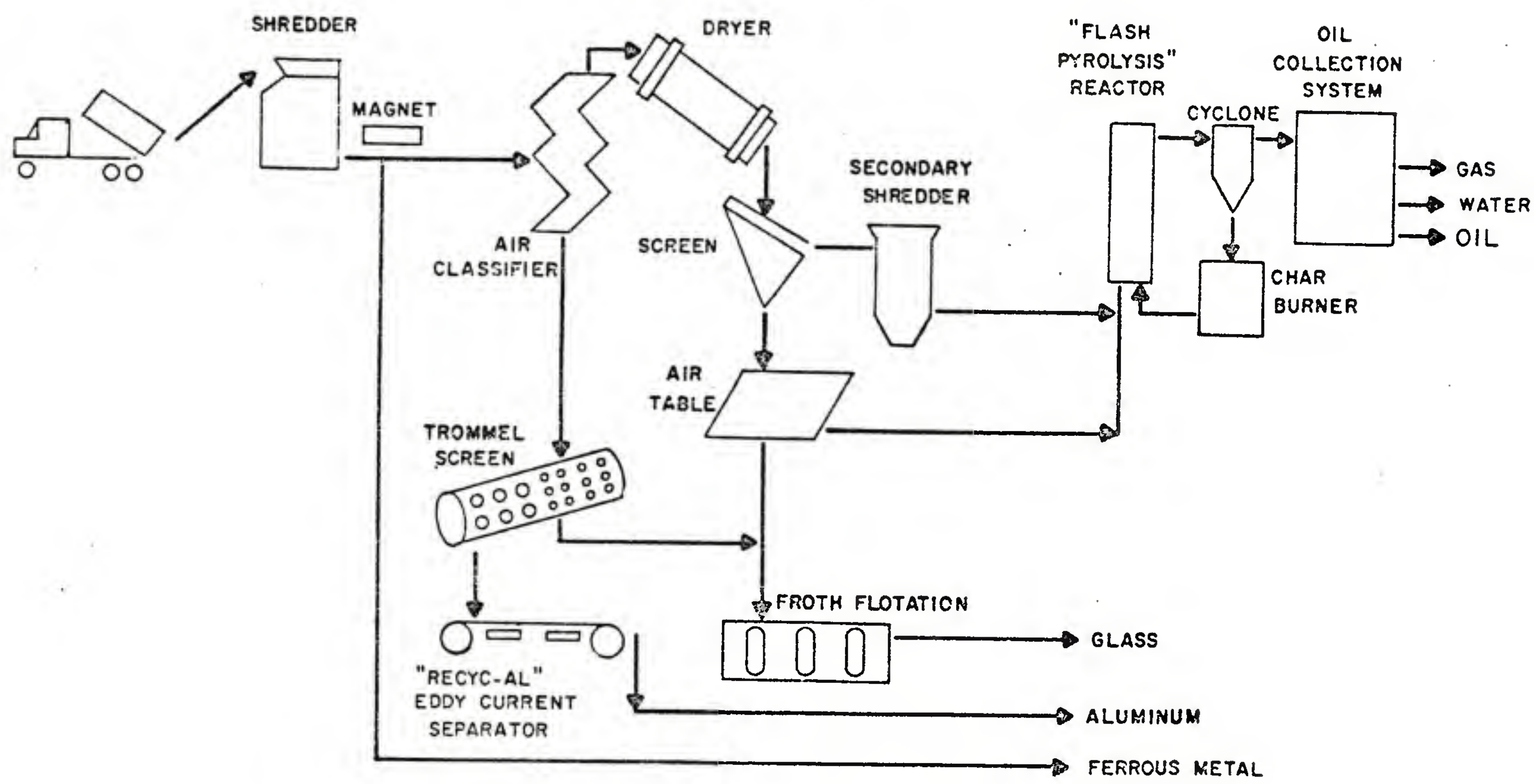


Figure 1. Schematic of the Occidental Resource Recovery System

Front End System

The first eight steps of processing prepare the raw refuse for the materials recovery systems. Several fractions are isolated, including one that is a finely divided organic "fluff" used as the feedstock for the pyrolysis unit. The elimination from this feedstock of most of the inorganics is an important function of the front end system. The pyrolysis process itself is not affected by these inerts, but the quality of the residual char would otherwise be lowered and maintenance costs for the secondary shredder would be increased.

From storage, unsorted municipal wastes are conveyed to the primary shredder, where size reduction to less than 10 cm (4 in.) is accomplished in a heavy duty hammermill. A magnetic separator then removes 95% of the ferrous metals as the shredded waste is conveyed to the air classifier. The classifier is of the zig-zag type and was designed by Occidental Research Corporation. Organics entrained with the inorganic fraction from the air classifier are reclaimed in a later stage of processing. Some 75% of the shredded refuse is taken off in the light (overhead) fraction. Approximately 95% of the original wet organics are recovered in this fraction and 8% of the inerts.

The heavy (underflow) fraction is further treated to recover glass, non-ferrous metals, and entrained organic material. A Trommel (rotating screen) is used for the initial separation. The first section, containing 1.2 cm (0.5 in.) holes, passes the more brittle waste components such as glass, ceramics, rocks, and bones. Typically, the composition of this fraction is approximately 50% glass and it is conveyed to multistage froth flotation tanks after having been ground in a rod mill to a size range of 840 to 44 cm (20 to 325 mesh). Proprietary chemicals in these tanks cause the glass particles to have an affinity for air and they rise through the water on air bubbles while non-glass materials sink. The float material after drying is 99.5% glass and represents about 70% of the total glass in the original refuse.

A second section of the trommel contains holes that are 10.2 cm (4 in.) in diameter. Material passing through these holes contains 10% metal and is conveyed to the "RECYC-AL" eddy current separator for recovery of aluminum. Material greater than the hole size is returned to the primary shredder feed. A pair of linear induction motors positioned beneath a conveyor belt causes non-magnetic electrically conductive materials to be deflected into a collection system. A traveling magnetic field is generated by the motors, inducing eddy currents in metal pieces such as aluminum. A magnetic field of opposite polarity to that of the motors is produced, resulting in the metal being ejected from the traveling belt. The product collected consists of about 90% aluminum and approximately 60% of the aluminum originally present in the refuse is thus isolated. The 10% impurities in the aluminum fraction consist of entrapped materials of all kinds from the grinding operation and objects displaced into the collection bin by moving aluminum pieces.

The light fraction from the air classifier is conveyed to a dryer, a rotary kiln of the type used for removing water from agricultural products, where the moisture level is reduced to about 3%. While not essential to the pyrolysis conversion step, this drying does help optimize the conversion and improves separation in the subsequent screening system.

Material not passing through a 1410 μm (14 mesh) screen has had its inorganic content reduced to about 4%. The undersized material contains approximately 65% organics and is further purified on an air table, where three fractions are obtained. The light fraction has a high organic content and is added to the screened oversized material. A heavy glass-rich fraction is introduced to the glass recovery system. The small intermediate fraction is landfilled.

High heat transfer rates are important to the rapid pyrolysis process. Small particles are required and, hence, the final front end processing step is to pass the organic fraction through a secondary shredder, an attrition mill consisting of counter-rotating disks. The product is quite fine, with 80% able to pass through a 1410 μm (14 mesh) screen. Because of the potential fire hazard in this operation, a pressurized inert atmosphere is maintained within the grinder. Power consumption tests demonstrate that approximately equal amounts of power are required in the primary and secondary stages of grinding. This amounts to 118 to 148 KJ/kg (40 to 50 hp-hr/ton) in each stage.

Pyrolysis System

In contrast to the rather high density, moving, solid bed converters of the Enterprise, Wallace-Atkins, Redker-Young and Tech-Air Pyrolysis system, the Occidental Research Corporation fuel production process occurs in a rapidly moving gas stream. Carried along by an inert turbulent gas (recycled product gas), the finely divided organics from the secondary shredder are heated by hot particles also flowing with the gas stream. These char ash particles are formed and heated in the char burner by combustion of the char that is one of the products of pyrolysis. It is introduced into the "Flash Pyrolysis Reactor" at a temperature of approximately 760^{o}C (1,400^{o}F) and at a mass flow rate five times greater than that of the waste material. Cooling occurs within the reactor so that the actual average temperature for the conversion process is about 510^{o}C (950^{o}F).

The gas exiting the reactor is passed through a mechanical cyclone, where the ash and the newly formed char are separated. As excess ash builds up during the process, a portion is periodically removed for disposal.

After most particulate matter has been removed from the stream, it is passed into the oil collection system where the temperature is rapidly quenched to approximately 80^{o}C (175^{o}F). This is accomplished by spraying a light fuel oil into the gas, effectively stopping any further thermal decomposition. The liquid fuel then settles to the bottom of a decanter, from which it is moved by pipe to storage tanks. A portion of the water formed in the pyrolysis process is retained with the oil for the purpose of reducing its viscosity.

After clean-up, the gas is compressed for use as (1) the oxygen-free transport medium and (2) fuel for preheating the combustion air into the char heater, the rotary kiln dryer for the coarse-shredded waste, and various process heat needs. All gas finally exits through an after-burner, heat exchanger, and baghouse filter system before it is discharged to the atmosphere.

Material and Energy Balance

For a 181.4 Mg/d (200 TPD) plant using municipal waste, the material inputs are:

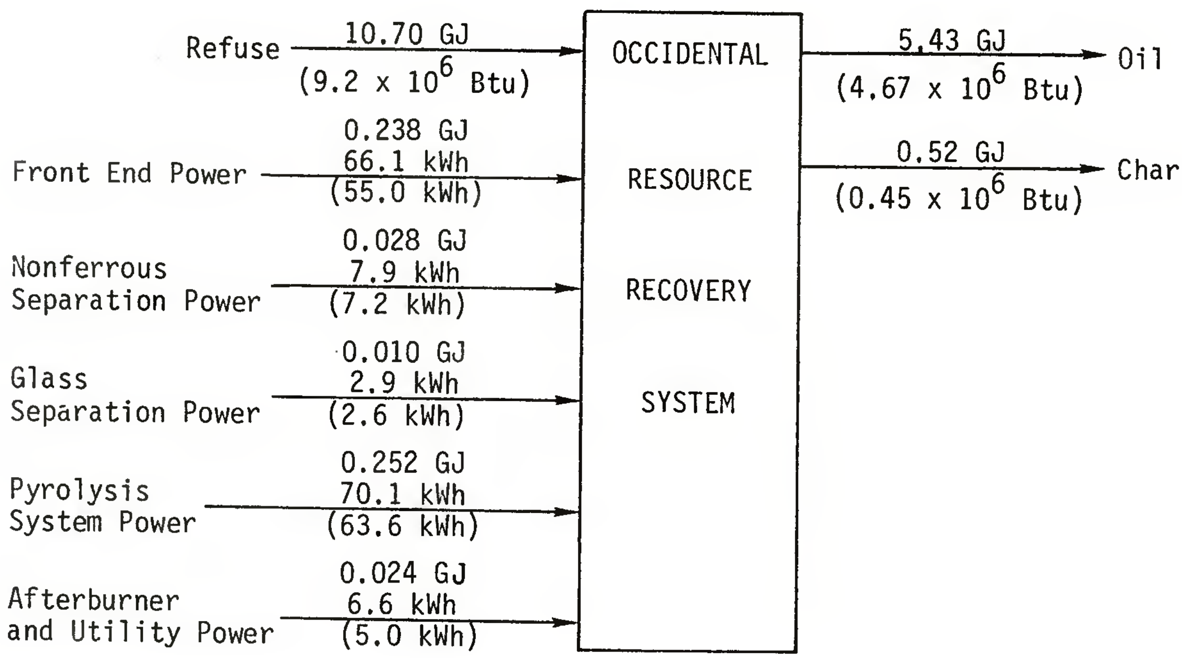
Component	Amount, Wt(%)	(Mg)	(Tons)
Organics (dry)	54.4	98.8	108.8
Magnetic metals	7.6	13.8	15.2
Aluminum	0.5	0.9	1.0
Other metals	0.3	0.5	0.6
Glass	9.0	16.3	18.0
Misc. other solids	3.2	5.8	6.4
Water	25.0	45.4	50.0
Total	100.0	181.4	200.0

The high heating value (HHV) of the as-received municipal waste is 10.70 MJ/kg (4,600 Btu/lb). The anticipated products from the process are as follows:

Products	Amount, Wt(%)	Daily output (Mg)	Daily output (Tons)
Oil (containing 14% water)	25.6	46.4	51.2
Gas	44.1	80.0	88.2
Char/Ash	8.2	14.9	16.4
Water to sewer	1.9	3.4	3.8
Residual to landfill	6.5	11.8	13.0

Products	Amount, Wt(%)	Daily Output (Mg)	Daily Output (Tons)
Ferrous Metal	7.2	13.1	14.4
Glass cullet	6.1	11.1	12.2
Aluminum	0.4	0.7	0.8
Total	100.0	181.4	200.0

The energy balance of the total system, based on 1 Mg or the parenthetical values for 1 ton[1] of input refuse, is as follows:



The energy recovery efficiency is based on the assumption that a heat equivalent portion of the product oil would be used to generate electricity (at a net plant heat rate of 10,550 KJ or 10,000 Btu/kWh). This energy

1. Note that the English units are not factored conversions from Systems International (SI), which would imply an input of 1.1023 tons, but for convenience are based on the convention of 1 ton input (exactly).

penalty is assessed against the product and this value then compared to the original energy content of the refuse. If only the oil is considered as a useful product, this mathematically (in English units) becomes:

$$\eta = \frac{4.67 \times 10^6 - 1.39 \times 10^6}{9.2 \times 10^6} \times 100 = 35.6\%$$

If the output energy is considered to include that in the char, a material that would be difficult to sell as a fuel because of its high ash content, the energy recovery would increase by 0.52 (0.45×10^6 Btu) and efficiency would then be 40.5%. Comparison to efficiencies of other processes, even pyrolysis systems, must be attempted only with a full recognition of the worth of final products. That some 60% of the originally totally wasted energy is required to operate a process able to "create" large quantities of a synthetic fuel oil should not be considered discouraging, but viewed as a factual description of a given chemical system. Further energy efficiency can be attributed to the savings that result from recovery of glass, ferrous metals, and aluminum, in that manufacture of new materials in contrast to recycling old ones is a more energy-intensive process. No consistent set of assumptions has yet been developed for quantification of the "inherent" energy in the recovered materials, but the additional 3.37 GJ/Mg (2.90×10^6 Btu/ton) sometimes cited by Occidental is an entirely reasonable value and would raise the efficiency to 67.2% (excluding char).

Product Characteristics

Typical distribution of the yield of products from the pyrolytic reactor is shown in Table 4, based on dry material entering the reactor exclusive of the gas stream and hot ash.

As with petroleum itself, the oil produced in the Occidental process is a complex mixture of molecular weights and structural configurations. While its chemistry has not been investigated to any great detail, sufficient characterization has been made to establish the probable value of the liquid as a utility fuel. Key properties of the product are shown in Table 5 along with those of No. 6 fuel oil for comparison.

Table 4. Typical Products of Occidental Flash Pyrolysis System Yields at 510°C (950°F), Based on Dry Weight of Feed to Pyrolysis Reactor

Oil (Dry) - 40%	C	57.0 wt (%)
HHV = 24.66 MJ/kg (10,600 Btu/lb)	H	7.7
	N	1.1
	S	0.2
	Cl	0.3
	Ash	0.5
	O	33.2
		100.0
Char - 20%	C	48.8 wt (%)
HHV = 19.0 MJ/kg (8,200 Btu/lb)	H	3.3
	N	1.1
	S	0.4
	Cl	0.3
	Ash	33.0
	O	13.1
		100.0
Gas - 30%	H_2	12 vol (%)
HHV = 14.96 MJ/Nm^3 (380 Btu/SCF)	CO	37
	CO_2	37
	CH_4	6
	C_2H_4	3
	C_2H_6	1
	C_3	1
	C_4^+	2
	H_2S	0.8
	HCl	0.2
		100.0
Water - 10%		

Table 5. Typical Properties of No. 6 Fuel Oil and Occidental's Pyrolytic Oil

Composition, wt (%)	No. 6 Oil	Pyrolytic Oil
C	87.5	57.0
H	10.5	7.7
S	0.7-3.5	0.2
Cl	-	0.3
Ash	0.5	0.5
N		1.1
O	2.0	33.2
Specific Gravity	0.98	1.30
Heating Value		
MJ/kg	42.33	24.66
MJ/dm3	41.47	32.03
Btu/lb	18,200	10,600
Btu/gal	148,800	114,900
Pour point, ^{o}C (^{o}F)	18-29 (65-85)	32* (90*)
Flash point, ^{o}C (^{o}F)	66 (150)	56* (133*)
Viscosity		
mm^2/s at 88^{o}C	48	160*
SSU at 190^{o}F	340	1,150*
Pumping temperature, ^{o}C (^{o}F)	46 (115)	71* (160*)
Atomization temperature, ^{o}C (^{o}F)	104 (220)	116* (240*)

*Pyrolytic oil containing 14% water, as marketed.

Important differences between the two oils that can be noted include:

Elemental Analysis

The high oxygen content of the pyrolytic oil, a result of the largely cellulosic composition of the original waste, results in a decreased HHV compared to normal hydrocarbon fuels and causes a marked solubility (60%) increase of the oil. Water is retained to decrease viscosity. The oxygen content, in addition to the chloride level, results in some acidity of the product; storage should present no particularly difficult problem and details of materials to be used will be established during the El Cajon demonstration plant study. An additional characteristic that thus far is attributed to the high oxygen content is that extended high temperature storage causes a further increase in viscosity and it is recommended the oil be maintained below 71°C (160°F) until just before atomization. The low sulfur content is a property of the pyrolytic oil that makes it an attractive refuse derived fuel (RDF). The low ash content, being markedly less than solid forms of RDF, is another important feature of the liquid fuel.

Specific Gravity

The pyrolytic oil has an unusually high density, some 34% higher than that of the usual fuel oil. The Occidental product has a higher energy content per volume than any other refuse derived fuel, a factor that will reduce its transportation costs relative to other RDF's.

Heating Value

While even on a volumetric basis the HHV of the pyrolytic oil is 23% less than that of fuel oil, it is higher than an average coal and if used in conjunction with a liquid fossil fuel, it can supply a substantial portion of the total heat input to the furnace without any major modifications to the system or its steam-generating characteristics.

Flow Properties

The presence of 14% water alters flow properties of the pyrolytic oil sufficiently to permit it's being handled with conventional equipment, although the Occidental product remains more viscous than No. 6 oil. The effect of temperature is greater for the synthetic oil, however, such that the atomization temperatures are only 12°C (20°F) apart.

The combustion properties of oil produced in the pilot plant were briefly examined in research burners by Combustion Engineering, Inc. Blends of pyrolytic oil of 25 and 50% by volume with No. 6 oil derived from Alaskan crude were used. Such blends eventually separated because of the solubility characteristics of the oxygenated oil, but were stable for several hours. It was established that ignition stability is equal to the fossil oil alone, and that combustion is successful with properly designed fuel handling equipment. At air levels over 2% excess oxygen, there were negligible quantities of unburnt carbon in the stack emissions.

Environmental

All front end handling and processing steps producing an air stream containing particulate matter are controlled by passing the gas through a baghouse fabric filter system. Effluents from the char burner and waste drier are passed through an afterburner, fueled by a portion of the pyrolysis recycled off-gases, where any combustible matter is exposed to a minimum of 649°C (1,200°F) for at least 0.5 second under oxidizing conditions. The gas then passes through another baghouse before being released to the atmosphere. A process heater within this system supplies heat to the dryer and various process lines.

Estimated emissions from the afterburner baghouse are:

Component	Concentration
SO_2	700 ppm (wt)
NO_x	8 to 1,000 ppm (wt)
HCl	100 ppm (wt)
Particulates	0.12 g/Nm^3 (0.05 gr/SCF)

The wide range in the value for nitrogen oxides is a result of the extremes of assuming that only atmospheric nitrogen is fixed according to the known thermodynamics of this reaction, and that in addition all nitrogen entering the afterburner is involved in the equilibrium.

Two contaminated water streams exist. The stream from the glass recovery system is the larger of the two, but tests have verified that standard flocculation reagent addition, clarification, and filtration brings the water to a quality level permitting discharge to a sewer system. The second stream, totalling approximately 3.6 Mg/d (4 TPD) for the demonstration plant, results from the product quenching and collection system. This effluent can contain up to 100,000 ppm of COD. Limited experiments indicate the organic contaminants are fully biodegradable, but typical local regulations would forbid discharge of this liquid directly to a sewer system. Reduction of the COD load would consist of the use of one of several standard biological waste water treatment systems. Occidental has suggested that in some applications of the recovery plant sufficient heat might be available for afterburning the entire water effluent.

Residual solids amount to 13 to 16% of the weight of the input refuse. About half of this is inert ash from the pyrolysis system; the remainder is rejected material from the air table and glass recovery system. The inert portion of the latter is approximately 50%.

Noise, as with other waste processing systems involving front end treatment, is principally from the size reduction equipment. Sufficient experience in attenuation of this sound energy has now been obtained and no problems are anticipated at the demonstration plant.

Economics

Table 6 lists the various elements of the 1976 capital costs for the two plants. The capital recovery factor of 0.10567 used for the yearly cost is based on a 20-year useful plant life and an 8.5% interest rate. Costs attributable to capital amount to $10.13 and $7.63/Mg of input waste for the 907 and 1814 Mg/d plants, respectively, ($9.19 and $6.92/ton).

Operating costs were estimated as follows:

Labor (including benefits)	$7.00/hr	
Taxes	0.75% of plant investment	
Maintenance and repairs (including labor)	7% of plant investment	
Parts and Supplies	0.75% of plant investment	
Electricity	$0.02/kWh	
Fuel	$0.09/liter	($0.35/gallon)
Water	$0.13/kiloliter	($0.50/1,000 gallons)
Insurance, fees, and Professional services	$1.10/input Mg	($1.00/input ton)
Residue transportation and disposal charge	$8.27/Mg	($7.50/ton)

Table 6. 1976 Capital Costs for 907 and 1814 Mg/d (1,000 and 2,000 TPD) Plants

Cost Element	Cost $ (000)	
	Smaller Plant	Larger Plant
Land	100	130
Site Preparation	35	46
Design	2,160	3,030
Construction and Installation	12,700	19,300
Real Equipment	8,100	12,400
Other Equipment	615	808
Contingencies (at 10%)	2,371	3,571
Startup and Working Capital	2,010	3,025
Financing and Legal	514	775
Total Capital Investment	28,605	43,085
Annual Capital Cost (20 years, 8-1/2%)	3,023	4,553
Capital Cost, $/Mg	10.13	7.63
Capital Cost, $/ton	9.19	6.92

This results in a net operating cost of:

	907 Mg/d (1,000 TPD) Plant		1814 Mg/d (2,000 TPD) Plant	
Capital Cost	$10.13/Mg	$ 9.19/ton	$ 7.63/Mg	$ 6.92/ton
Operating Cost	19.07	17.30	14.52	13.17
Total Cost	29.20	26.49	22.15	20.09

These costs include the front end processing and materials separation equipment which may not be required for this application. Additionally, land costs are not appropriate here.

Tech-Air Pyrolysis System (ref 9)

History

The initial work on the Tech-Air pyrolysis system was started at the Georgia Institute of Technology in Atlanta, Georgia, approximately ten years ago.

The first pyrolysis unit built in this program was a retort approximately five feet high with a single air tube, an electric starter, and a movable grate for periodic char removal. The retort was built and operated with dry agricultural wastes in the late 1960's. Information on the process and potential products obtained from this work was used as the basis for designing and building the first continuous pilot plant at the Georgia Institute of Technology in 1970. This unit was designated Blue I. The system incorporated a vertical bed, gravity fed, counter flow pyrolysis chamber with a continuously operating char output system.

Blue I was operated for approximately one year on dry agricultural wastes. This plant demonstrated that the process could be operated continuously with simple means of control and that the mechanical char output system was reliable. Information obtained on the process showed the importance of distributing the process air within the bed and the wide variations in char yields which could be obtained without producing slag.

The results of this first pilot plant program led to the construction in 1971 of the second pilot plant, Blue II. This system was similar to Blue I, but had refractory walls and more instrumentation. The input system consisted of a bin, a covered belt conveyor, and a rotary air lock. The off-gas system was changed significantly by installing an air cooled condenser, an off-gas control fan, and a refractory-lined, swirl chamber for combustion of the non-condensed gases. The off-gas fan permitted the pyrolysis chamber to be operated at a sub-atmospheric pressure and allowed the installation of simple, weighted doors for pressure relief on each component in the system.

Blue II was operated for approximately four years on a wide variety of feedstocks. These included bark, sawdust, wood chips, cotton gin trash, various nutshells, automobile shredder wastes and municipal wastes. In each case, significant variations in processing characteristics and in the quality of the different products, char, oil and gas were observed.

In 1971, based on the technology represented by Blue II, Tech-Air Corporation designed two field test units, each with a nominal capacity of 1.8 Mg/hr (2 tons/hr). These systems were built and installed at a peanut shelling plant in Georgia. The two pyrolysis units were operated for approximately one year. The successful operation of these units, although on a test and development basis and using only dry agricultural wastes, resulted in a decision by Tech-Air Corporation to design and build a commercial prototype plant.

The commercial prototype plant was installed in a small lumber mill in Cordele, Georgia, in 1973 and was operated intermittently for approximately two years. During this period, the char was sold to the briquette industry and work was performed on burning the oil on a demonstration basis in several commercial applications.

A third pilot plant, known as Blue III, was designed to handle municipal waste. This plant was constructed and placed in operation in 1974. Since then approximately 59 runs have been made on municipal refuse alone. These runs included light fraction, heavy fraction (with and without metals), whole garbage, sewage sludge blended with light fraction and light fraction blended with shredded tires. These runs demonstrated that the technology developed for agricultural and forestry wastes could be applied successfully to processing municipal refuse and sewage sludge. Work in this area of application is currently continuing, particularly in new product development and the next step for the municipal refuse application is a field test program of at least one year's duration.

In 1975, Tech-Air Corporation became a wholly owned subsidiary of the American Can Company. At that time, two different efforts were initiated to carry forward the work of commercializing the wood waste system and to establish a continuing research and development program at the Georgia Institute of Technology to support the area of waste utilization. First, a six-month program was carried out to upgrade and extend the capacity of the commercial prototype plant at Cordele and to permit a long term, around-the-clock operation. Second, a fourth, smaller pilot plant was constructed for further study and development of the process. This fourth pilot plant was designated Blue IV.

The Cordele plant was operated on a 24-hour day basis for 18 months until June of 1977. All the products, char and oil, produced at Cordele were sold during this period in the bulk char and fuel oil markets.

Process Description

The process flow diagram for a 6.4 dry megagrams-per-hour (7 dry tons-per-hour) wood waste system is shown in Figure 2. The system receives wet waste which has been hogged. The size of the hogged feed is not critical but a maximum particle size of 2.54 centimeters (one inch) is desirable. The hogged wood waste is received in a metering bin which supplies a metered feed rate to the dryer. The dryer operates with some of the gaseous fuel generated in the process and pyrolysis oil can be used as a back-up. The dryer was designed by Tech-Air Corporation and is a compartmented, screw conveyor dryer. The inlet temperature to the dryer operates within the range of 202 to 315^{o}C (400 to 600^{o}F) with a bulk exhaust temperature 55 to 60^{o}C (130 to 140^{o}F). The dryer reduces the moisture content from a nominal value of 50% to a final value below 7%.

The dried feed is conveyed to the storage bin which supplies feed to the pyrolysis unit on demand and provides surge capacity. The dried feed from the storage bin is fed through a rotary airlock into the pyrolysis chamber where it is thermally decomposed into char and hot gas. The char is discharged at the bottom of the unit and the pyrolysis gases flow upward through the vertical bed and exit at the top of the unit. The rate of char discharge controls the throughput rate and a bed height sensing device is used to control the input to the chamber.

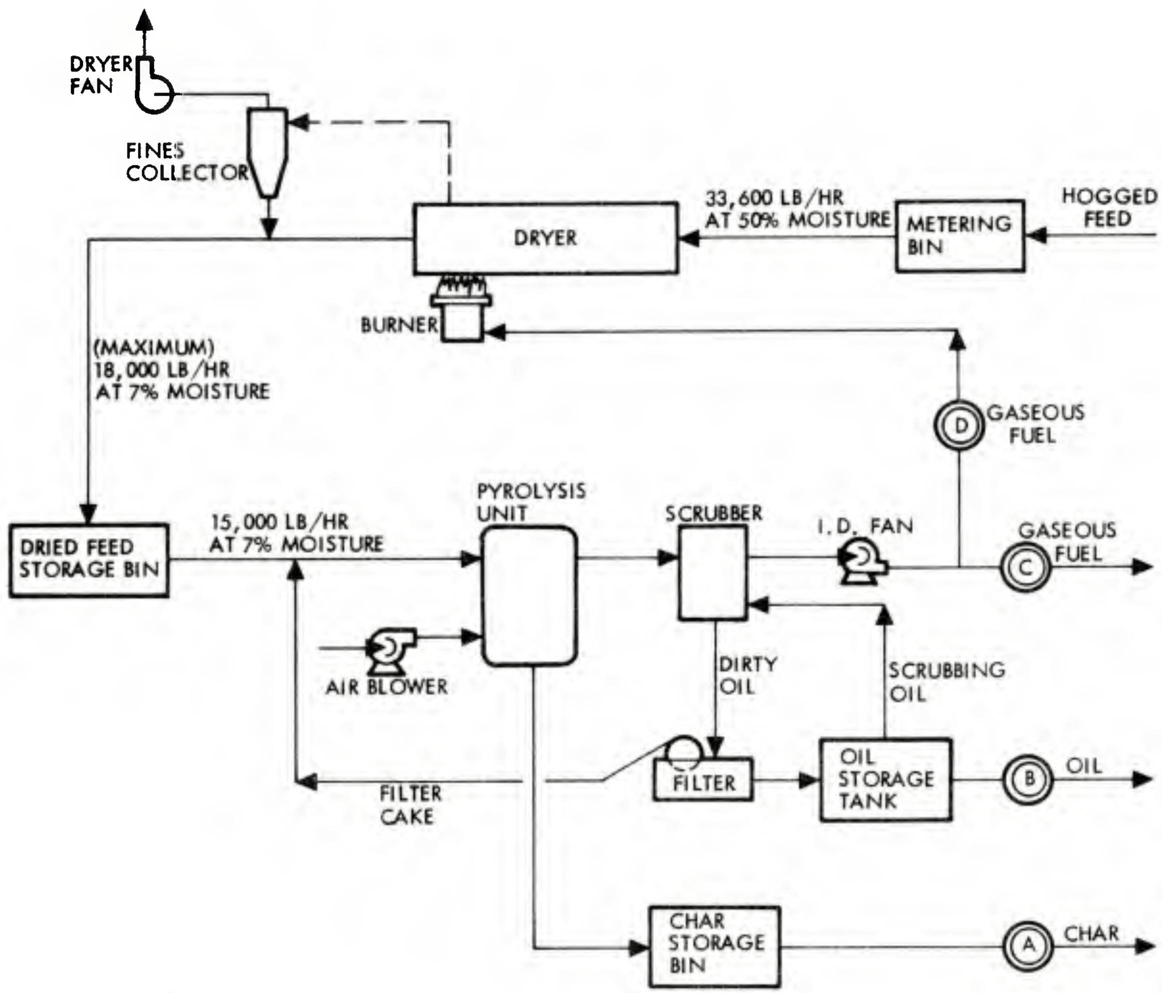


Figure 2. Wood Waste Pyrolysis System - 7 Dry Tons Per Hour

The char is discharged into a sealed conveyor, cooled with a water spray and fed through a rotary airlock into a char conveyor. The char is conveyed to a storage bin from which it is retrieved by gravity flow for subsequent shipment. The char bin incorporates a pressure-relief deck and low pressure, self-closing, relief doors.

The pyrolysis gases leave the top of the converter at a temperature ranging from 176 to 260^{o}C (350 to 500^{o}F) and at a pressure near atmospheric. The gas stream contains non-condensible gases, oil vapors, water vapor and entrained particulates. These gases are immediately sprayed with cooled pyrolysis oil in a scrubber-condenser which serves to remove the particulates and cool the gas stream to a temperature between 82 and 93^{o}C (180 and 200^{o}F). The cooling process is controlled to condense pyrolysis oil and limit the amount of water vapor condensed. The cooled gases flow through a rotary demister which removes the small liquid droplets from the gas stream. The unfiltered pyrolysis oil from the scrubber and demister is discharged through a rotary valve directly into a continuous filter. The filtered oil is pumped to a small holding tank from which the oil is recirculated through a cooler back to the scrubber. As the oil level in the holding tank increases due to condensation, oil is pumped to bulk storage. The filter cake, which has a dry appearance even though it contains about 30% solids, is conveyed back to the input feed system and reinjected into the pyrolysis chamber. Upon reheating of the filter cake, most of the oil is revaporized, but some is decomposed to light gas, water vapor, and char.

The pyrolysis gases leaving the demister contain water vapor and some low boiling point fractions in addition to the non-condensible gases and this mixture is nearly saturated. Hence, it is desirable to use these gases close to the pyrolysis plant.

An induced draft fan controls the pressure in the pyrolysis chamber and directs the flow of gases through the off-gas system from the converter. A portion of the gases leaving the fan are piped to a burner supplying heat for drying the feed. The remainder is supplied to a burner which provides heat for a boiler or other heat device. A flare stack is used to burn the gases during start-up or in case of a rapid change in gas demand.

Material and Energy Balance

The material balance for the 6.4 Mg/hr (7 tons/hr) pilot plant is shown in Table 7. Since the yield of products varies with the air injection rate, three sets of output are shown for the cases of maximum char, maximum oil, and maximum gas.

These results for the pilot plant indicate the weight of char to be 20 to 35% of the weight of the dry input. Similarly, the oil output varies from 22 to 34% and the net gas output from 19 to 51%.

The estimated energy balance for the pilot plant is shown below.

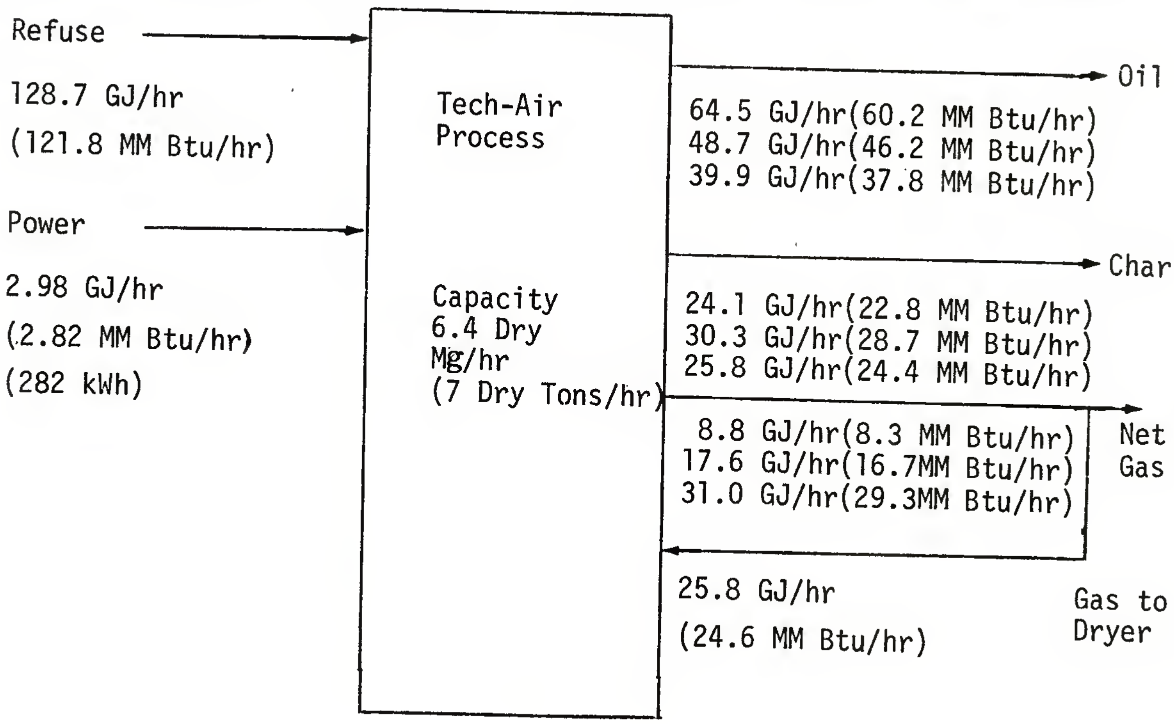


Table 7. Product Mass Balance

Feed = Bark and sawdust
Capacity = 6.4 dry Mg/hr (7 tons/hr)

	Max Char		Max Oil		Max Gas	
Inputs	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr
Organics	6,350	14,000	6,350	14,000	6,350	14,000
H_2O	6,350	14,000	6,350	14,000	6,350	14,000
Air to pyrolysis unit*	1,480	3,274	1,652	3,624	1,620	3,554
Total input	14,180	31,274	14,352	31,624	14,320	31,554
Outputs						
Char	2,220	4,900	1,590	3,500	1,270	2,800
Oil	1,140	2,520	1,430	3,150	1,210	2,660
Net Gas	1,240	2,738	2,200	4,842	3,230	7,118
Total output	4,600	10,158	5,220	11,492	5,710	12,578
Gas to dryer	3,680	8,116	3,232	7,132	2,710	5,976
Moisture removed in dryer	5,900	13,000	5,900	13,000	5,900	13,000
	9,580	21,116	9,132	20,132	8,610	18,976

* Computed as the difference between inputs and outputs.
Air to dryer is not included in inputs or outputs.

The numbers are for 6.4 dry Megagrams (7 dry tons) of input of sawdust and pine bark. No data were available on the electrical power requirements for the Cordele plant. Therefore, estimates prepared by Ralph M. Parsons Co. (ref 8) were used. These estimates are based on the mobile pyrolysis concept which Parsons analyzed and are scaled linearly to the 6.4 Mg/hr(7 tons/hr) plant. A utility heat rate of 10,559 KJ/kWh is used to convert the electrical load to equivalent thermal load.

The thermal efficiency for the system is then calculated, for the assumed power requirements, and is shown below as a function of the oil output. Calculations are made for two cases. The first is strictly on energy balance and assumes oil, char, and gas are equally useable outputs. The second assumes that only the oil is a useful output.

Oil Output			
GJ/hr	MM Btu/hr	η Overall	Oil η Only
64.5	60.2	.73	.47
48.7	46.2	.73	.36
39.9	37.8	.75	.29

The overall efficiency of the Tech-Air process is high compared to the Occidental system. Two facts enter into this: first, the heating value of the sawdust and pine bark (KJ/Mg) is much higher than for municipal garbage requiring less front end processing per given Btu; secondly, the feed material is much coarser and for the same feed stock less grinding energy is needed.

Product Characteristics

Typical data for the pyrolysis oil are presented in Table 8. Note that the moisture content is 26%. Normally, the condensation process is operated to provide oil with a moisture content of about 20%. At 26% moisture, as shown in the table, the heating value is 21,100 KJ/Kg (9081 Btu per pound) which is 60% of the heating value of No. 6 Fuel Oil.

Table 8. Typical Data for Pyrolysis Oil From Pine Bark Sawdust

Item	Value	
Chemical Composition	Wt (%)	
Carbon	49.4	
Hydrogen	4.7	
Oxygen	19.7	
Nitrogen	0.16	
Water	26.0	
Ash	0.04	
Viscosity	mm^2/s	SSU
@ 20^oC (68^oF)	39	276
@ 38^oC (100^oF)	16	114
@ 66^oC (150^oF)	13	90
Higher Heating Value	21,100 KJ/Kg (9081 Btu/lb)	
Density	1180 to 1230 Kg/m^3 (9.88 to 10.27 lb/gal)	
Flash Point (Open Cup)	128 to 151^oC (262 to 305^oF)	
Pour Point	- 16^oC (2^oF)	

The viscosity of the oil can be reduced below 14 mm^2/s (100 SSU) by heating to 66^oC (150^oF). The flash point of the oil places it in the Code 1 category for explosivity. The oil is highly corrosive to mild steel, but the corrosive rate is a fraction of a mil per year for 304 stainless steel and copper.

The use of pyrolysis oil as a fuel has been demonstrated. It also has a potential as a chemical raw material. The oil has been sold commercially for use as a fuel in a cement kiln, a power boiler, and a lime kiln. In the cement kiln several months production from Cordele was fired as a 20% blend with No. 6 Fuel Oil. The remainder of the oil produced has been sold as a fuel which was fired in parallel with several No. 6 fuel oil guns in a power boiler and also directly fired in a lime kiln. Prior to these applications the oil was test fired in a Trane Thermal Vortex burner and at KVB in a test boiler system. The burner used at Trane Thermal performed equally well with air or steam as the atomizing media. The maximum oil pressure required was 120 kiloPascals (3 psig).

The unburned hydrocarbons were measured to be 11 ppm at 6% excess air and the combustion chamber temperature was measured at 1380°C (2520°F). In the tests at KVB the carbon monoxide level was about 15 ppm, and NO_x level was about 110 ppm at 4.5% excess air. The oil, also, has a potential use as a fuel for a hot gas turbine. Research work along these paths is expected to be performed in the near future.

Laboratory investigations indicate that pyrolysis oil has potential as a raw material for the production of phenolic resins and rubber tackifiers. Other research has shown that it may be used as a substitute for wood tars produced by other methods.

Environmental Considerations

Many hundreds of hours of pyrolysis and off-gas combustion have been accumulated on the several units thus far constructed with no visible emissions being noticed under steady state conditions. In an analysis of the stack while wood waste was being used as the feed, Georgia Tech found the following:

Component	Concentration
Oxygen	0.9%
Nitrogen	69%
Carbon Dioxide	7.7%
Carbon Monoxide	30 ppm
Particulates	0.0005 g/Nm^3 (0.0002 grains/SCF)
Hydrogen Sulfide	0.009 ppm*
Nitrogen Dioxide	0.04 ppm*
Ammonia	0.09 ppm*
Sulfur Dioxide	0.4 ppm*

*None detected; value listed as limit of detection.

Such results are to be expected from the combustion of a clean pyrolysis gas. NO_x could be significantly higher if high temperature combustion occurred.

Gaseous and particulate matter could be emitted from the waste introduction and char discharge systems of the pyrolysis converter unless proper valving and pressure differentials are designed into the equipment.

Emissions from the drying system need to be examined for the final dryer-mechanical separator equipment chosen. Wastes containing large quantities of fines could require a fabric filter (bag house) emission control unit and odor levels should be examined in the final configuration. Careful control of excessive temperatures within the dryer should eliminate this potential problem other than with unusual wastes that might contain a high degree of volatile matter.

Through operation of the off-gas condensing system above the dew point temperature of water, no liquid wastes will be formed at the facility. The converter should not be permitted to be washed down onto open ground and the finished product(s) should be protected against leakage by any route into ground water supplies.

Noise power levels below OSHA regulations can be readily obtained through proper design.

Economics

No economic data was available for the Tech-Air stationary pyrolysis plant. An economic analysis of a proposed 181.4 Mg/d (200 TPD) mobile pyrolysis unit was completed by Parsons (ref 7). However, before this mobile unit can be considered ready for the commercial market, several critical technical problems have to be solved.

Parsons, in their economic analysis for the mobile pyrolysis unit, arrive at the following cost estimates:

Item	Original (Prototype)
Major Equipment	
Loader	$18,100
Receiving Bin	3,100
Conveyors (4)	9,100
Hammermill	15,600
Dryer, with Fans	115,000
Converter and Accessories	72,500
Cyclones (2)	15,000
Condenser	8,000
Gas Burner	57,400
Process Air Blower	3,500
Engine-Generator	41,000
Water Radiator, with Accessories	6,300
Char-Oil Mixer	3,400
Control Room	2,500
Engine Blower	2,000
Electrical System	19,000
Instrumentation and Controls	74,200
Trailers (3) Including Catwalks	46,000
LPG System and Controls	5,000
Painting	3,000
Other Equipment	14,200
Material Sub-Total	533,900
Labor Sub-Total	51,000
Sub-Total	584,900

Sub-Total	$584,900
Direct Material	30,000
Labor	20,000
Direct Cost Total	634,900
Engineering	40,000
Total Direct Cost	674,900
Contingency @ 15%	101,200
Freight Allowance	4,000
Grand Total	$780,100

Based on a 10-year useful life and 8.5% interest, the annualized equipment cost is therefore $121,936.

Total costs with no dumping fees or charges for the waste are estimated to be:

COSTS

Capital Amortization	$121,936
Waste	0
Labor	191,280
Maintenance	20,000
Transportation	33,440
Supplies	4,000
	$370,656

This results in a net operating cost of $8.57/Mg ($7.78/ton). For this output, 43,173 Mg (47,600 tons) of waste were processed.

The Enterprise Company's Resource Recovery and Energy Conversion System (ref 10)

History

This process was invented by Mr. Bill Chambers in the early 1970's. Much of the early developmental work was performed by Duke Engineering Company (DECO) of Irvine, California. In 1975 DECO negotiated with Enterprise Company for demonstrating the process on a large scale. While DECO retained the patent rights to the process, Enterprise acquired all of the manufacturing and marketing rights. In later transactions BW Energy Systems Inc. acquired the marketing rights for the area east of the Mississippi River.

Enterprise Company constructed a pyrolysis demonstration plant in South Gate, California. The plant went into operation in June of 1976. The plant has been designed to process 45.4 Mg/d (50 TPD) dry weight of refuse. Since the refuse is of average household quality, this dry weight includes approximately 6% ferrous materials, 0.5% aluminum, 5% glass grit, sand, dirt and other metals, all of which cannot be converted to energy products (oil, gas or char). However, under average economic conditions, they all have a market value and contribute income.

Utilities serving the plant include electric power, gas, water, and a sewage system connection. Natural gas is used to provide the initial heat to start the pyrolytic action in the reactor. Continued heating is maintained by burning either the product gas or char. Because of its site location at an existing refuse transfer station, this particular installation is not enclosed within a building. Depending upon site location, the plant could be partially or entirely housed in a building. Both noise and odor can be effectively reduced to acceptable limits if the plant is contained within a building. Air pollution control devices will be included in the plant design to reduce combustion products to acceptable levels.

Process Description

The plant layout for the system is shown in Figure 3. Refuse collection vehicles dump their loads on a level concrete dumping floor where a front-end loader pushes the waste into a pit. A pit conveyor transports the waste material to another conveyor which carries it to the top of a shredder. Prior to entering the feed chute which leads into the shredder, the waste material passes under a unit called a floating feeder. Its primary function is to provide an even flow into the shredder's hammer area.

The shredder reduces incoming solid waste to less than four inch particle size, after which the processed material is gravity fed into a discharge conveyor. The conveyor transports it to a magnetic separator. After leaving the ferrous metal separation point, the remaining waste stream fraction is transported to a storage module which stores and feeds shredded waste to the continuously operated pyrolysis section of the plant. Shredded waste from the storage module is transported into a dryer. The cylindrical rotating dryers function to reduce the solid waste and sewage sludge moisture content to approximately 10%. Movement through the dryers is by gravity. Hydraulic ram lifts at one end of the dryer automatically adjust the tilt of the rotating drum, thus controlling the feed of the shredded refuse into each reactor's infeed conveyor. Excess heat from the reactor is used to operate the dryers. Moisture-saturated air is vented from the rotating dryers to flue gas scrubbers where the moisture is removed and the clean air exhausted to the atmosphere.

Enclosed steel belted conveyors take the dried waste fraction from the dryers and feed it into the inlet ends of the pyrolytic reactors. Each of these conveyors is equipped with a hydraulically operated ram to ensure even feeding.

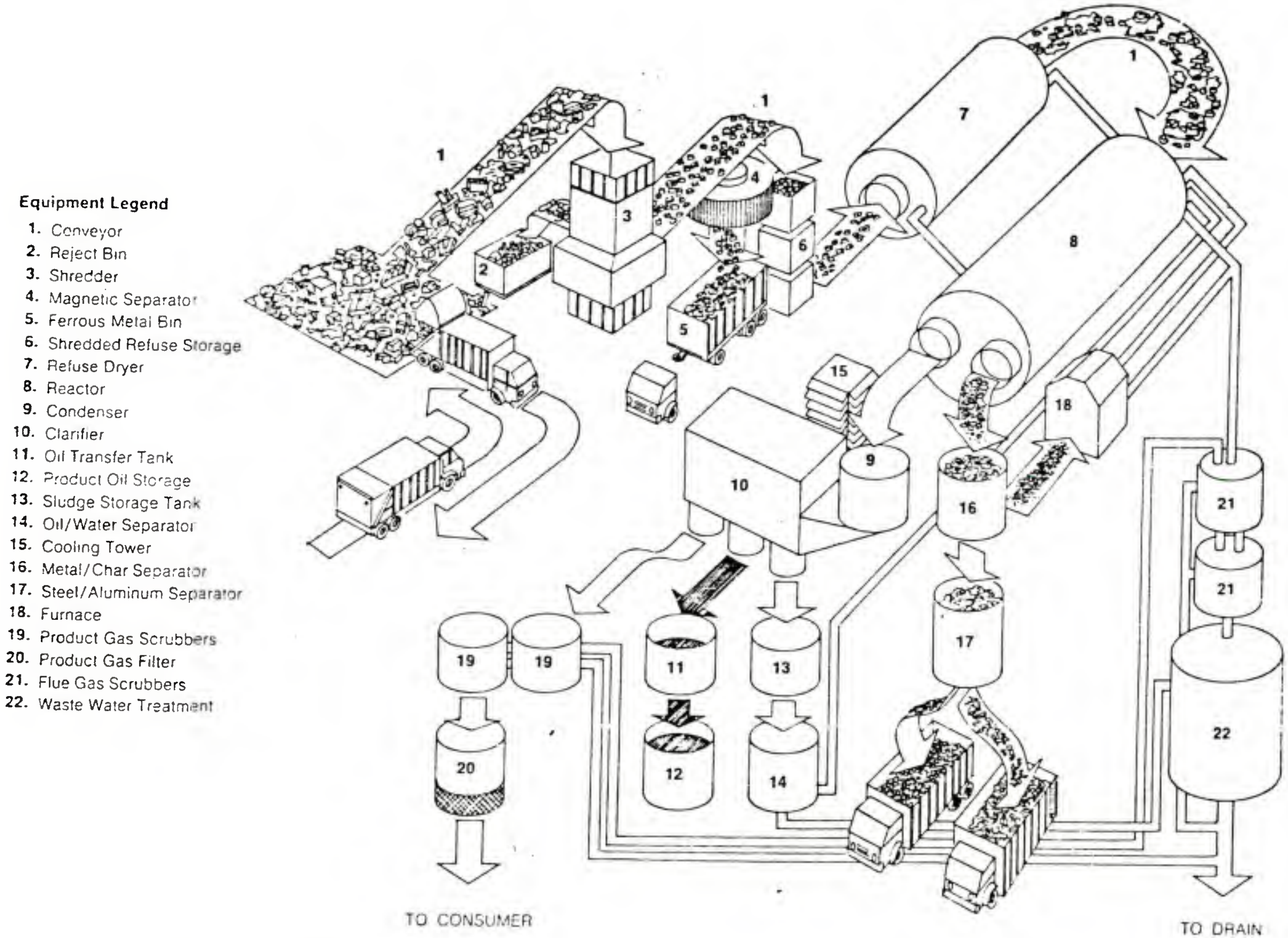


Figure 3. Enterprise Company Resource Recovery and Energy Conversion System

The reactor consists of two coaxial cylindrical chambers with a screwtype conveyor incorporated to transport the shredded waste material through the inner cylinder where it is subjected to controlled temperatures in an oxygen-free environment. This action converts the waste materials liquid and chemical properties into a gaseous state and the remaining material is reduced to a char.

In order to maintain adequate temperatures in the reactor-normal range is 537-782°C (1000-1400°F)- a char and heat processing system is incorporated into the pyrolysis reactor. This part of the system provides for char and metal separation, heat for the reactors and heat for the rotary tumble dryers. Additionally, this part of the system has provisions for cleaning up flue gas emissions to ensure against air pollution.

Materials and Energy Balance

Based on .907 Mg (1 ton), Enterprise Company reported the following yields from municipal garbage:

Separated By-Products	Quantity	GJ	(MM Btu)
Ferrous metals	63.6 Kg (140 lb)	——	
Nonferrous metals	4.5 Kg (10 lb)	——	
Pyrolysis By-Products			
Oil	0.2 Nm^3 (1.25 bbl)	7.0	(6.6)
Gas	160.8 Nm^3 (6000 ft^3)	6.4	(6.0)
Char	181.2 Kg (400 lb)	3.4	(3.2)
	Total:	16.8	(15.8)

Assuming the waste feed stock has the same composition as that in the Occidental process, the yields as a percentage of dry input are:

	Wt (%)
Ferrous metals	7.0
Nonferrous metals	0.5
Oil	20.0
Gas	28.0
Char	20.0

The energy efficiency does not include the electrical power requirements for the process which would reduce the efficiency from that quoted below. The converter efficiency is determined by measuring the Btu content of the waste material entering the pyrolytic converter, the amount of energy used for heating, and the total amount of by-products derived from the converter. They are:

	GJ	MM Btu
Total derived by-products =	16.8	15.8
By-products used for self-heating =	3.7	3.5
Net salable by-products=	13.1	12.3
Waste product input at 14 MJ/Kg (8000 Btu/lb)*	16.9	16.0

Total system efficiency = 13.1/16.9 = 77%

*Since moisture content of the input waste material can vary over a wide range, the Btu content is based upon dry weight of the input material.

Product Characteristics

The oil and gas have been analyzed and typical analyses are shown in Tables 9 and 10.

Table 9. Pyrolytic Oil Comparison

Properties		Flash Pyrolysis[a]		Enterprise Oil[b]	
Sulfur	Wt(%)	0.2		0.23	
Carbon	Wt(%)	57.5		85.34	
Hydrogen	Wt(%)	7.6		11.17	
Oxygen	Wt(%)	33.4		2.22	
Ash	Wt(%)	0.3		0.021	
MJ/kg		24.5		40.3	
Btu/lb		10,500		17,300	
Specific Gravity		1.30		0.9176	
Pour point °C (°F)		32	(90)	-21	(-5)
Flash point °C (°F)		56	(133)	24	(75)
Atomization temperature °C (F)		115	(240)	77	(170)
Viscosity	mm^2/s	141	@ 88°C	6.8	@ 38°C
	SSU	1000	@ 190°F	48.5	@ 100°F

[a] Data source - EPA report SW-80d. 2/Grant No. S-801588/U.S. EPA 1975.

[b] Data source - Performance test/analysis by NAD Industries/James D. Yearout, December 1975.

Table 10. Gas Analysis-Averaged Composition

Component	Mole (%)[a]	HHV	(dry basis)
H_2	10.54	1.35	34.25
CH_4	7.01	2.81	71.08
N_2	8.10	0	0
CO	14.01	0.76	44.97
C_2	16.40	10.45	262.89
C_3	11.04	10.15	258.12
C_4+	13.94	16.45	418.20
CO_2	18.96	0	0
		42.87 MJ/m^3	1089.51 Btu/ft^3

[a] Molecular weight of mixture = 35.33

Environmental

Environmental problems are expected to be similar to those of other systems. The most difficult problem is the high BOD of the waste water which will require water treatment prior to discharge into the enviroment. An analysis of the waste water showed the following:

• Biochemical Oxygen Demand, mg/l	2,400
• Chemical Oxygen Demand, mg/l	2,300
• Oil and Grease, mg/l	37
• pH	6.25

Economic

The following cost estimates, supplied by the Enterprise Company, are not broken down in terms of equipment items, interest, depreciation, maintenance, etc.

Plant Size (Mg/d)	(TPD)	Installed Cost (millions)	Operating Costs ($/Mg)	($/Ton)
136.0	150	6.4	7.40	6.72
181.4	200	7.6	4.44	4.03
362.8	400	9.9	3.47	3.15
544.2	600	14.8	3.03	2.75

Since these operating costs are much lower than those of the Occidental and Tech-Air processes, these may not include all of the factors which Occidental and Tech-Air used; they may also include credit for dumping fees, etc. If the same factors were used as those used to determine the Occidental cost estimates, the following calculated costs would result (calculations are based on 240 operating days per year):

Plant Size Mg/d	TPD	Annual Capital Costs, $(000)	Annual Operating Costs, $(000)	Total Cost $/Mg	$/Ton
136	150	676	874	47.50	43
181.4	200	803	1,019	41.80	38
362.8	400	1,046	1,392	27.60	25
544.2	600	1,564	1,986	26.50	24

Wallace/Atkins Process

History

The Wallace/Atkins process started in the early sixties and has progressed through larger and larger batch processing to a 45.4 Mg/d (50 TPD) plant. This plant was 75% complete in early 1978. The effort has been privately financed up to this point.

Process

The Wallace/Atkins process for the destructive distillation of waste material is a continuous atmospheric pyrolysis process. Waste material is ground to a maximum 10 cm (4 inch) particle size, conveyed to a sealed distillator containing a series of conveyors. The waste is heated by indirect contact with hot air. Solids temperatures range from 342°C (650°F) at the top of the vessel to 538°C (1000°F) at the bottom. Pyrolysis gases are removed, cooled in stages, and the hydrocarbon products recovered. The oil recovered is similar to a Bunker C fuel oil . It can be further cracked to a multitude of products. The gases are treated with a proprietary hydrogenation catalyst, further cooled, and compressed for plant feed uses and for sale as pipeline gas.

The process is described in U.S. Patent 4038152 issued July 26,1977. The patent was filed April 11, 1975. The process described in this patent is shown schematically in Figure 4. No information was available as to the present configuration of the plant. The incoming material is shredded to 10 cm (4 inch) and fed to a storage bin. From there the material is conveyed to the distillator where it travels along a series of conveyors. The waste is dried and pyrolyzed by heat supplied by the combustion gases from the process. Char, metals, glass, etc., drop into the solids collector at the bottom of the distillator where they are removed and separated into various components. The vapors from the distillator flow to an oil settling tank which is maintained above the

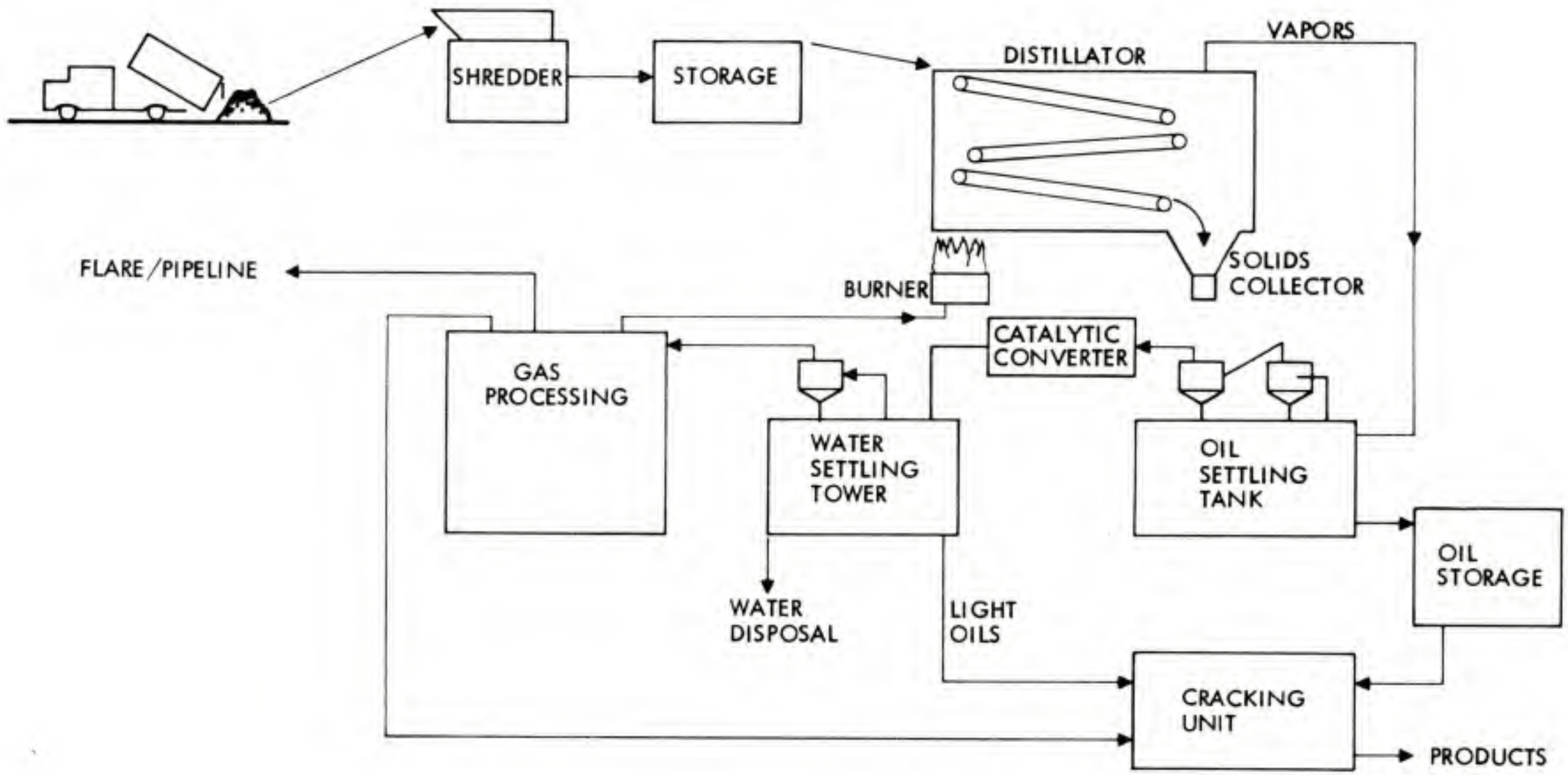


Figure 4. Schematic of Wallace/Atkins Pyrolysis Process

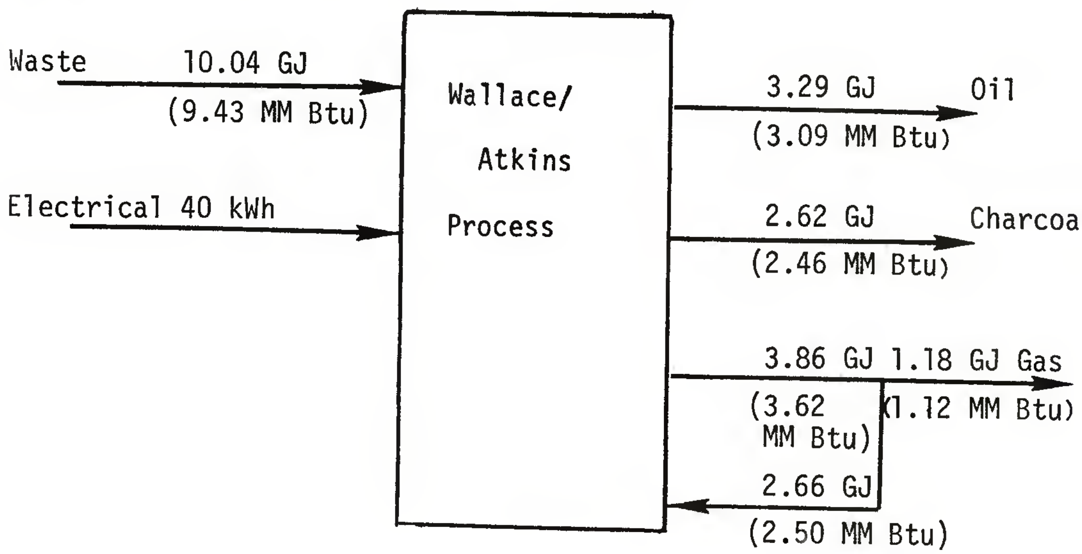
water condensation temperature. From here the gases and water vapor flow through a catalytic converter to a water settling tank which removes water and light oils. The remaining gas is processed to remove condensible components, then it passes to the cracking unit, the burner for the distillator, or to flare or pipeline. The catalytic converter and cracking unit are proprietary and no information is available on their function or performance.

Material and Energy Balance

Tests with batch pyrolysis units show the following distribution of products for an input consisting of 15% tires, 5% wood, and 80% municipal garbage:

Input	Wt(%)	Output	Wt(%)
Organics	67	Metals	11.5
Metals	11	Water	21.8
Water	22	Gas	22.5
		Oil	9.4
		Char	34.8

The energy balance for the same situation is shown below for .907 Mg (1 ton) per hour of dry waste feed.



The estimates for the process heat and electrical load are based on requirements for the Enterprise system, which has a similar pyrolyzer process. The efficiency for the system, assuming a utility heat rate of 10,550 GJ/kWh (10,000 Btu/kWh), is

$$\eta = \frac{7.09 - 0.42}{10.04} = 66\%$$

Product Characteristics

The oil product has been analyzed and the following data reported:

	Pyro Oil	Dehydrated Pyro Oil
Gravity		
Kg/m^3	885.0	853.0
lb/gal	7.4	7.2
Viscosity		
mm^2/s at 38°C	8.1	7.1
SSU at 100°F	57.3	49.9
Heat of Combustion (Gross)		
KJ/kg	will not burn	45,700
Btu/lb	will not burn	19,605
Flash Point		
°C	< 2	-
°F	< 35	-
Water and Sediment		
Wt (%)	11.0	

These data appear to be from a batch process. No data from a continuous process were available.

The pyrolysis gas had the following analysis:

H_2	25.74%	Methane	24.86%
CO	4.36%	Ethane	4.09%
CO_2	16.77%	Propane	0.76%
O_2	3.02%	Butanes +	0.43%
N_2	19.47%	Argon	0.50%

No analysis of the char was available.

Environmental

The following water analysis was reported:

pH	4.03
Biochemical Oxygen Demand, mg/l	36,500
Chemical Oxygen Demand, mg/l	119,079
Total Organic Carbon, mg/l	52,480
Oil and Grease, mg/l	110
Chloride, mg/l	2,000

No gaseous emissions data were reported, but careful design should reduce the emissions to a minimum. Refer to the discussion of the Occidental process for typical values.

Economics

Table 11 shows the cost estimates prepared by Ternion (ref 11) for the Wallace/Atkins process.

Table 11. Economic Data for the Wallace/Atkins Process

	Pyrolysis Plants			Wood Waste Pyrolysis Plants			
	113.5 Mg/d (125 TPD)	227 Mg/d (250 TPD)	454 Mg/d (500 TPD)	45.4 Mg/d (50 TPD)	113.5 Kg/d (125 TPD)	454 Mg/d (500 TPD)	907 Mg/d (1000 TPD)
Capital Cost							
Dump pit and screw feed	$ 5,000	$ 10,000	$ 11,500	$ 3,000	$ 5,000	$ 11,500	$ 17,400
Shredding	182,500	365,000	415,500	52,600	91,250	210,000	318,300
First conveyor	4,000	8,000	9,000	2,300	4,000	9,250	14,000
Storage bin	5,000	10,000	11,500	3,000	5,000	11,500	17,400
Second conveyor	4,000	8,000	9,000	2,300	4,000	9,250	14,000
Cooker	375,000	750,000	1,500,000	125,000	375,000	1,500,000	3,000,000
Magnetic, flotation and other separation	160,000	320,000	367,500				
Char				10,000	17,000	28,000	42,000
Refinery	332,000	664,000	763,000	125,000	332,000	763,000	1,526,000
Oil processing	50,000	100,000	110,000	25,000	43,000	110,000	166,000
Building and other	350,000	525,000	804,000	202,000	350,000	804,000	1,219,000
	1,467,500	2,760,000	4,001,000	550,200	1,226,250	3,456,500	6,334,100
10% Contingency	146,750	276,000	400,100	55,020	122,625	345,650	633,410
	$1,614,250	$3,036,000	$4,401,100	$605,220	$1,348,875	$3,802,150	$6,967,510
Annual Operating Cost							
Labor	$ 224,000	$ 294,000	$ 434,500	$224,000	$ 224,000	$ 364,400	$ 637,700
Overhead	67,000	88,000	130,000	67,000	67,000	109,000	190,750
Feedstock				91,250	228,125	912,500	1,825,000
Utilities and other	102,800	205,600	411,000	41,000	103,000	411,000	822,000
Maintenance	51,500	100,000	200,000	20,000	43,000	173,000	300,000
Depreciation (20 year straight line)	80,700	151,800	220,000	30,300	67,400	190,100	348,500
Interest	129,100	242,900	352,100	48,400	107,900	304,200	557,600
	$ 655,100	$1,082,300	$1,747,600	$521,950	$ 840,425	$2,464,200	$4,681,550

Total Debt Service - 13%

Redker - Young Process (ref 12)

History

This system for the pyrolytic conversion of refuse was developed by Mr. Redker. After about a year of development work on his bench-scale unit, he entered into a contract with Ingham County Board of Public Works (Ingham County, Michigan) to develop a pilot plant. During late 1974 a 36.3 Mg (40 ton) per day pilot plant was constructed and operated in Ingham County. The pilot plant had encountered several major problems and Wheeler Industries had taken over the rights to the process. Wheeler Industries indicated that they had several innovations which they felt would make the process successful, and they were in the process of submitting a proposal to the Department of Energy (DOE) to design and construct a 9.07 Mg (10 ton) per hour demonstration plant.

Process Description

In the Redker-Young Process, incoming waste is preprocessed by conventional machinery which is used for many solid waste systems. First, the waste is shredded and passed through a series of classifiers which sequentially remove ferrous metals, nonferrous metals, and high density material such as glass and stones. The product is then partially dried.

The material is fed into a continuous reactor which has a rotating screw that forces the material along its axis inside a confined cylindrical barrel. As the material waste moves along the screw, it is heated by external heaters and the friction of the screw so that pyrolysis takes place. At several points along the barrel surrounding the screw, taps are provided to remove some of the pyrolyzed products. The solid residue or char is extruded from the end of the screw. The four taps on the barrel correspond to the different zones of pyrolysis, going from gaseous products at the first tap to increasingly heavier liquids along the barrel. The composition of the products from these taps can be varied by adjusting the operating conditions according to the desirability of a particular product. A schematic diagram of the Redker-Young Process is shown in Figure 5.

The operational temperature at which the pyrolytic reaction occurs varies from about 399°C (750°F) at the feed end of the retort to about 649°C (1200°F) at the final vent. The rotating screw which forces the material along its axis is tapered with diminishing flights from the feed opening to the discharge end of the retort. This design enables the process to operate at pressures of 34.5 to 51.6 X 10^6 Pascals (5000 to 7500 psi).

Products

From the limited amount of data available, process samples have shown the following characteristics:

1. The light oil condensate collected from the first two vents was confirmed to contain: 50% saturated straight chain hydrocarbons (C_7-C_{34}), 25% carbonyls (acetone, etc.), aldehydes and organic acids (acetic acid, etc.), 10% straight chain hydrocarbons unsaturated (C_7-C_{34}), 6% esters (acetates, etc.), 6% aromatics (benzene, toluene, etc.), and 2-3% napthanics, vinyl and vinylidene chloride.

2. The heavy oil or tar condensate collected from the third and fourth vents contains the following: 80% carbonyls, 7% hydroxyls (alcohols and acids), 4% saturated straight chain hydrocarbons, 1% unsaturated straight chain hydrocarbons, 1% aromatics and 7% inorganic carbonates.

3. The char residue produced was found to contain more than 80% carbonaceous material, with less than 15% inorganic carbonates, 3% hydroxyls, and 2% saccharides.

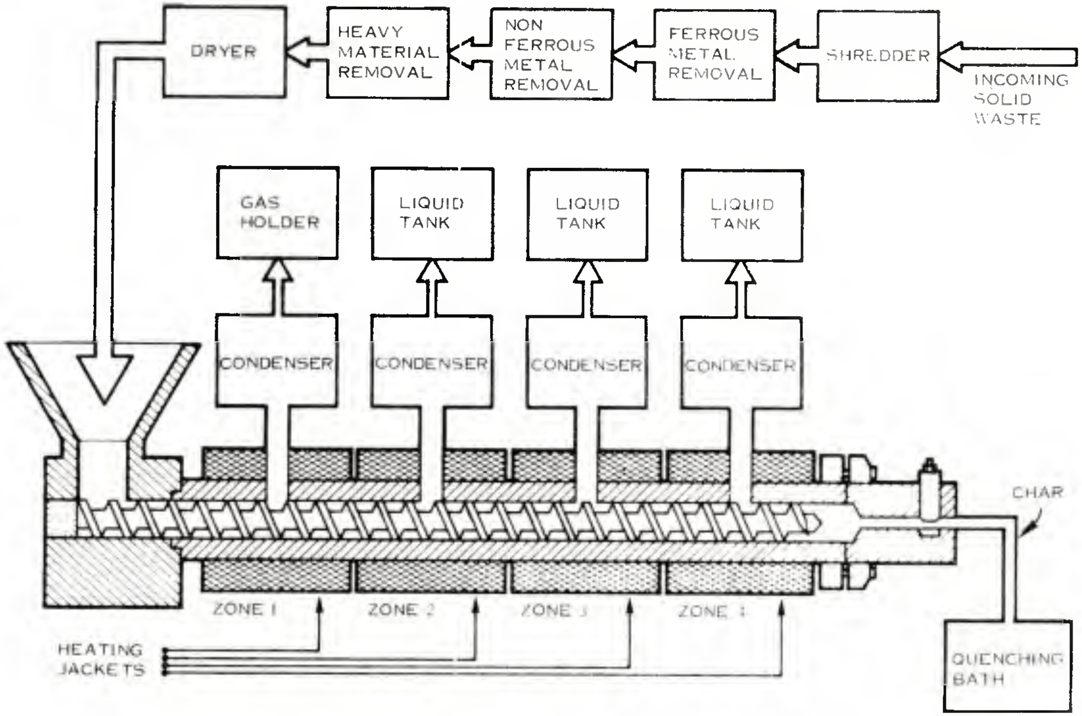


Figure 5. Schematic Diagram of the Redker-Young Process

4. Off-gas contained methane, ethane, and butane.

Both the light and heavy oils have potential for use directly as fuel oils with a consistency of about a #6 fuel oil which is in high demand in all industrial centers. The carbon char can be either briquetted for use as a fuel with a very low sulfur content or as a soil conditioner with the fortification of the ammonia sulfate derived from the scrubbing of the gases. The gases can be used on site for electrical generation or directly in the drying operation.

Information is not available for mass and energy balances, environmental consideration, or for economic analysis.

Comparison of Various Processes

Comparative data for the five systems are shown in Table 12. As seen from column 2, all of the systems except the Tech-Air system were designed for municipal waste feedstock. The Tech-Air system was intended primarily for agricultural by-products such as rice and peanut hulls, wood chips, etc. The differences between the feedstocks are primarily due to the much higher water content of agricultural waste and its relative purity. That is, the agricultural waste does not contain glass, aluminum, steel, tires, refrigerators, etc., as does municipal waste. The differences result in substantial changes in feedstock handling and preparation equipment. Agricultural waste requires much larger drying equipment to remove the excess water. It does not, however, need the extensive size reduction and material separation equipment which are necessary with municipal waste.

It is interesting to note that the organic components, which are pyrolyzed, have very similar elemental compositions for both agricultural and municipal wastes.

The feedstock size and water content entering the pyrolyzer differ somewhat between the processes and depend on the ability of the pyrolyzer

Table 12. Comparison of Pyrolysis Processes

PROCESS	FEEDSTOCK						
	Type	Composition Wt (%)	Organic Elemental Analysis	% H_2O Received	% H_2O Dried	Feed Matl. Size	Separation
Occidental	Municipal Waste	Organics: 57.5 Iron 7.0 Al .7 Other metals .4 Glass 7.6 Misc. solids1.8 H_2O 25	C 44.2 H 5.7 N .7 S .2 O 42.3 CL .2 Ash 6.7	25	3	841 to 44 µm (-20 +325 mesh)	Yes
Enterprise	Municipal Waste	Same as Occidental	Same as Occidental	25	10	< 2.5cm (1-in)	Ferrous Metals Only
Tech-Air, Georgia Tech.	Forest and agricultural waste	Organics: 70-30 H_2O: 30-70	C 49 H 5 N .2 S 0 O 34 CL .2 Ash 11.7	30-70	7-10	< 2.5cm (1-in)	No
Redker-Young	Municipal waste, wood products	Same as Occidental	Same as Occidental	25	6	N.A.	N.A.
Wallace-Atkins	Organic waste, wood tires, coal plastics	Same as Occidental	Same as Occidental	25	Wet O.K.	< 10cm (< 4 in)	Ferrous only

Continued

Table 12. Continued

REACTOR							
Process	Heat Application	Catalytic	Bed Type	Temp °C (°F)	Conditions Pressure	Time	Reactor Materials
Continuous	Char and Combustion gases	No	Entrained bed, vertical	510 (950)	Atm.	4 sec.	N.A.
Continuous	Indirect	No	Moving packed bed, screw feed, horizontal	537-782 (1000-14000)	Atm.	2 hr.	Stainless Steel
	Air blown, Partial Oxidation	No	Vertical bed, gravity feed, counter flow	315-593 (600-1200)	Atm.	N.A.	Refractory Lined Steel Shell
Continuous	Indirect Electrical Heating	No	Moving packed bed, screw feed	399-649 (750-1200)	31.5 to 51.6 MPa	N.A.	N.A.
Continuous	Indirect Combustion gases	Yes	Moving packed bed, traveling grate	342-538 (650-1000)	Atm.	N.A.	Carbon Steel

Continued

Table 12. Continued

PRODUCTS
Product Composition and Heating Value
Char, 20 %, 19,000 KJ/kg (8200 Btu/lb) Oil, 40 %, 24,600 KJ/kg (10,600 Btu/lb) Gas, 30 %, 14.96 MJ/Nm^3(380 Btu/ft^3) Water,10% (40 % organic recovered, as oil, gas and some char process heat)
Gas, N.A., 25.4 MJ/Nm^3 (1000 Btu/ft^3) Char,N.A., 21,800 KJ/kg(9400 Btu/lb) Oil, N.A., 23,200-44,200 KJ/kg (10,000- 19,000 Btu/lb)
Oil, 10-30%, 21,100 KJ/Kg (9100 Btu/lb) Gas, 10-30%, 11.2 MJ/Nm^3 (225 Btu/ft^3) Char, 8-45%, 26,700--31,300 KJ/Kg (12,300--13,500 Btu/lb) (20% H_2O in Oil)
Oil, N.A., 32,400 KJ/Kg (14,000 Btu/lb)
Char, 25-30% 18,500—27,800 KJ/Kg (800—1200 Btu/lb) Oil, 10-30% 27,800—37,000 KJ/Kg (12,000—16,000 Btu/lb) Gas, 35-75% 11.8—23.6 MJ/Nm^3 (300—600 Btu/lb)

to handle foreign material. In the Enterprise system, only ferrous materials are separated initially. Aluminum and glass are separated from the product char by flotation. While not designed for municipal waste, the pyrolyzer section of the Tech-Air system will handle foreign material, but modifications to the feed system would be required for use with municipal waste. The Occidental system uses an entrained vertical pyrolyzer and, therefore, cannot accept foreign material; thorough separation of the feedstock is required prior to introduction into the pyrolyzer. The Redker-Young system is apparently capable of accepting foreign material if the size is small enough to pass through the discharge section of the pyrolyzer. Work on this system is inactive at this time and few technical details were available. The system uses a modified plastic extruder as a pyrolyzer and it appears to have some unique capabilities. The last system listed, the Wallace/Atkins, uses a traveling grate to convey the feedstock through a pyrolyzer furnace. This design permits the use of 10 cm (4 in) sized feedstock with no separation of foreign material.

All processes at this stage of development are continuous feed, although most have evolved through batch reactor designs. Also the pyrolysis temperature is about the same in all processes. The pressure is also atmospheric in all except in the case of the Redker-Young System. Very high compressive pressures may exist in this system. This summarizes the similarities between the processes.

The method of heat application, feedstock movement in the bed, and the residence time in the pyrolyzer are widely different. The Enterprise, Redker-Young, and Wallace/Atkins all use indirect heating. That is, the process heat is transferred to the feedstock material through the walls of the pyrolyzer vessel. Process heat is usually derived from combustion of the product gases and char. At this stage of development, the Redker-Young process uses electrical heating (since it is a modified plastic extruder); however, there appears to be no fundamental reason why product gases cannot be used as the source of heat. The Occidental system may be considered indirect heating in that the heat is transferred to the feedstock from heated ash and char particles entrained with the feedstock in the pyrolyzer.

Heat for the Tech-Air process comes from partial oxidation (within the reaction vessel) of the feedstock. This feature of Tech-Air process makes this system similar to an air-blown gasifier rather than a pyrolyzer.

Residence time depends on the process method of heat application and varies from a few seconds, as in the Occidental flash pyrolysis process, to several hours as required by the indirect heating processes.

The method of heat application affects the choice of material for the reactor. When indirect heating is used, the pyrolyzer walls must transfer the heat to the feedstock, while resisting corrosion from chlorine in the wastes. Hydrogen embrittlement may also be a problem. The gasifier or direct heat processes, on the other hand, have much less severe materials problems. The reactor may be refractory lined and made of mild steel. The refractory must be replaced periodically, but overall, costs are usually lower than for the indirect processes.

Product distribution appears not to differ much between the processes, but is influenced by the time, temperature, and pressure of the pyrolysis reaction. The primary effect is that of temperature. High temperatures result in more gas and less oil and char production. Most processes use much of the gas and perhaps part of the char to produce the process heat. The only products which may be sold as a process product are the oil and some of the char unless an on-site use for the excess gas is available.

The oil has a heating value of 23,200 to 37,100 KJ/kg (10,000 to 16,000 Btu/lb) which is strongly influenced by the amount of water in the oil. Even though water lowers the heating value, it is desirable since it also lowers the viscosity of the oil. Because the oil is quite viscous, it may solidify if it is stored for long periods of time.

Pyrolysis Products From PEP-Contaminated Waste

Knight and Elston (ref 6) conducted a pyrolysis test on waste contaminated with TNT to simulate the type of wastes expected at different AAP's. The tests were conducted in a heated bomb and the results should be similar to those obtained in a full scale pyrolysis plant. The results taken from Reference 6 are shown in Table 13.

The results of these tests show that the oil yields are around 15% of the original dry weight of the feed material while the char yields are around 27% and gas yields are 21 to 26%. These results agree quite closely with those reported for the various systems.

System Selection Criteria

Examination of the system characteristics and the results reported for actual pyrolysis of PEP-contaminated waste indicate that all systems are suitable for this application, although some questions still must be answered about the grindability of the waste. In selecting the pyrolysis system most suitable for application to PEP-contaminated waste, five additional factors seem appropriate to consider. The relative importance of these factors is a judgemental decision, and the weighting selected here represents the combined judgement of the preparers of this study. The factors are:

1. Environmental Impact: Prior methods of disposing of PEP-contamined waste by open pit burning were relatively safe and cost effective. However, air quality standards are making this type of disposal less acceptable and, in fact, it may be banned by legislative action in some areas.

2. Energy Recovery: If energy recovery were not desired, incineration of waste would be environmentally acceptable. Recovering oil from the waste is a very appealing concept. This reduces foreign oil dependence. In times of national emergency when foreign oil may not be available every source of oil becomes of prime importance.

Table 13. Mass and Energy Balances*

	Run No. 1			Run No. 2			Run No. 3			Run No. 4		
	% (wt)	Kg/Kg	KJ/Kg	% (wt)	Kg/Kg	KJ/Kg	% (wt)	Kg/Kg	KJ/Kg	% (wt)	Kg/Kg	KJ/Kg
Inputs												
Feed		1.00	17,700		1.00	17,700		1.00	17,700		1.00	17,700
TNT		0	0		0.005	77		0.01	154		0.02	308
Total		1.00	17,700		1.005	17,777		1.01	17,854		1.02	18,008
Yields												
Char	26.1	0.261	8580	26.9	0.269	8530	27.3	0.273	8960	27.1	0.271	8930
Heavy Oil	14.2	0.142	4340	11.2	0.112	3530	13.5	0.135	4140	14.4	0.144	4450
Light Oil	1.6	0.016	515	2.2	0.222	940	1.7	0.017	528	1.6	0.016	524
Water	32.1	0.321	--	31.6	0.316	--	31.6	0.316	--	29.9	0.299	--
Gases	21.1	0.211	2340	25.0	0.250	2915	26.9	0.269	3420	26.0	0.260	3290
Latent Heat	--	--	724	--	--	712	--	--	712	--	--	672
	95.1	0.951	16,499 (93.3%)	96.9	0.969	16,627 (93.8%)	10.10	1.010	17,760 (99.4%)	99.0	0.099	17,866 (99.3%)

*Basis on lb dry feed.

Kg/Kg expressed as Kg input on yield per Kg of dry feed

KJ/Kg expressed as KJ per Kg of dry feed

3. Technical Development: Since there is an urgent need for the process, long research and development (R & D) periods would not be acceptable. Therefore only those systems which are in an advanced state of development were considered.

4. System Economics: Cost information is necessary in order to perform an economic evaluation of pyrolysis (p. 66).

5. Engineering and Construction Time: This factor is important in that the demonstration needs to be timely. Even if the technology is demonstrated, if excessive scaling and construction times are involved the timeliness of the project may be impaired.

Table 14 shows the rating of the candidate systems using the previously discussed criteria. The results of this rating may be summarized as follows:

1. The Occidental and Enterprise systems are acceptable except for the high cost. Final selection between these should be based on lowest cost, performance guarantees, and delivery schedules.
2. Tech-Air stationary system as tentatively considered is acceptable in all categories except cost. There is no cost data available at this time, therefore it cannot be considered fully acceptable.
3. Tech-Air mobile unit is attractive from the lowest cost point of view. If technical development improves it should also be considered.
4. The Wallace/Atkins and Redker/Young systems are unacceptable.

Table 14. System Selection Criteria

	OCCIDENTAL	ENTERPRISE	TECH AIR		WALLACE/ATKINS	REDKER/YOUNG
			Stationary Plant	Mobile Unit		
Environmental Impact	Gaseous Emission - Controlled by afterburner and bag house. Waste Water - Requires treatment. May be possible to after burn entire stream. Rating - Acceptable.	Gaseous Emissions - Cyclones remove particulates. May require improvement to control fugitive emissions. Waste Water - Requires treatment. High BOD and COD. Rating - Acceptable	Gaseous Emissions - No control used on Cordele plant. May require bag house for fines control. Waste Water- No water streams exist. Operation at temperatures above dew point prevent condensation Rating - Acceptable		Gaseous Emissions - Cyclones remove particulates - no other data available. Waste Water - Will require water treatment. High BOD and COD. Rating - not rated for lack of data.	Data not available (N/A) Rating - Not rated
Energy Recovery	35.6% (MSW) Rating - Acceptable	40% (MSW - does not include electrical load) Rating - Acceptable	29 - 47% (Wood Waste) Rating - Acceptable		33% (MSW) Rating - Acceptable	N/A - Should be similar to Enterprise add Wallace/ Atkins Rating - Not rated.
Technical Development	181.4 Mg/d (200 TPD) plant at EL Cajon, Ca. starting up. Rating - Acceptable	45.4 Mg/d (50 TPD) plant at South Gate, Ca. operating since ' 76 Rating - Acceptable	6.4 Mg/hr (7 ton/hr) Demonstration plant at Cordele, Ga. Rating - Acceptable	.907 Mg/hr (1.0 ton/hr) Pilot plant at Georgia Tech. Not considered commercial. Rating - Insufficiently developed	45.4 Mg/d (50 TPD) plant at Houston, Texas. Not operational at this time. Rating - Insufficiently developed	Pilot plant only. Rating - Insufficiently developed.
System Economics for 45.4 Mg/d (50 TPD)	$ 4.7 million (MSW) $ 2.0 million wood waste Cost is high but probably firm.	$ 4.1 Million Cost is high but probably firm	Data not available	$0.4-0.8 million Rating - Excellent, cost will probably increase with commercial development	$0.6 million Subject to change as more experience is gained.	not available
Time for 45.4 Mg/d (50 TPD) unit on-line	Reworking to scale down needed. Rating - Acceptable	45.4 Mg/d (50 TPD) unit in operation. Will need evironmental control equipment. Rating - excellent	Rating - Acceptable	Rating - Unacceptable, considerable engineering R & D needed to bring on-line.	Rating - Unacceptable, completion of Texas plant could change this.	Rating - not rated.

COST DATA FOR A 4.5 Mg/d (5 TPD) PILOT PLANT

Personnel connected with the candidate systems were reluctant to discuss costs on such a small unit. However, both Enterprise and Tech-Air agreed to work up a rough estimate of costs for a 9.07 Mg/d (10 TPD) and a 6.4 dry Mg/d (7 dry TPD) pilot plant, respectively. Only Enterprise responded.

For the Enterprise - Resource Recovery and Energy Conversion System, the capital costs are:

Capacity		Capital Cost
Mg/d	TPD	$
9.07	10	1,598,000
45.4	50	4,250,000

Purchase proposals for these plants were submitted by BW Energy Systems Inc. They would not furnish operating costs for these plants; however, the costs for the 9.07 Mg/d plant breaks down into the following:

Front-end	$ 785,000
Back-end	$ 813,000
Total:	$1,598,000

The front-end includes the shredder, magnetic separator, conveyors, and storage tank, while the back-end includes the dryer, reactor, furnace, non-ferrous separator, scrubber, and water treatment.

For Army application, the metals separating steps would probably not be required. This reduces the cost by $105,000 or a final cost of approximately $ 1.5 million. If the Army were to order this system, it would take six (6) months for the system to be installed and operating from the time the contract was signed.

Since costs for a 45.4 Mg/d (50 TPD) unit are only a little over 2.5 times greater while the capacity is five times greater, it appears to be much more cost effective to consider a 45.4 Mg/d (50 TPD) unit rather than a 9.07 Mg/d (10 TPD) unit. Further, since 45.4 Mg/d modules are engineered and in operation, re-engineering to smaller size may involve added technical problems. Also a 45.4 Mg/d plant will be more than sufficient to handle the solid wastes generated at any AAP, even under mobilization conditions.

ECONOMIC ANALYSIS OF PYROLYSIS UNDER CURRENT AND MOBILIZATION PRODUCTION LEVELS

Much remains to be accomplished in pyrolysis technology before accurate economic analysis can be performed. Only the Occidental Flash Pyrolysis, Tech-Air, and the Enterprise systems have been run on a pilot or demonstration size plant. No commercial size plant has been built and until this occurs, economic projections are only speculative. Another difficulty involves the manner in which the various process promoters calculate the economics. There is a great variety of credits that can be claimed for fuel value, materials, and charge mode for waste disposal. Proper selection of values can tend to favor a particular system.

For the Occidental Flash Pyrolysis System, the reported capital costs are:

Capacity		Capital Cost
Mg/d	TPD	
907	1000	28,6000,000
1814	2000	43,000,000

In Figure 6, these values are plotted in terms of absolute capital cost versus daily unit weight. The dashed line represents the function

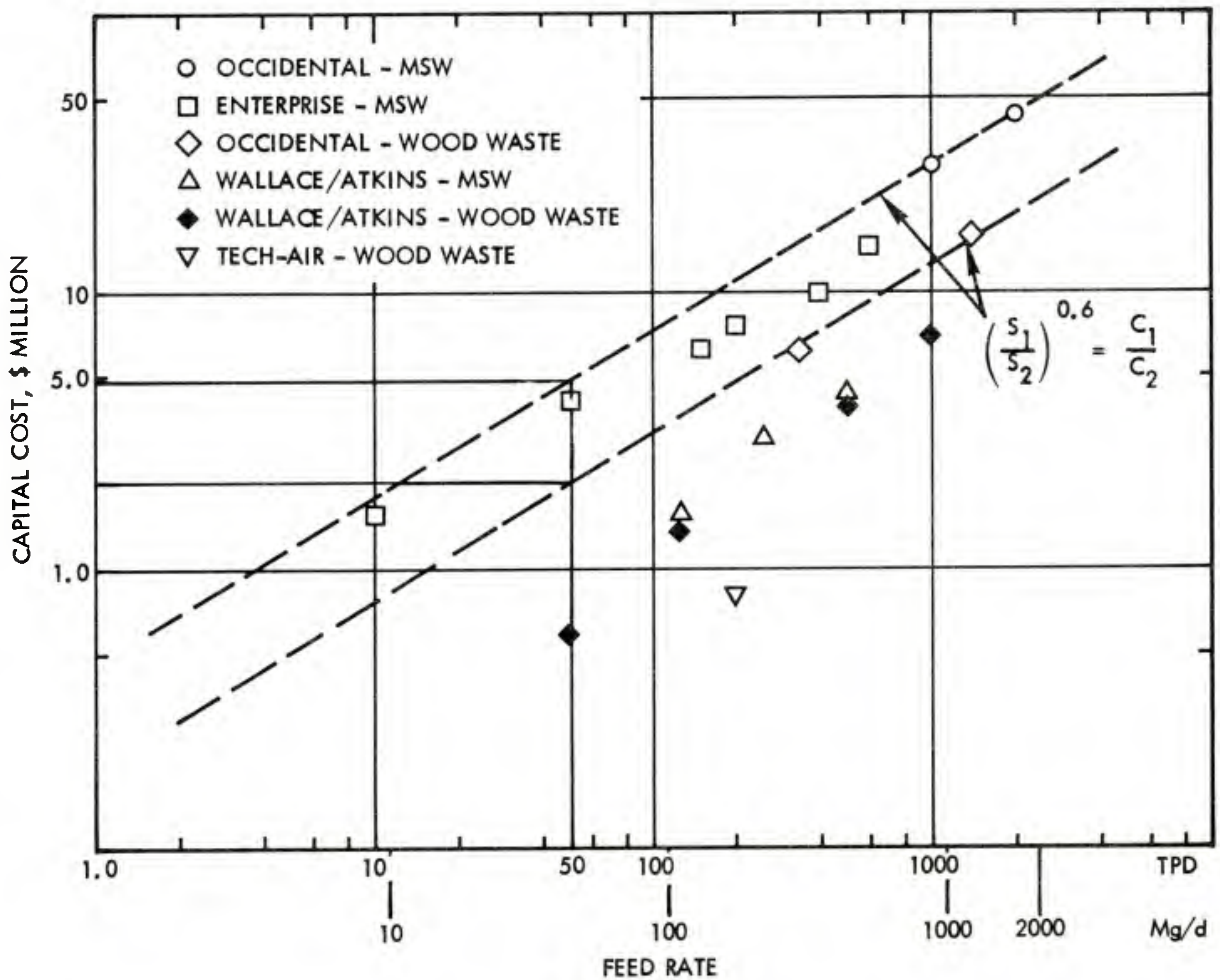


Figure 6. Capital Costs vs Capacity of Pyrolysis Facilities

often found to describe capital costs, where these costs are proportional to the 0.6 power of the capacity. In the equation, S_1 and S_2 are the sizes of two plants having costs of C_1 and C_2, respectively. The 0.6 exponent capacity cost curve will serve to estimate plants until more operating experience is obtained.

Occidental (ref 13) also performed some pyrolysis of industrial wastes for oil. Economic projections showed that a 1090 dry Mg/d (1200 dry TPD) and a 272 dry Mg/d (300 dry TPD) tree bark conversion plant could be built for $13.3 million and $4.96 million, respectively. These costs are based on February 1974 levels. By using the Chemical Engineering (CE) plant cost index these figures updated to 1977, become $16.5 million and $6.13 million, respectively. If it is assumed that AAP solid waste contains 15% moisture, these costs would correspond to capacities of approximately 1270 Mg/d and 313 Mg/d (1400 TPD and 345 TPD) These values are plotted in Figure 6 and, again, the dashed line represents the capital cost where the costs are proportional to 0.6 power to capacity.

Also plotted in Figure 6 are cost estimates for various capacity plants for the Enterprise and Wallace/Atkins systems. Only the cost estimate for a Tech-Air mobile pyrolysis unit is available at this time. They have promised to send cost estimates to TRW in the near future on the stationary systems. As shown in the figure the Occidental and the Enterprise systems seem to be fairly close to each other in costs. The Wallace/Atkins costs tend to be much lower. Figures for the Occidental and Enterprise systems have a sounder foundation because these figures were projected from large pilot or demo plants. As far as costs go, the Tech-Air mobile unit looks very promising; however, there still are some critical technical problems that have to be solved before this unit can be considered ready for the commercial market.

The cost benefits of a pyrolysis system may be examined by looking at the projected oil production and costs for the two largest plants, Holston and Iowa. Since the mobilization waste levels of these plants are near the 45.4 Mg/d (50 TPD) size, which is considered commercial, comparisons will be made for this size pyrolysis plant. Using the 0.6 exponent capacity cost curves (Figure 6), the estimated cost for this plant ranges from $2-4.8 million. Capital cost for an Enterprise 45.4 Mg/d plant are $4.1 million (Appendix).

Table 15 shows that the mobilization waste levels are 34.5 and 24.26 Mg/d (38 and 27 TPD) for the Holston and Iowa plants, respectively. The normal levels are 12 to 30% of this. The annual revenue for the Holston plant varies from $14,196 to $233,896 depending on the conditions and the cost of crude oil and revenues for the Iowa plant vary from $23,660 to $164,944. The savings incurred by not incinerating this waste result in additional cost savings of $130,000 and $126,000 respectively.

Using a capital cost of $4.1 million for the Enterprise plant, the net operating costs for the 45.4 Mg/d (50 TPD) plant are estimated to be:

Capital Costs (@ 8.5% interest, 20 years)	=	$ 433,291
Labor (2,240 hr/yr)($7.00/hr)(13 people)	=	204,000
Electricity (50 kWh/ton)(9,100 tons/yr)($.02/kWh)	=	9,100
Insurance - 0.75% of plant investment	=	30,075
Taxes - 0.75% of plant investment	=	30,075
Maintenance - 5% of plant investment	=	205,000
Total Annual Cost	=	$ 911,541

These assumed costs are normal to a commercial operation. If no charges are made for interest, insurance, and taxes, the costs are reduced to:

Capital costs (20 year depreciation)	=	$ 205,000
Operating costs	=	418,100
Total Annual Cost	=	$ 623,100

Table 15. Pyrolysis Oil Production for Holston and Iowa AAP's

Waste Category	HOLSTON				IOWA			
	Normal		Mobilization		Normal		Mobilization	
	Mg/d	TPD	Mg/d	TPD	Mg/d	TPD	Mg/d	TPD
PEP	0.18	0.2	1.8	2.0	2.49	2.75	7.48	8.25
PEP-Contaminated	1.0	1.1	10.0	11.0	.45	0.5	1.36	1.50
Non-Contaminated	3.0	3.3	22.7	25.0	3.99	4.4	15.42	17.0
Total Solid Waste	4.18	4.6	34.5	38.0	6.93	7.65	24.26	26.75
Total Energy[a]								
10^9 Joule		74.8		617.9		124.4		434.9
10^6 Btu		70.8		585.2		117.8		411.9
Oil Produced[b]								
m^3/Day		0.66		5.5		1.11		3.87
BBL/Day[c]		4.2		34.6		7		24.4
m^3/Yr[d]		173.6		1,430		289.4		1,008.7
BBL/Yr		1,092		8,996		1,820		6,344
Revenue/Yr								
@ \$81.76/m^3 (\$13/BBL)		14,196		116,948		23,660		82,472
@ \$163.52/m^3 (\$26/BBL)		28,392		233,896		47,320		164,944

[a] Heating value 17,925 KJ/kg (7,700 Btu/lb) as received.

[b] Assume pyrolysis system converts 35% of total energy to oil and crude equivalent = 39.15 x 10 Joule/dm^3 (5.9 x 10^6 Btu/BBL).

[c] Barrel (oil) = 42 gal.

[d] 260 operating days per year.

It is apparent that the 45.4 Mg/d (50 TPD) pyrolysis plant will not generate enough revenue to make it economically attractive, even under mobilization conditions. The price of oil would have to reach approximately $55 per barrel in order that the revenue generated by the plant equal the total annual cost minus the incineration offset costs.

CONCLUSIONS

Based on the study conducted, the following conclusions are made:

1. Technically any of the five candidate processes can accept PEP-contaminated waste.

2. PEP material would have to be wet-ground and water-slurried before mixing with shredded waste.

3. Additional work is needed to determine if PEP-contaminated waste can be safely shredded dry.

4. The Occidental and Enterprise systems are acceptable from the standpoint of environmental impact, energy recovery, technical development, and time required for engineering and installation; costs, however, are high.

5. The Tech-Air stationary system looks attractive for this application but could not be considered because an economic analysis could not be performed due to lack of cost data.

6. Tech-Air mobile system is very attractive on a cost basis, but needs technical development.

7. A 45.4 Mg/d (50 TPD) unit would be more than sufficient to process all the solid waste generated at any of the AAP's studied, even under mobilization conditions.

8. Under mobilization conditions at Holston, the equivalent of approximately 9,000 barrels of oil could be produced annually. At $13 per barrel this amounts to $117,000 a year. Even with the avoidance of incineration costs ($130,000) this would not offset the annual costs for a 45.4 Mg/d (50 TPD) plant of approximately $623,100. It can, therefore, be concluded that even under mobilization conditions, pyrolysis is not currently economically viable.

RECOMMENDATIONS

1. The low costs projected for the Tech-Air mobile system are so attractive that the technical development of this process should be followed. If it becomes commercially available at the prices quoted, it would be the most cost effective system.

2. An economic analysis of the Tech-Air stationary system should be carried out when cost information becomes available for the system.

3. Further experimental work is needed to determine how to shred the PEP-contaminated waste safely and how to feed the water slurried PEP waste into the pyrolysis system efficiently.

4. Alternate energy recovery methods should be examined on a site-by-site basis to determine if more cost effective methods for waste disposal and energy recovery are feasible. In particular, waste heat furnaces and fluidized bed combustors with energy recovery systems such as gas turbines or steam generators should be examined. If there is an on-site use of the steam or electric power these might be very attractive systems.

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