**PROSPECTS FOR PYROLYSIS TECHNOLOGIES
IN MANAGING MUNICIPAL, INDUSTRIAL, AND DOE
CLEANUP WASTES**

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Preface

This report on the status and potential of pyrolysis technologies was prepared by Dr. Sheldon Reaven from the State University of New York at Stony Brook's Waste Management Institute and College of Engineering for the Northeast Waste Management Enterprise (NEWME). NEWME is a new kind of partnership between industry, federal laboratories, and universities formed to increase the economic, commercial, and environmental effectiveness of solid-waste management through implementation of new technology, and to foster the emergence of a U.S. waste management industry more competitive internationally. With initial funding from the U. S. Department of Energy (DOE), NEWME is managed by the Long Island Research Institute, in cooperation with Brookhaven National Laboratory.

Of particular interest to NEWME are problems related to solid-waste management in areas of high population density, and problems associated with DOE's waste management and environmental clean-up programs. Pyrolysis is one of the initial technologies chosen for consideration, and Professor Reaven's report provides ample justification for its inclusion. Pyrolysis is a technology that has wide applicability, but whose potential often has been overlooked. The analysis and recommendations in this report will lead to the next steps in the NEWME process. NEWME expects to invite companies to present specific proposals for pyrolysis projects on Long Island. The issues to be addressed in NEWME's review of such specific proposals include: costs, revenues, and financing for the pyrolysis system versus competing technologies, relevant regulatory and local government concerns (including implications of the recent Supreme Court decision on incinerator ash); and overcoming barriers to commercializing the technology. After weighing the relative merits of the different pyrolysis systems in light of these issues, NEWME will make the final decision whether to proceed with a demonstration project.

The characterizations of pyrolysis technologies contained in this report and the recommendations are those of the report's author, and do not necessarily reflect the positions or policies of NEWME, the Long Island Research Institute, or Brookhaven National Laboratory.

Summary

Pyrolysis converts portions of municipal solid wastes, hazardous wastes, and special wastes such as tires, medical wastes, and even old landfills into solid carbon and a liquid or gaseous hydrocarbon stream. Pyrolysis heats a carbonaceous waste stream typically to 290 - 900°C in the absence of oxygen, and reduces the volume of waste by 90% and its weight by 75%. The solid carbon char has existing markets as an ingredient in many manufactured goods, and as an adsorbent or filter to sequester certain hazardous wastes. Pyrolytic gases may be burned as fuel by utilities, or liquefied for use as chemical feedstocks, or low-pollution motor vehicle fuels and fuel additives.

In the past 20 years, advances in the engineering of pyrolysis systems and in sorting and feeding technologies for solid waste industries have ensured consistent feedstocks and system performance. Several vendors offer complete pyrolysis systems with performance warranties.

This report analyzes the potential applications of pyrolysis in the Long Island region and evaluates for the four most promising pyrolytic systems their technological and commercial readiness, their applicability to regional waste management needs, and their conformity with DOE requirements for environmental restoration and waste management. This summary characterizes their engineering performance, environmental effects, costs, product applications, and markets.

After evaluating the economics of specific proposals for applications of these pyrolysis systems in the region, NEWME may develop a tactical plan to demonstrate and commercialize this technology for regional waste management and for DOE environmental restoration programs. Because it can effectively treat those wastes that are inadequately addressed by current systems (e.g., tires, medical wastes, automobile shredder fluff, unrecycled plastics, food wastes, and hazardous organic wastes), pyrolysis can play an important complementing role in the region's existing waste management strategy. Its role could be even more significant if the region moves away from existing commitments to incineration and MSW composting. Either way, Long Island could become the center for a pyrolysis-based recovery services industry serving global markets in municipal solid waste treatment and hazardous waste cleanup.

Important Note: During the preparation of the final draft of this report, the United States Supreme Court ruled, in Carbone vs. Clarkstown, that typical municipal flow-control ordinances are illegal. Such measures have required private waste haulers to bring wastes they collect to recycling, incineration, or landfilling facilities designated by the municipality. Proponents say that flow control undergirds the economic viability of these facilities; opponents say that it stifles competition. The court also decided, in EDE vs. Chicago, that incinerator ash must be tested to determine whether it should be treated as hazardous waste. Pending Congressional legislation and further court decisions may affect the movement of garbage across state lines. While it is too early to sort out their specific ramifications, all of these developments are likely to generate pressure for new arrangements for managing Long Islands wastes. This could widen the window of opportunity for pyrolysis.

Glossary

ABS	acrylonitrile butadiene styrene	NYSDEC	New York State Department of Environmental Conservation
ANL	Argonne National Laboratory	NYSERDA	New York State Research and Development Authority
APC	American Plastics Council	ONP	old newspaper
BNL	Brookhaven National Laboratory	PAR	Pan American Resources
Btu	British thermal unit, the quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit	PCB	polychlorinated biphenol
BUD	beneficial use determination	PE	polyethylene
CAAA	Clean Air Act Amendments	PET	polyethylene terephthalate
CFC	chlorofluorocarbon	PMMA	polymethyl methacrylate
CRADA	Cooperative Research and Development Agreement	PP	polypropylene
DOD	U.S. Department of Defense	PS	polystyrene
DOE	U.S. Department of Energy	PUR	polyurethane
EP Toxicity	Extraction Procedure Toxicity Test	PURPA	Public Utilities Regulatory Policy Act of 1978
ER/WM	Environmental Restoration\ Waste Management	PVC	polyvinyl chloride
HDPE	high-density polyethylene	RCRA	Resource Conservation and Recovery Act
HGR	hydrogasifier	RD&D	research, development, and demonstration
HIC	high impact container	RDF	refuse-derived fuel
HCFC	hydrochlorofluorocarbon	RFP	request for proposals
ISTEA	Intermodal Surface Transportation Efficiency Act	SARA	Superfund Authorization Renewal Act
LDPE	low-density polyethylene	SNGL	stripped natural gas liquid
LIRI	Long Island Research Institute	SPR	steam pyrolysis reactor
LIRR	Long Island Rail Road	SWMP	Solid Waste Management Plan
LLDPE	linear low-density polyethylene	TDF	tire-derived fuel
MRF	municipal recycling facility	TRI	Toxics Release Inventory
MSW	municipal solid waste	U.S. EPA	U.S. Environmental Protection Agency
MTBE	methyl tertiary butyl ether	VOC	volatile organic carbon
NASA	National Aeronautics and Space Agency	WSDOE	Washington State Department of Ecology
NEWME	Northeast Waste Management Enterprise		

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PART I

BACKGROUND ON PYROLYSIS TECHNOLOGIES

I.1 Plan of the Report

(a) Introduction

Pyrolysis is a versatile technology that can convert many components of ordinary municipal solid waste (MSW), many kinds of hazardous organic industrial wastes and pollutants, and certain "special" wastes, such as tires, hospital wastes, and old landfills themselves, into hydrocarbon vapors and/or liquids, and into solid carbon. Waste volumes typically are reduced by some 90%, weights by some 75%. The hydrocarbon products readily can be recycled into new consumer products or made into fuels for transportation (including low-emissions methanol or oxygenated gasoline), electricity generation, and residential and commercial heating. The solid carbon products have broad applications as a substitute for coal, as an ingredient of manufactured goods (including secondary materials), and as filters that can prevent and reduce pollution from hazardous wastes.

What products are made, and their quality, depend on what wastes are processed and on the engineering design of the pyrolysis system. That system has three elements: preparation of feedstocks, the pyrolytic reactions themselves, and processes that turn the outputs from pyrolysis into value-added products.

Suitably configured pyrolysis systems can play a very significant regional role in (i) managing and recycling municipal solid wastes and similar wastes generated at national laboratories and other DOE/DOD facilities, (ii) minimizing hazardous and non-hazardous chemical wastes (and bulk solid wastes) generated by industries and DOE/DOD facilities, including wastes generated in Federal Environmental Restoration and Waste Management (ER/WM) cleanup operations, and (iii) providing energy for electricity, transportation, or heat, so decreasing our reliance on virgin, non-renewable fossil fuels.

Each of these regional roles can contribute to compliance with the Resource Conservation and Recovery Act (RCRA), the Clean Air Act Amendments (CAAA), the Superfund Authorization Renewal Act (SARA), and the panoply of local, state, and other federal solid waste and recycling regulations.

Moreover, (iv) there are many indications of attractive national and worldwide commercial prospects for pyrolysis technology, and for allied environmental services and technologies. Japanese and German companies and government-industry consortia are rapidly investing in several pyrolysis technologies. In the United States, many new pyrolysis ventures have been undertaken by segments of the plastics industry and waste-management industry. Some of these ventures are ripe for commercial operations; others are not.

In each role (i - iv), there are significant opportunities for collaborations among partners from industry, universities, national laboratories, and state and local governments.

As a waste-management technology and as a source of materials for environmental cleanup and waste minimization services, pyrolysis systems appear to be cheaper than alternatives in many applications, especially because pyrolysis lends itself to modular, "just-in-time" systems that can be scaled and configured to match the quantities and kinds of waste.

(b) Scope and Purposes of Study

This report identifies opportunities for using pyrolysis that deserve consideration by the Northeast Regional Waste Management Enterprise (NEWME). NEWME is a regional consortium of university, national laboratory, government, and industrial partners administered by the Long Island Research Institute. Seed support for NEWME was provided by the U.S. Department of Energy, through its Brookhaven National Laboratory (BNL) [LIRI 1993].

NEWME is a regional arm of the broad national effort to help national laboratories, industries, and universities work together on faster, better, cheaper technologies for environmental and waste management that American business and industry can use and market worldwide. NEWME's charge is to upgrade the competitive position of the region's waste management and related environmental businesses and industries by assisting in commercializing promising technologies for attacking problems involving MSW, hazardous and industrial waste, remediation of Department of Energy and other contaminated sites, and other important environmental concerns.

Pyrolysis technologies from around the world were studied, and their engineering performance, environmental effects, costs, and product applications and markets were examined. These technologies then were judged according to five criteria:

1. **Technological readiness.** The technology clearly must be out of the research and development stage. There must be a record of demonstration on a significant scale or commercial operations either of the system as a whole, or of the principal components where the processes are separable. Some additional engineering design (say, on monitoring or separation equipment), environmental testing for regulatory purposes, or extension of the technology to new applications (such as secondary materials or DOE wastes) may be advisable -- here, NEWME should take the lead. But any such additional work must be ancillary in nature, and must not call for the solution of new fundamental technical problems.
2. **Commercial readiness.** The pyrolysis system must be offered by private companies with solid, proven, experienced managers possessing the requisite financial, organizational, and technical skills. The technology must be economically viable. While the company itself need not have large financial resources -- one purpose of NEWME is to help new entrepreneurial ventures succeed -- just having a good idea is not enough. For example, the company should have formed active contractual relationships with venture capital organizations, engineering design and consulting firms, marketing companies, or equipment manufacturers for selling and building pyrolysis facilities. NEWME also could assist the less mature company, if the company's product is attractive enough to investors.
3. **Applicability to NEWME's regional concerns.** The primary concerns of NEWME are the potential contribution of the technology in addressing regional MSW (and industrial waste) management needs in a way that is environmentally beneficial (enhances recycling, reduces or avoids pollution, or saves energy), affordable, and consonant with regulatory requirements and the concerns of local governments.

Perhaps the most important test in this regard is that the pyrolysis technology be designed to process a comprehensive range of carbonaceous wastes. For example, one of the pyrolysis systems assessed in this study is well-suited for processing "...garbage, pharmaceutical waste, printers' inks, paper, plastics, railroad ties, barnyard waste, oil, paint, grease, rubber, solvents, agricultural waste, and other organic material" [Pfeffer et al. 1985]. This means that an otherwise superior technology that was designed solely for (say) tire pyrolysis would not qualify.

Secondary NEWME regional concerns include the potential contribution of the technology to more reliable, more sustainable, and less polluting energy use by utilities and vehicles, to improved cleanups at contaminated sites, and to wider markets for secondary materials.

4. **Applicability to NEWME's federal environmental restoration and waste management (ER/WM) concerns.** The technology must be able to process hazardous and non-hazardous wastes from pollution prevention and waste minimization programs to active facilities, and from programs to clean up existing polluted sites in the Department of Energy (DOE) and Department of Defense (DOD). Applicability to similar efforts supervised by the Environmental Protection Agency and state regulatory bodies, such as the New York State Department of Environmental Conservation, also is desirable.
5. **Global market potential and regional economic benefit.** The technology must hold promise of significant sales outside the United States (as well as domestically), so enhancing America's economic competitiveness on the "faster-better-cheaper-smarter environmental technology" model. Such sales would expand the employment base in the region, and perhaps provide careers that help offset the downsizing of the region's defense industries. Also, there should be spin-off development opportunities for universities, national laboratories, and industries.

Four American companies offer pyrolysis technologies that best appear to meet these criteria: Pan American Resources (Pleasanton, California); Conrad Industries (Chehalis, Washington)/Tuttle Technologies (Charlotte, Michigan); Hynol Corporation (New York, New York); and, Entropic Technologies (East Lansing, Michigan).

The four pyrolysis technologies differ in engineering design, waste-processing capacity of individual units, cost, and in the principal final product. For example, the Entropic Technology system makes a clean synthetic coal, the Hynol system makes methanol for a vehicle and utility fuel or fuel ingredient, the Conrad/Tuttle system produces a mixed alcohol that is blended with synthetic natural gas liquids to make a less polluting gasoline, and the Pan American Resources system makes electricity or pyrolytic liquids that can be converted to new plastics. The capabilities of each system are somewhat more flexible than this summary suggests, and other products also are produced.

(c) Organization of Report

Part I explains pyrolysis and surveys its role up to now in waste management and in other applications. This background is important because the definitions of pyrolysis have been confusing or misleading. Consequently, some of the discussion about this family of technologies has been at cross purposes. Partly, this reflects the fact that pyrolysis technology has independent traditions and customary niches within distinct industries (tires, MSW, hazardous wastes, synfuels, biomass, recycling). The material on the history of pyrolysis technology is divided into what might be called the earlier history -- from ancient times to the mid-1980s -- and recent developments.

Another purpose of Part I is to delineate how pyrolysis developers have addressed, and, in many cases, solved the engineering and economic problems that have marked some of its history. This assessment is important in gauging technological maturity and commercial readiness. Part I also lays out the recent attempts to promote pyrolysis technology on Long Island, and identifies local companies selling pyrolysis systems.

Part II details the four technologies recommended for further consideration by NEWME. For each technology, processes, environmental effects, and regional and DOE prospects are sketched.

Next, the potential applications of pyrolysis to the Long Island waste stream are considered, in terms of the amounts of pyrolyzable wastes that might be treated, and the particular components of

the waste stream that should be targeted as a priority. Following the discussion of MSW (including plastics), prospects are examined for processing of a huge pile of old, discarded tires. Applications for hospital wastes, industrial waste treatment and minimization, and landfill mining are discussed briefly.

Regulatory and public acceptance issues are treated in some detail because pyrolysis lies in a regulatory *terra incognita*, and because there was much discussion in 1993 about relationship between pyrolysis and recycling. One question is whether pyrolysis should be considered a form of recycling; the answer can affect the attractiveness of pyrolysis to local governments striving to meet statewide target rates for recycling.

The remaining sections of Part II cover regional energy applications, applications to national laboratory and other federal ER/WM efforts, national and international market opportunities, and potential institutional partners or funders.

The final section of the report identifies unresolved technical issues suitable for national laboratory and university projects, and recommends possible steps for NEWME if regional opportunities for pyrolysis are pursued.

1.2 General Features of Pyrolysis

Pyrolysis breaks materials into simpler molecules by heating them in the absence of oxygen. (As explained below, terminology has been inconsistent, and some definitions allow reduced oxygen environments to qualify). Longer molecules snap apart into smaller, lower molecular-weight molecules, beginning with the weakest bonds at 237°C. All organic (i.e., hydrocarbon or hydrocarbon-derived) molecules break down completely with sufficiently long exposures and at sufficiently high temperatures. Virtually any organic material can be decomposed by pyrolysis into simpler molecules -- food, fiber, plastics, coal, rubber, crude oil, and organic chemicals. Pyrolysis takes place in a sealed vessel called a reactor. Figure 1 shows a generic pyrolysis system.

Pyrolysis of most materials yields three principal products: hydrocarbon gases, hydrocarbon liquids (typically condensed from the vapors), and char (a fine particulate mixture of carbon black and ash). The composition of each can vary from simple to complex mixtures, and can vary in purity, depending on the homogeneity and chemical and physical makeup of the feedstock, and on temperature and other processing environments. The relative proportions of oil, gas, and char products depends on temperature and other details of the reactor's design (Table 1). Higher temperatures generally mean less char.

Figure 1: Generic Pyrolysis System

Source: U.S. EPA (1991)

Table 1: Materials Balance for Pyrolysis

Temperature °F (°C)	Wastes (lb)	Gases (lb)	Pyroligneous acids and tars (lb)	Char (lb)	Mass accounted for (lb)
900 (482)	100	12.33	61.08	24.71	98.12
1200 (649)	100	18.64	59.18	21.8	99.62
1500 (816)	100	23.69	59.67	17.24	100.59
1700 (927)	100	24.36	58.7	17.67	100.73

Source: Tchobanoglous et. al., (1993)

The product gases and/or liquids readily can be recycled into plastics and related products, or made or incorporated into fuels for transportation (such as methanol and low-emissions oxygenated gasolines), electricity generation, and residential or commercial heating. Depending on its purity, char can be used as-is as utility or other fuel – i.e., as syncoal, as a filter to prevent or clean up pollution from hazardous organic chemicals, or as an ingredient in paints, plastics, rubber, and copy-machine toner. Char also may be used as an ingredient in secondary materials. The relative suitability of pyrolysis products for particular applications depends on the feedstock and on the engineering design of the entire processing system – the pyrolysis reactor(s) and any pre- or post-treatments.

Nomenclature varies with the industry, and within industries. Pyrolysis has been called thermal depolymerization, destructive distillation, thermal cracking, coking, carbonization, and low-temperature carbonization. Because these terms often derive from the industrial background behind a particular pyrolytic system, they do not always refer to exactly the same class of processes. Modern pyrolytic systems have emerged from the petrochemical industry, attempts to find fuel substitutes during the Second World War, the plastics industry, the tire-disposal industry, fuel-from-biomass projects, and various synthetic fuels projects, such as coal gasification. There are dozens of pyrolytic processes in the tire industry alone. It is striking that the roots of modern pyrolytic technology lie equally in large-scale petrochemical industry and in biomass, agriculture, and "alternative" technologies.

Some quasi-pyrolytic systems have oxidative regimes (albeit substoichiometric – that is, insufficient oxygen for full combustion); these include some "hydrogasification" systems (here too, terminology has been flexible). Such processes often are grouped with strict (i.e., reductive) pyrolysis systems because most steps and products are the same; the heat from oxygen combustion can promote additional thermal degradation in certain ways. Pyrolysis in the presence of injected steam also can be seen as a variant of oxidative combustion. Steam cracking typically increases yields of combustible gas products.

It is helpful to understand the range of pyrolysis technologies in terms of four key engineering design parameters.

- (1) **Reactor atmosphere:** For example, some tire pyrolyzers use pressurized (inert) nitrogen. Others inject hydrogen into the system to transform the sulfur in the tires to recoverable hydrogen sulfide.
- (2) **Reactor design:** In order of increasing complexity, established designs are a sealed box, rotary kiln, screw kiln, traveling grate kiln, and vertical fluidized bed. (Laboratory and pilot-scale designs include a hot oil bath, molten salt bath, microwave, and plasma pyrolysis). The design strongly affects the char's quality, for example, by affecting temperature gradients

and the mutual abrading of the char particles. Sealing ability is also important, the main concern being keeping air out, not preventing leaks to the outside, especially for continuous-feed systems with air-lock devices. The generally much smaller screw kilns are easier to seal, but the screw may show additional mechanical wear of the screw in a hot, erosive environment.

- (3) **Internal or external heating:** Strict pyrolysis systems are endothermic. Most use external heat that may be applied directly or indirectly. Some are heated internally by friction, electromagnetic fields, or other means. In some pyrolysis systems, such as the Hynol process described in this study, exothermic reactions also may occur.
- (4) **Operating temperature:** Higher temperatures generally favor hydrocarbon production; lower temperatures generally favor carbon production. Processes are easier to control at lower temperatures. Tire pyrolysis reactors operate between 237°C and 1,000°C, with a maximum yield of oils at 451°C. [U.S. EPA 1991]

One of the general design goals in pyrolysis technology has been to lower the ash fraction in the char and to make char of commercial carbon-black grade. Steam activation, pulverizing, screening, acid leaching, benzene extraction, and filtering have had mixed results [U.S. EPA 1991]. Some methods generate fugitive volatile organic carbon (VOC) emissions; however, these are readily controllable. In any event, virgin carbon black (and carbon black from substoichiometric combustion of hazardous organic wastes) has commanded the market. Fluidized-bed pyrolysis reactors have yielded some of the best char, but removing solids and maintaining fluidizing gas temperatures can be a challenge for them. Several promising new technologies have been developed to use (and/or upgrade) char as an activated carbon filter in environmental applications [see, e.g., InnCon 1993]. Demand for high-quality carbon media is strong, and is expected to rise.

1.3 History of Pyrolysis Technology

Ancient Roman and Egyptian, and traditional African, Caribbean, and Southeast Asian cultures made charcoal, pigments, and/or wood distillate fuels by heating biomass (or other substances, such as pitch) underground with little or no air. These process often produced lightweight, portable, smokeless cooking fuels with higher heating values than wood. In the nineteenth century, illuminating gas was manufactured almost entirely by pyrolysis. This was the major form of lighting in the industrial world until the discovery and industrialization of oil and natural gas fields (and later, the electric light bulb) made illuminating gas obsolete. Some experimentation with pyrolytic manufacture of automobile fuels was carried out in the 1920s.

In the 1930s, Pan American Resources invented and marketed a small batch-pyrolysis system that was widely used on farms and ranches. Hay stack bottoms, waste feed, and dried manure were packed and bolted airtight into an oven that was heated by a burner underneath. The pyrolysis gases were used for cooking, space heating, and lighting. Other companies developed similar processes. This technology became obsolete with the advent of cheap bottled propane.

Development of a variety of small-scale pyrolytic biomass and related biogas systems has continued, especially in India, China, and the Caribbean. Pyrolysis also is still widely used to make charcoal from wood, and coke and coke gas from coal.

Several technologies were developed in the 1930s and during the Second World War to provide liquid, solid, and gas fuels for domestic and military vehicles, for power production, and for use as industrial feedstock. Some of these systems were strictly pyrolytic; others were gasification systems or other partly oxidative systems. Development efforts were most vigorous in Germany, Japan, the

Soviet Union, France, Denmark, and South Africa. Efforts succeeded in some countries and failed dismally in others. After the war, these technologies fell by the wayside amid the flood of cheap oil.

In the 1950s, Pan American Resource's Dae Lantz, Jr., patented the Lantz converter, a continuous-feed reactor that kept out air and oxygen with air-lock seals; this was the nucleus of PAR's Destructive Distillation system.

PAR's 50 ton/day destructive distillation plant successfully processed several kinds of industrial waste from the Naval Ammunition Depot in Concord, California between 1962 and 1964. This ended when the Navy decided to landfill these wastes instead (landfilling was immeasurably cheaper then). PAR pyrolyzers also were used in the 1960s as timber industry charcoalizers, as a coal coker, and for recovering mercury from cinnabar.

A 50 ton/day PAR pyrolysis system ran from 1968 to 1969 at the Ford Motor Company's Assembly Plant in Milpitas, California, its purpose being to eliminate all wastes generated there. The pyrolyzer's performance was excellent. However, the shredder and conveyors failed constantly; this may have reflected a poor choice of equipment. PAR re-designed the shredder and conveyor equipment, but there was not enough money to carry out the changes in design. The PAR system is described in greater detail in Section II.1.

Also in the 1960s, the U.S. Bureau of Mines, Firestone, Goodyear, and TOSCO (formerly called the Oil Shale Corporation) ran well-funded tire pyrolysis research and development operations [Petrick 1991] that led to the construction of a 15 ton/day fluidized bed reactor. An auger fed in the tire chips. The 300 ton/day machine sought by the rubber manufacturers was not economical then because collection and transportation would have been too expensive within the "tireshed" that would supply tires for so large a plant, and enthusiasm languished in consequence.

The energy crisis revived interest in pyrolysis of tires and other materials. In the 1970s, the Environmental Protection Agency, the Energy Research and Development Agency, and the Department of Energy (in turn), the Tennessee Valley Authority, the Institute for Gas Technology, and other organizations funded research, development, and demonstration (RD&D) projects on coal gasification, oil-shale pyrolysis, and other synfuels technologies (here, including biomass). The results on the whole were disappointing, on account of high overall costs, especially for the very large-scale projects, and owing to engineering problems, as discussed below [see, e.g., Kuester 1983].

Some pyrolytic and quasi-pyrolytic (oxygen was present, or direct heat was used) systems also were offered commercially during the late 1970s and early 1980s. They included the Occidental Petroleum OxyFlash, Monsanto Landguard, Andco Torrax, Union Carbide Purox, and Duke Engineering DECO processes. Like the RD&D projects, these efforts chalked up a decidedly mixed record (often due to economic factors, such as low prices of virgin materials), and gave pyrolysis a bad reputation. Some of these systems were intended for industrial wastes.

For example, the Andco-Torrax, Monsanto Landguard, and Union Carbide Purox systems used direct heating and partial combustion, and, in many ways, could be described as incinerators. The vertical retorts and very high temperatures (1,650°C) of the Torrax and Purox systems created severe problems controlling temperature zones. Incompletely dried feedstock yielded product gases with unduly low Btu values. The Purox system counteracted this tendency by injecting large quantities of oxygen, which ruined the system economically.

The Duke Engineering DECO process was a strict pyrolysis system (apparently, there were problems scaling up its auger feed system), as was the OxyFlash system. In the 1970s, the Occidental Flash Pyrolysis system, in El Cajon, California, the only full-scale MSW pyrolysis plant in the United States, closed after two years of operation. It did not produce enough saleable oils -- Btus were lower

than anticipated. Feeding of the finely ground organic MSW to the reactor was not reliable, and there were problems separating sufficiently pure aluminum and glass for reclamation.

In 1980s Power Recovery Systems' fluidized-bed gasification technology was perhaps the leader among the few companies offering to build and operate commercial MSW pyrolysis systems [Kuester 1983].

The data obtained from the government-supported synfuels/biomass projects and these private efforts led to improvements during the next cycle of development, and created a valuable data base, especially for biomass and other relatively homogeneous feedstocks. While not all of these projects involved pyrolysis, many of the technologies for equipment, feedstock preparation and processing, production control, and environmental control contributed to the advances in pyrolysis engineering identified in section I.5.

As for tire pyrolysis, by 1966 only 6 were operating of the 34 tire pyrolysis processes cited in a 1983 DOE worldwide survey as built, proposed, designed, patented, or licensed at that time. Falling oil prices and certain engineering problems were blamed. The 1983 DOE study held that "...tire pyrolysis is only economic with unique situational variables" [Dodds, et al. 1983]. By 1990, only one or two of the 34 processes mentioned in 1983 were operational which was attributed to noncompetitive capital costs and to variations in the yield, composition, and selling price of oils and char [U.S. EPA 1991]. The resurgence of tire pyrolysis since 1991, though, has been strong, as is the case with pyrolysis generally.

The National Bureau of Standards chose PAR's Destructive Distillation system, which had evolved during the previous decade as one of the best inventions of 1979. That recognition led to a commercial-scale (50 ton/day) demonstration plant at the Marcal Paper Mills, Elmwood, NJ, in 1982, under a grant to Pan American Resources from the U.S. Department of Energy. During the two and a half years of operation, performance was monitored, emissions were measured, and product composition was assayed for the DOE by three chemical engineering professors at the City University, New York [Pfeffer, et al. 1985]. This report was highly favorable, as explained in the section on the suitability of Pan American Resources systems for Long Island and for other uses of interest to NEWME. The more recent history of Pan American Resources also is catalogued in that section.

I.4 Recent Developments in Pyrolysis Technology

A review of recent commercial and near-commercial developments in (a) plastics pyrolysis technology, (b) advanced pyrolysis technology, and (c) tire pyrolysis technology shows where pyrolysis fits within the spectrum of emerging recycling and waste management technologies, and brings out the European and Japanese competitive challenge to American industry.¹

(a) Plastics Pyrolysis and Chemical Recycling

(i) Rationale and Terminology

Plastics pyrolysis is undergoing explosive development, notably in Germany and Japan. This wave of development now has reached the United States: large multinational corporations, and several

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¹ Recent developments in MSW pyrolysis technology generally are covered in sections II.1 - II.4, on the four technologies singled out for possible encouragement by NEWME (Entropic, Tuttle/Conrad, Hynol, and Pan American Resources). Certain developments on hazardous waste pyrolysis are covered in section II.7, on DOE applications of pyrolysis, and elsewhere in this study. The Nu-Tech (now Universal) and Envirotire tire pyrolysis systems, which are being developed by Long Island companies, are discussed in section I.6.

established mid-size and new small companies, have seized upon this technology during the last two years. Plastics, general MSW, and industrial/hazardous wastes are the waste streams that mark the greatest market opportunities, both national and global.

As described in section II.5(a), the plastics currently being recycled in the United States -- largely polyethylene terephthalate (PET) and high-density polyethylene (HDPE) bottles and other containers -- represent a very small fraction of the plastics in the waste stream. Existing reclamation processes are not economically viable for complex waste streams, including wire, cable, medical disposables, blended and compounded plastics, automobile shredder residue, most thermosets (including acrylonitrile butadiene styrene [ABS], and non-container products made of polyethylene, polypropylene, polyvinyl chloride, and polystyrene). The conventional recycling costs of collecting, sorting, cleaning, melting, and reforming are high. The multitude of compounding ingredients and the mix of resins complicates the reprocessing of the great majority of plastics.

Chemical recycling promises to lower this cost because these plastics, individually or commingled, are usable without extensive decontamination. The term refers to chemically converting plastics (and other polymers) into their starting materials -- either into monomers or other precursor chemicals, such as ethylene -- which then can be made into what are, for all intents and purposes, virgin plastics, or into other materials, including fuels. The term "fuel recycling" also has been used, so viewing the recycling loop not as turning discarded consumer products into more consumer products, but as running, instead, from fuel-related raw material to the plastic or other consumer product and back again to the raw material. Tertiary recycling is another term that is sometimes used.

Chemical recycling, including pyrolysis of wastes, falls into largely uncharted regulatory territory. Two policy issues raised by plastics pyrolysis prompted much discussion during 1993: (1) Should pyrolysis be considered a form of materials recycling for regulatory purposes, so that, for example, wastes subjected to pyrolysis would count towards a town's overall recycling goals? and, (2) Will pyrolysis undercut existing, mechanical forms of plastic recycling? These issues are analyzed in section II.5(d), Regulatory, Public Acceptance, and Siting Considerations.

The viability of chemical recycling depends on the hydrolytic and thermal properties of the polymer resins, the environmental effects of processing (including avoided effects), local solid waste circumstances, and economics [Modern Plastics 1993].

Pyrolytic liquefaction of plastics occupies a particularly advantageous position within the realm of emerging chemical recycling technology generally.

One type of chemical recycling under rapid development is chemical depolymerization by alcoholysis-hydrolysis (either methanolysis or glycolysis). Such methods, including so-called "solvent dissolution" techniques, work only with polymers derived from reversible processes, such as PET, polyamides (such as nylon), and polyurethanes (PURs).

These methods are in contradistinction to thermal depolymerization, in which plastics are heated in the absence of oxygen. Thermal depolymerization may be distinguished from pyrolysis chiefly by the fact that the process yields monomers only, rather than liquid (or gas) precursors to monomers (with or without accompanying monomers). Thermal depolymerization holds promise for recycling other reversibly-created polymers, such as polystyrene (PS) and polymethyl methacrylate (PMMA).

However, neither chemical nor thermal depolymerization can treat polymers, such as high-density polyethylene (HDPE), polypropylene (PP), and polyvinyl chloride (PVC), that are made in irreversible processes. A great advantage of pyrolysis is, firstly, that it works for both classes of polymers -- reversible and irreversible, including the entire range of packaging plastics. A second advantage is that the pyrolytic liquids are especially valuable because of their high content of hydrogen-rich aliphatics.

Thirdly, pyrolytic regimes can be selected to meet the requirements for thermal degradation of most plastics, so that prior separation by resin, or from food and paper contaminants, is unnecessary. Some plastics revert to monomers (e.g., polystyrene and polymethacrylates), and others (e.g., the polyolefins and polyvinyl chloride) form methane, ethylene, and benzene. Catalysts, or other gases, yield other intermediates, or allow yields at lower temperatures. There are well-established markets for all of these end products, especially because the products mesh with the existing infrastructure of refining and petrochemical processing (cokers, catalytic crackers, steam crackers, and hydrocrackers). Initial capital costs are relatively low. For these reasons, "...pyrolytic liquefaction is therefore ideal for recycling commingled waste plastics" [Modern Plastics 1993, p. 38].

(ii) Recent Worldwide Projects in Plastics Pyrolysis and Other Chemical Recycling

Several efforts to commercialize pyrolytic liquefaction of plastics are of interest (some developments in non-pyrolytic chemical recycling also are listed):

(1) Conrad Industries has been operating two tire pyrolysis units in Chehalis, Washington since 1987. (Their tire-processing regime, product yields, economics, and environmental effects are discussed later under "tire pyrolysis"). The facility is being converted to use mixed post-consumer plastics feedstock with technical and financial support from the American Plastics Council [APC], a trade organization composed of 25 major resin producers. The hydrocarbon products are to be sent to Texas for refining and/or to plastics manufacturers to be made into petrochemical fuels, or plastic goods.

One retrofitted pyrolyzer is designed to accept up to 3 units tires mixed with 1 unit plastics (by weight); the other unit is planned to be for "plastics only" (including scrap film) [Plastics Recycling Update, December, 1993]. Shredded (2") feedstock passes through an airlock into the 540°C pyrolyzer (most plastics pyrolysis equipment operates between 500°C and 750°C). Eighty per cent of the output consists of pyrolytic liquids whose properties depend on the feedstock. For example, a 100% polystyrene feedstock yields a liquid that is 50% styrene. The liquids will be sent to the refinery to make new synthetic fibers, new plastics, and other petroleum-based products. Seventeen per cent of the output is uncondensed pyrogas, a natural gas substitute, of which one-third is used to drive the pyrolysis. Five to ten per cent of the output is carbon for sale for making activated carbon, pigments, rubber goods, and in other applications.

A small, 300 pounds/hour capacity unit with a mix of post-industrial bottle scrap is being tested (60% of the pellets are polyethylene, 20% are polystyrene, and 20% are polypropylene). PVC also is being tested. The unit has processed 115 pounds/hour 24 hours a day, 5 days a week, since June, 1993. Conrad is working to lengthen the residence time, and to fire the system so that it will yield higher butane and propane fractions. Engineering design also is focusing on controlling high-temperature excursions, which can damage the hearth and grate.

Six thousand gallons of hydrocarbon liquids from the test unit were sent to a major Texas refinery in November, 1993, where it was thermally cracked in a coker. Heavier hydrocarbons were made into gasoline and heating oil. Lighter hydrocarbons were used to make monomers for subsequent polymerization into plastics.

Commercial-scale processing of mixed post-consumer MSW plastics was scheduled to begin in 1994, under contracts with the collecting municipalities, in the first pyrolysis unit. Tire fractions in the feedstock may be limited if sulfur in the tires are found to complicate the capture by the scrubber system of chlorines from the plastics. The second, "plastics only" pyrolysis unit (2,000 pounds/hour) was scheduled to begin operation in 1994 with colored HDPE bottles. Nearby equipment would remove PET and other containers that have attractive end-use markets when recycled mechanically.

One source suggested that regulators had concerns about potential emissions from the plant [Plastics Recycling Update, October, 1993], but officials from the Washington State Department of Ecology [WSDOE] stated that they found no air or water emissions and that, therefore, WSDOE has nothing to regulate. The only issue before WSDOE is that local governments want to know whether MSW materials diverted under contract to the Conrad facility will count towards satisfaction of the state's recycling and waste management goals [WSDOE 1993; American Plastics Council (APC) 1993].

Plans to spread the use of this technology are based on what is claimed to be a relatively low capital cost. Through its Eastern United States representative, Tuttle Technologies, Inc., Conrad is developing a project in Michigan with a major waste hauler (this will include rail hauling). The Conrad system would be used in conjunction with a standard cracking tower to synthesize alcohol as the highest-value product with the best market. Tuttle Technologies also has approached the City of Newark and has sent introductory letters to some Long Island towns. The Tuttle/Conrad system is one of the four identified in this report as appropriate for NEWME involvement. Margaret Tuttle, President of Tuttle Technologies, has stated that the firm is strongly interested in developing a project on Long Island or elsewhere in the region. (Additional details are found in section II.4).

(2) A 150 ton/day plant in Salzgitter, Germany that is virtually identical to PAR's Lantz Converter system (apparently the Germans had access to details of the Lantz design before designing the Salzgitter system) has run highly successfully for three years on a commercial scale. The plant pyrolyzes pre- and post-consumer plastics (MSW is not pyrolyzed). Condensed gases are made into more plastics. Polychlorinated biphenols (PCBs) and other hazardous wastes that are processed are destroyed.

(3) Toshiba Corporation is building or has built (reports are unclear) a destructive distillation-type pyrolysis plant that converts 2.2 pounds of chlorine-containing plastics -- PVC, for example, is 50% chlorine by weight -- to one liter of gasoline.

(4) Mazda Corporation is developing an all-plastic car body that can be thermally decomposed by destructive distillation pyrolysis at low temperatures. The car also is being designed for easily, snap-apart disassembly, which will facilitate collection and mechanical pre-processing. Similar projects are underway in the U.S. automotive industry.

(5) Germany's PVC industry plans to construct a pyrolysis plant by 1998 to turn PVC scrap into hydrochloric acid. The hydrocarbon output would be burned. [Plastics Recycling Update, October 1993].

(6) Petrofina, BP Chemicals, DSM, Elf-Atochem, and Enichem (major European resin producers) have formed a consortium to commercialize BP's pyrolysis process. A sand or gravel bed transfers heat and liquefies the plastics. A 27,500 ton/year, 100 kg/hr unit that opened in 1994 will pyrolyze commingled plastic wastes for an expected charge of between \$100 and \$200 per metric ton (2,200 lbs). This follows successful pilot tests (10- and 20-kg/hr). An olefin mixture, derived from the mixed plastic feedstock, will be 80% polypropylene and polyethylene, 15% polystyrene, 3% polyethylene terephthalate, and 2% polyvinyl chloride. [Chemical and Engineering News, August 1993; Modern Plastics, December, 1993].

(7) Alliance Technologies (United States) has designed a system to convert polypropylene to No. 6 and No. 2 fuel oil in fluidized bed furnaces at 430°C to 480°C.

(8) General Motors Corporation has developed a technology to pyrolyze at 760°C automotive shredder residue (ASR), a mix of many plastic resins, textiles, rubber, and other materials. The system makes products with higher Btu value (15,000 -18,000 Btu/lb.) than No. 2 heating oil ["Industry Backs Pyrolysis as a Recycling Option," Modern Plastics, January 1994, p. 93].

(9) The American Plastics Council also is supporting Grand Forks, North Dakota's Energy and Environmental Research Center's work on fluidized-bed pyrolysis of plastics into monomers for reuse in virgin polymer resins. The fluidized-bed design may allow better control of the decomposition process than with some rotary kilns.

(10) Battelle has a patent pending on a pyrolytic gasification unit that reduces commingled high-density polyethylene [HDPE], linear low-density polyethylene [LLDPE], low-density polyethylene [LDPE], polystyrene [PS], and polyvinyl chloride [PVC] to a gas that is 40% ethylene, 27% methane, 17% hydrogen, and 16% other fractions. Preliminary economics suggest that ethylene is recoverable for less than its 1992 selling price (20 to 25 cents per pound), where recovery costs include capital and non-feedstock operating costs (feedstock costs would be negative in any event) [Modern Plastics 1993].

(11) Germany's Veba Oel Technologie und Automatisierung GmbH [VEBA] has formed a chemical recycling consortium with BASF, Hoechst, Bayer, Dow, and Huls. In 1993, the consortium's commercial plastics-to-hydrocarbons plant in Bottrop, Germany doubled its capacity to 44,000 tons of plastic scrap annually [Plastics Recycling Update October 1993 and December 1993]. Mixed thermoplastics scrap is converted to a refinery feedstock that is dissolved in "heavy bottoms" (a refinery waste), run through a cracking plant, and then hydrogenated. Elastomers and car-shredder fluff are among the materials that have been tested. BASF itself is building a 16,500 tons-per-year plant in Ludwigshafen, Germany to turn targeted mixed plastics scrap into α -olefins by chemical depolymerization.

(12) Amoco has patented a hydrolysis process to recycle PET into monomers. DuPont and BASF have developed a new system for polyamide chemical recycling. Hoechst Celanese, Eastman Chemical, Shell Chemical, and DuPont are commercializing methanolysis and glycolysis systems for PET bottle recycling into new PET soft drink (and other food contact) bottles. Shell International Chemical (The Netherlands) is promoting a solvent dissolution technique for mixed plastics. Japanese systems under development would recycle plastic films into oil, certain other plastics into gasoline, and polystyrene food-service trays into a product that is blended to form high-octane fuel [APC 1993].

Petrick [1991] notes that, in 1991, 50 to 60 tire pyrolysis projects were under consideration in the United States.

Several other projects are underway or proposed by the four U.S. firms whose technologies are highlighted in this report (Hynol, Entropic, Tuttle/Conrad, and Pan American Resources). These projects are discussed in the separate sections on each of these technologies.

(b) Tire Pyrolysis

Note: The Nu-Tech (now Universal) and Envirotire tire pyrolysis technologies are discussed in section 1.6 (on local developments concerning pyrolysis).

There are dozens of tire pyrolysis processes (including oxidative and steam injection along with wholly reductive processes), with design temperatures lying approximately between 240°C and 1000°C. Some accept whole tires, others require chips. Maximum oil yields tend to cluster near 450°C. The light oils raise octane when added to gasolines. Heavy oils are burnable in any device that burns No. 6 fuel oil; some systems produce higher-grade oils. The heating value of product gases run from 170 to 2,375 Btu/ft³ (natural gas averages 1,000 Btu/ft³). The char typically is a fine particulate made of carbon black, ash, zinc oxide, carbonates, and silicates.

(1) One noteworthy, recent, and much studied tire pyrolysis technology is the original Conrad system that led to the Conrad plastic pyrolysis project mentioned above.

The reactor, which operates between 900°C and 1,000°C for this feedstock [U.S. EPA 1991], began processing 100 tires/hr in 1986. Tires average 20 pounds, and one ton of tires becomes [U.S. EPA 1991]:

600 lbs carbon black
90 gallons oil
8000 ft³ (30 therms) gas
(Steel also is recovered from tire belting)

The facility also was used to process rice hulls, nut shells, wood, paper, compost, and plastics (polyester, polypropylene, polyethylene). In 1991, five additional units were being built for four different feedstocks.

The Conrad design separates two oil streams: heavy condensed oils (eight carbon atoms or more), and light condensed oils (three to seven carbon atoms). Oils from standard tire pyrolysis systems contain benzene and toluene. Conrad did not remove benzene and toluene from the pyrolysis oils because this was too costly. Instead, these oils were sold as a substitute for no. 6 fuel oil. (The Conrad oils also contained up to 1.5% sulfur). U.S. EPA [1991] found that the product oils had a promising market as a blending oil for commercial fuels. This is the option being advanced for the Long Island region by Tuttle Technologies, as discussed in section II.4.

Conrad's product gas contains paraffins and olefins with one to five carbon atoms, and averages 835 Btu/ft³. Gas not used to run the reactor is either flared at high temperature or sold as a replacement for natural gas boiler fuel. Emissions from burning this gas are similar to those from burning natural gas [U.S. EPA 1991, p. 8-7].

Conrad overcame some difficulties in marketing the char; it contained 10% - 15% ash which depletes its reinforcing ability when used to make tires. Its particle size was too large to be used as high-grade carbon black. (Steel and fiber contaminants can be removed). Conrad's carbon black contained 0.75% sulfur, on average, and found a market as a copier toner and plastic additive.

U.S. EPA [1991] measured particulate, volatile organic compound (VOC), and other air emissions at the Conrad tire facility, as the centerpiece of a broad study of tire pyrolysis, and concluded

"Pyrolysis units are expected to have minimal air pollution impacts because most of the pyro-gas generated in the pyrolysis process is burned as fuel in the process. During burning, the organic compounds are destroyed. Assuming complete combustion, the decomposition products are water, carbon dioxide, carbon monoxide, sulfur dioxide, and nitrogen oxides." [U.S. EPA 1991, p. 8-13]

Emissions to air and water were low and easily controllable. (See II.4.b).

According to U.S. EPA [1991], small-scale tire pyrolysis is the most economical. Economics are marginal without a densely populated "tireshed" and when fees for disposal of the tires are low. Higher tipping fees were adjudged to be the best way to improve economics of tire pyrolysis in marginal locations. State charges for tire disposal were said to end up mostly in the hands of middlemen and administrators. Reliable revenue from high-quality, marketable char also was found to be important to overall economics.

Petrick's review of the state-of-the-art of tire pyrolysis technology concluded that

"we are at a point where fine tuning of existing systems will result in improving productivity by a factor of 2 to 3. This should make tire pyrolysis competitive with the alternatives for

disposing of scrap tires at locations where the cost of transportation to existing facilities or large central points is not prohibitive." [Petzrick 1991]

This remark also appears to hold true for pyrolysis of MSW, plastics, and organic hazardous wastes.

(2) ECO², a Florida company, has patented a scrap-tire pyrolysis process. Tires are shredded, the steel belting is removed, and the tire chips are converted to oils, carbon black, and methane. Crumb rubber also can be produced. A 60-ton order for crumb rubber was filled in 1993 using a 100-tire-per-hour facility. Thomas Engineering Associates (North Carolina) will make the crumb rubber into landfill liners. ECO² envisions compressing the methane for use as a fuel in alternative-fuel vehicles. The ECO² process does not appear to be particularly novel, but the landfill liner and methane fuel applications are interesting. Two experts in tire recycling had reservations about the company's experience and the performance of its technology.

(c) Advanced Pyrolysis Systems

Note: other developments in technology for pyrolysis of hazardous wastes are found in sections II.5(c)(ii) and II.7.

(i) Plasma Arc Pyrolysis

These very high temperature systems (up to 30,000°C) are designed for the most recalcitrant, highly toxic, liquid hazardous wastes. Ethanol is injected during a three-minute warm-up period to maintain the reducing atmosphere. A cool-down time, of about twenty minutes, is required for maintenance. Problems have been encountered in controlling the heat.

A prototype, mobile, 6 ton/day plasma arc pyrolysis system, the first of its kind, was developed in the 1980s by a joint venture of Westinghouse and Pyrolysis Systems, Inc., Ontario (later CWM), in collaboration with The New York State Energy Research and Development Authority, the New York State Department of Environmental Conservation, and the U.S. Environmental Protection Agency. The 45-foot long device was intended primarily to process Love Canal cleanup wastes (sludges containing dioxins, PCBs and hundreds of hazardous chemical species) at 10,000°C, and to produce a 50% hydrogen, 30% carbon monoxide, and 20% nitrogen mixture. Hydrogen was flared at 1,150°C, despite plans for its eventual conversion to fuel.

The plant was given a permit to operate near Buffalo. Problems developed with refractory materials that did not hold up under the high heat, so this project was scrapped by the company before commercial operation began.

(ii) High Temperature Fluid Wall Pyrolysis

This electric pyrolysis reactor was developed by Thagard Research Corporation to pyrolyze organics from soil and similar particle surfaces. Finely ground (-20 mesh) feedstock is heated to 2,200°C by high electromagnetic power densities (1200 watt/m²). The refractory, porous core becomes hot enough to activate reactants. Destruction is very fast. A curtain wall of inert gas keeps the hot reactants from contacting the vessel's walls. A medium-Btu, recoverable product gas and a char of ash, other inorganics, and carbon are produced. There is a commercial demonstration unit. Systems used in the chemical industry are being examined for possible adaptation to pyrolyzing waste.

(iii) High Temperature Thermal Distillation

The HT-6 High Temperature Thermal Distillation Process subjects hydrocarbon-contaminated soils and other hazardous wastes to temperatures up to 1200°C in a nitrogen atmosphere [Seaview Thermal

Systems, 1993]. Most of the water and some of the light ends are vaporized in a low temperature chamber. Then, an electrically heated high-temperature chamber vaporizes the heavy ends, and the remaining light ends and water. Condensates are separated into water and oil, both of which can be treated for reuse. Tests have been made on soils and sludges contaminated, variously, with crude oil, jet fuel, PCB-contaminated motor oil, and creosotes. Seaview Thermal Systems owns the patented process, which was developed by TDI Services, Browning-Ferris Industries, and Xytel, Bechtel.

1.5 Signs of Maturation of Pyrolysis Technology

The most celebrated modern technologies have undergone ups and downs, cycles of optimism and pessimism, false starts and unheralded breakthroughs before they became economical and "proven." The vicissitudes of pyrolysis technologies, as portrayed in the sections on their earlier history and contemporary renaissance, then, are in themselves nothing exceptional. However, there are specific reasons for thinking pyrolysis is now a mature technology that will take hold in many applications in the United States and worldwide.

One sign of a matured industry is that there are several established engineering-service companies, pyrolysis equipment, and of carbon-processing equipment offering turnkey pyrolysis services with warranties on performance. Several such firms were listed in Petzrick [1991]; many more have since been added. Most of these firms have been soliciting new design projects. Many are venerable companies -- for instance, Kleenair, maker of Conrad's equipment, has made heavy industrial equipment for nearly 70 years; Seco/Warwick has been making industrial heating equipment for nearly a century. Several other examples are given in the sections on the four technologies selected for consideration by NEWME.

Another indication of maturity is that the principal engineering problems faced by some pyrolysis systems in the 1970s have been solved. Those pyrolysis systems were sometimes jury-rigged, designed without adequate literature searches, and poorly funded. The effects of heat on the expansion of equipment, on structural strength, and on lubrication were poorly understood. Engineering advances over the past decade have solved these problems. Furthermore, many new technologies have emerged for upgrading char and many new environmental applications for char [see, e.g., Inncon 1993].

Helt et al. [1987], reviewing MSW pyrolysis capabilities through 1985 (before the Marcal/PAR/DOE study), attributed difficulty in making MSW and biomass pyrolysis economical to an inadequate yield and quality of fuels. Since then, however, engineering development of pyrolysis processes for complex, heterogeneous fuels has stressed:

- (1) methods to decrease oxygen content, moisture content, corrosiveness, and frequency of repolymerization during storage of liquid pyrolysis products,
- (2) better understanding of the complex, simultaneous reaction pathways as a function of temperature, heating rate, residence time, particle size, moisture level, and the presence of cellulosic vs. noncellulosic hydrocarbon feedstock,
- (3) increasing the yield and quality of fuel products, and
- (4) upgrading the char. Many results of laboratory-scale tests at the national laboratories, especially Argonne National Laboratory's (ANL's) MSW pyrolysis program of the 1980s on product yield and quality vs temperature for different waste stream components [e.g., Helt, et al. 1987], also have been incorporated into practical engineering knowledge.

The fact that some of the world's largest corporations are investing large sums of private, at-risk, largely unsubsidized capital in pyrolysis technologies also suggests that pyrolysis is poised for commercialization.

Many of the difficulties encountered by earlier attempts to pyrolyze MSW and other materials concerned "front-end" problems in separating materials, controlling contamination and moisture, and feeding materials to the reactor. Huge engineering strides have been made in these areas with the arrival of innovative, adaptable, proven, high-capacity front-end systems for municipal recycling facilities (MRFs), incinerators, and other waste management installations. The wherewithal to satisfy the "front-end" design constraints now is widely available off-the-shelf.

Similarly, standards and grades for materials separated for reclamation, such as metals and glass, have become far more institutionalized, with brokers, waste exchanges, recycling cooperatives, curbside recycling programs, recycling market development programs, procurement requirements for recycled goods, and other instrumentalities available to help in marketing and quality control. These improvements also mean that waste haulers and other waste suppliers can ensure more consistent feedstocks.

The final difference between circumstances today and yesterday is economic. As Petzrick [1991, p. 1] commented in a review of the history of pyrolysis, "When the cost of raw materials, plant and operations exceeded revenue from products, the technology and engineering know-how were available for a successful operation. Pyrolysis does not have to be invented. It does have to be tailored to produce the optimum products from the available feedstock."

However, today's high costs of MSW disposal and hazardous waste disposal are unprecedented. High tipping fees, regulatory mandates, high cleanup costs, and tax and other financial incentives make pyrolysis economically attractive in many applications. Similarly, mandates and incentives encouraging alternative fuels and materials and energy recycling redound to the benefit of the products of pyrolysis.

Cheap mega-landfills may undercut markets for pyrolysis as a waste management tool, and severe drops in oil prices may undercut markets for fuels and materials made from the products of pyrolysis. These developments appear unlikely, but there are never any guarantees. However, such a state of affairs would undermine the economic viability of other waste management systems, too -- incineration, recycling, and MSW composting. Even then, pyrolysis is considerably cheaper than incineration; recycling is becoming ever more expensive (it is too early to assess cost trends for MSW composting).

1.6 Earlier Developments on Long Island Concerning Pyrolysis

Certain events on Long Island concerning pyrolysis are of interest: (i) a never-executed plan to build an MSW pyrolysis facility in eastern Long Island, (ii) proposals for a tire-pyrolysis facility under Suffolk County auspices, and (iii) efforts of two Long Island vendors of pyrolysis systems, Nu-Tech (now Universal) and Envirotire.

(i) In the 1980s, Waste Distillation Technologies, a defunct Greenport, Long Island firm, acquired rights to market the PAR systems. In 1986, the Town of Southold became very interested in acquiring the PAR Destructive Distillation system to handle MSW and certain other Town wastes [Abeysekera 1993]. The plant would generate 335 kwh per ton MSW at tipping fees under \$10/ton. A former regional commissioner of the New York State Department of Environmental Conservation (NYSDEC), D. Goldbach, also had been a strong supporter of pyrolysis technology for handling regional wastes, although NYSDEC's solid waste manager was skeptical, apparently being unaware of the favorable outcome of the DOE-sponsored tests at the Marcal plant in New Jersey.

Town officials endorsed the idea of siting a pyrolysis facility in Southold. They thought that it would be far cheaper and less polluting than an incinerator, and cheaper than the \$9 million MSW composting plant that had been turned down in a referendum as too expensive. The plan was strongly endorsed by environmental and citizen groups, including the North Fork Environmental Council and the League of Women Voters [Abeysekera 1993]. Professor T. Goldfarb of SUNY/Stony Brook indicated that the Waste Distillator (as it then was called) dovetailed with the longstanding contention of environmental organizations that starved air and no-air processing at lower temperatures polluted less and posed a lower risk to the health of humans and ecosystems than did incinerators.

The matter languished until 1990, when the Town asked for a ruling from NYSDEC on the regulatory status of MSW pyrolysis. N. Nosenchuck, NYSDEC's former solid waste director, determined that MSW pyrolysis and ash from MSW pyrolysis would be subject to the same waste regulations as incinerators and incinerator ash (6NYCRR360-3.5). NYSDEC also ruled that the char is exempt from RCRA section 3001(1) regulations. [Note: several important regulatory developments have occurred since -- see section II.5(d)].

Town government changed hands, a new engineering consulting company was hired to handle many of the Town's waste issues, and the pyrolysis proposal died.

(ii) In 1992, Suffolk County issued a request for proposals for the disposition of discarded tires. The presumption was that the disposal facility would be on County land near Yaphank. Two of the proposals submitted came from Long Island pyrolysis vendors: Envirotire and Nu-Tech. For several reasons, none of the proposals were acted on.

Although the County Legislature had resolved that the County, rather than the separate Towns, should take a lead role in disposing of tires, it also was the case that by 1992-3, the disposal problem largely had been brought under control.

None of the five major Suffolk County towns saw a need for a County tire project or facility. It would have been too expensive, and private "tire jockeys" assiduously were acquiring old tires and shipping them off the Island. Some were sold in South America; others were burned in the Catskills or in Connecticut. One town had a NYSDEC permit for testing tire incineration.

Another reason the proposals were rejected was that the Yaphank site was politically infeasible because of its proximity to the Pine Barrens. The head of the Regional Planning Board, also died during this period, interrupting the normal process of proposal review.

According to several persons involved in assessing the proposals, there was convincing evidence that the technology was safe. The very successful Wind Gap, Pennsylvania Nu-Tech tire pyrolysis facility had received no complaints from citizens or environmental groups. The reviewers had questions about the marketability of the carbon black and pyrolytic liquid products.

(iii) (a) Universal (formerly Nu-Tech). This tire pyrolysis system is similar to Conrad's tire pyrolysis technology (see section I.4(b)), but prices for their pyrolysis reactors are lower. Conrad sells a set of two reactors with a total capacity of one ton/hour for \$4 million. Universal offers a set of two reactors with the same total capacity for \$1.4 million. The Universal reactors burn at 950°C, which is high for tire pyrolysis. Tires are shredded into 1" x 1" and 1" x 2" pieces. When the tires' beading is removed, the resulting ash content is 0.5% of the carbon char.

Such a system has been operating at the Wind Gap, Pennsylvania facility. Independent sources state that its main revenue product, carbon black, is of unusually high quality, and has a steady market. The firm plans a 200 ton/day, \$7 million plant in Ireland whose principal product would be

pyrolytic oils (the Wind Gap plant makes a blendable, burnable heating oil that sells for 25 - 40 cents/gallon).

General Motors apparently has tested Universal technology on auto shredder fluff, but has kept results proprietary.

Legal difficulties apparently have limited Universal's efforts, and financing appears to be uncertain.

(b) **Envirotire** plans to build and run a dedicated tire pyrolysis plant in Riverhead, Long Island. The company is completing financial and management arrangements to build a turnkey system. Front-end separation equipment has not been chosen. The company stresses that the facility will be the first of its kind in the United States, but details have not been available. The plant is to process new tire discards from Long Island and New York City. The company is not interested in pyrolysis of the two million stockpiled in Kings Park, Long Island, nor pyrolysis of MSW, plastics, and other materials of interest to NEWME.

Neither the **Envirotire** nor the Universal pyrolysis system currently meet the criteria given in section I.1(b) for endorsement for the broad applications of primary interest to NEWME. For example, both target a very limited portion of the solid waste stream, and plan to stick to the tire market. Universal has some interest in specialized waste streams, such as car fluff, but their financial and other resources are limited as of this writing. Many processing and equipment details of the **Envirotire** system have not been settled, and the unavailability of key information on the process muddles any determination as to their technological readiness. Neither company has an active interest in raw MSW or hazardous/remediation wastes.

As noted in section II.5(b), these firms' interests in other wastes, and their financial and engineering circumstances, may change in this quickly moving arena. NEWME should keep these companies "in the loop" and abreast of developments of potential interest.

PART II

RECOMMENDED COMMERCIAL-READY PYROLYSIS SYSTEMS WITH HIGH MARKET POTENTIAL IN MUNICIPAL, INDUSTRIAL, AND DEPARTMENT OF ENERGY WASTE APPLICATIONS

II.1 Pan American Resources, Pleasanton, California

Note: information in this section is based on Pfeffer et al. [1985], Heckman [1993], Pan American Resources [1992, 1993], FioRito [1993], Coulter and Simpson [1992], and on discussions with company officials, regulators, and scientists.

(a) Company Experience and Partners

Pan American Resources invented and marketed a small batch pyrolysis system, described in Part I, that saw common use on farms and ranches from the 1930s until the 1960s. In the 1950s, Pan American Resource's Dae Lantz, Jr., patented the Lantz converter, a continuous-feed pyrolysis reactor that kept air and oxygen out with air-lock seals. The engineering design of this and ancillary devices evolved during several projects and applications. [Note: this patent expires in 1998. PAR states that improvements will extend the patents beyond 1998.]

The National Bureau of Standards chose PAR's Destructive Distillation system, which had evolved during the prior decade as one of the best inventions of 1979 from thousands of applicants. That recognition led to a commercial-scale (50 ton/day) demonstration plant at the Marcal Paper Mills, Elmwood, NJ, in 1982, under a grant to PAR from the U.S. Department of Energy, pursuant to a recommendation from MITRE. The plant processed raw residential and commercial MSW from Monmouth County, New Jersey. During the 2.5 years of pyrolyzer operation, performance was monitored, emissions were measured, and feedstock and product compositions were assayed for the DOE by three chemical engineering professors at the City University, New York [Pfeffer, et al. 1985]:

The results of the final testing and evaluation ... indicates [sic] that the invention has the ability to provide substantial energy savings in an environmentally safe manner, utilizing municipal solid waste as its sole source of fuel. The technology, dry distillation, should be able to convert a wide variety of potentially hazardous waste products into useable energy without polluting the atmosphere. These include garbage, pharmaceutical waste, printers' inks, paper, plastics, railroad ties, barnyard waste, oil, paint, grease, rubber, solvents, agricultural waste, and other organic material.

Of the four companies whose pyrolysis systems are assessed in this report, Pan American Resources clearly has the most experience with pyrolysis, and with pyrolysis of solid wastes in particular. This experience includes eight years' accumulated commercial operating time with 50 ton/day units, the standard module.

However, PAR's long history appears to have included some episodes of poor management decisions, misguided oversight by the inventor's family, and successful recent litigation against Waste Distillation Technology, once a licensee, to recover possession of a the 50 ton/day Marcal unit stored on Staten Island. These problems appear to have been overcome. New leadership with major national technical, large-scale project (including DOE), and financial credentials has been established since 1990. The backgrounds of PAR officers are described in Pan American Resources [1992].

In addition, Pan American has subcontracted with M3 Engineering and Management (Tucson) for process engineering and facility design. The firm conducts \$150 million in projects each year with its

professional and technical staff of more than 100. Schuff Steel Company (Phoenix) is licensed to make the Lantz Converter and other facility equipment. It is the fourth largest steel fabrication and erection company in the United States, and is certified by the AISC to fabricate nuclear and fossil fuel plants, high-rise buildings, and other specialized projects. Facility construction itself would be supervised by Sundt Corp (Tucson), an award-winning firm that has more than 100 years experience on major industrial and commercial projects.

Pan American's reorganized management has launched a major marketing effort and has submitted proposals in California, Arizona, Ontario, Puerto Rico, and other areas (see below). A wide range of waste streams is being sought: MSW, old landfills, hospital wastes, hazardous wastes, and tires.

(b) Process Description and Feedstocks

The PAR system accepts raw MSW feedstock (with glass and metals removed by 'front-end' separation devices), and all types of organic solid wastes individually or in combination (plastic, paper, wood, yard wastes, food). The system also is designed to process old landfills, hospital wastes, and tires.

Feedstock is shredded into 1" pieces and dried at 170°C -- for MSW, this reduces moisture content from 25% to under 10% -- and fed continuously through an air seal into an oxygen-free Lantz Converter retort. Residence time in the 650° retort is 15 minutes. (Its rotating kiln design is superior to that of a "drop-it-in-a-box" pyrolysis reactor once offered by Total Energy Systems.) Char exits continuously through an air seal. Gases produced vary from a low- to a medium-Btu fuel, depending on feedstock, that can be enriched with methane to bring the Btu value to desired levels. Table 2 compares the chemical composition of the product gas to that of other commercial fuels. Fifteen per cent of the product gases are burned under the retort to drive the endothermic pyrolytic reaction. [See Fig. 2, System Flow Chart]

Table 2: Gas Comparisons, as Percentage Volumes

The gas produced by the Destructive Distillation Process is compared with other commercial fuel. The specific analysis may vary with the area and conditions.

	MSW Non-Recycled Distilled Gas	Wood Distilled Gas	Natural Gas	Landfill Gas	Blast Furnace Gas	Coke Oven Gas	Refinery Gas 1	Refinery Gas 2
Hydrogen	6.1	22.6			1.3	54.0	5.6	46.3
Nitrogen	33.8	.4	1.86	6.6	59.8	5.6		2.5
Carbon Monoxide	32.0	22.5			25.6	7.4		
Carbon Dioxide	13.4	30.7	0.44	41.0	12.6	2.0		
Oxygen	.09	0.2		1.8		0.4		
Methane	6.5	23.6	95.3	49.0	0.7	28.0	10.3	13.8
Acetylene	.06							
Ethylene	3.34							
Ethane	.92		2.16			2.6	10.4	23.3
Propane			0.02				2.1	14.3
Butane			0.02				0.7	
Isopentane			0.01					
Carbon	3.74							
Water vapor				1.6				

Source: Pan American Resources (1993)

One ton of MSW yields roughly 928 pounds of gas, 160 pounds of carbon char, and 260 pounds of inert materials (glass, non-ferrous metals) incorporated in the char. Options for upgrading it are discussed below.

One ton of organic solid waste feedstock yields about 60 gallons fuel oil. The yield from a 250 ton/day destructive distillation plant is estimated to result in a net savings of 100,000 barrels of oil annually. With catalysis, the oil can be synthesized into C7 or C8 oxygenated fuel additives, such as MTBE (methyl tertiary butyl ether), that comply with provisions of the Clean Air Act Amendments applicable to the Long Island region.

Figure 2: System Flow Chart

Source: Pan American Resources (1992).

Several options are available for the product gas mixture. (a) In PAR's basic configuration, product gases are burned directly in a steam boiler on-site to provide energy for the facility, and to make electricity for sale to local utilities at Public Utilities Regulatory Policy Act of 1978 (PURPA) prices. Steam and/or cogenerated waste heat could be used by a collocated or adjacent industrial park or institution. Storage of pyrolytic gases or liquids is not required. (b) Also, the gases can be transported to a utility or industrial cogeneration plant for electricity generation there. As with the Tuttle/Conrad process, product gases instead can be liquefied, and then (c) catalytically synthesized into MTBE or other C7 or C8 oxygenated fuels, or (d) sent to a refinery for conversion to heating oil, petroleum, plastics, or other petroleum products. Finally, (e) gases could be flared at 1,650°C to dissociate any dioxins, furans, PCBs, or other hazardous organic materials that may have been present in the original feedstock and survived pyrolysis.

The char is 50% carbon. The volume of char is 3% of that of the original, unseparated MSW, a reduction that is significantly greater than that from incineration. By weight, char averages 15% of the organic material in MSW, and 21% of the original MSW before metals and glass separation.

The char can be treated. Char is 3% (by weight) ash for MSW feedstock, and 6% - 11% ash for tire feedstock. Ash is removable with air classification or by the newer degreasing and acid-leaching process developed by Petrich and commended by the 1993 DOE InnCon program [InnCon 1993]. This latter process lowers ash content to 0.5%, yielding a high-value activated carbon.

The carbon in the char is either semiactivated or fully activated, depending on feedstock and processing regime. High-pressure steam can fully activate any partially activated carbon. Activated char is a marketable filter/adsorbent that removes pollution from liquid/gas waste streams in several industries, and from oil-spill cleanup wastes. Following such applications, the then VOC-laden activated carbon can be decontaminated and regenerated by running it through the destructive distillator again.

An interesting emerging use for carbon black is as a dispersant in HCFC-141b, a substitute for chlorofluorocarbon blowing agents in the manufacture of certain foamed plastic products. Most CFC substitutes do not provide the foam insulating value of CFC. Using high-quality carbon black with HCFC-141b raises the insulating value of the foam by 6% - 9%. [Modern Plastics 1994]; the feasibility of this application has not been explored.

Activated carbon also has uses in making rubber, paints, and other materials, as noted in section 1.2. It may be possible to use new processes, such as the Enviro-Clean process [InnCon 1993 (Lewis)], which has been targeted for further development by the Department of Energy, to recycle heavy metals that may be present in the char (whether from a contaminated original feedstock or from environmental remediations). The process uses acid regenerants to remove heavy metals adsorbed onto granular-activated carbon, after which the metals are recovered electrolytically from the solution. Alternatively, such heavily contaminated chars can be sent to a hazardous materials landfill.

For landfill mining, PAR would employ special high-speed carbide shredders, "Carlisle beaters," that dry and grind simultaneously, and then remove the dirt by air classification. PAR states that the principal factor limiting the performance of the system with such trying materials is that the destructive distillator must produce sufficient byproducts to power itself. Theoretically, MSW should yield ten times as much energy in heating value as is required to obtain that energy. However, dirt and rocks can act as heat sinks, and lower these net energy gains. Previous landfill mining demonstrations have used grinders that wore out and clogged too easily [NYSERDA 1992]. NYSERDA's Edinburgh, New York demonstration project learned that landfill materials "as is" are too contaminated for either recycling or incineration; better screening, or other pre-treatment is needed.

Hospital wastes can be delivered in sealed containers, shredded by a sealed shredder, and passed to the Lantz Converter. PAR has designed a sealed shredding/processing system that uses off-the-shelf equipment, including the "Medsafe" sodium hypochlorite sterilization system.

With the ram injection system that is standard equipment on the PAR system, up to 20% tires (by weight) can be mixed with MSW or other feedstock. Higher percentages are feasible, but the feed system would require modifications. Steel would be recovered for recycling.

Finally, the system is designed to decompose liquid and solid hazardous organic wastes from industry and from site remediations; these include solvents, chlorinated hydrocarbons, VOCs, treated railroad ties and CCA lumber, and printers' inks. Certain non-hazardous industrial wastes also may be treated. PAR states that its systems can process most hazardous organic materials along with MSW or separately, in either case with no modifications in equipment. Sewage sludge and some industrial sludges also are processable. These materials are beyond the scope of this report.

(c) Environmental Effects

(i) Char

Few metals vaporize or melt at the destructive distillation temperature of 650°C. This represents an advantage over incineration, which proceeds at much higher temperatures. In the PAR system, any heavy metals and other inorganics present in the feedstock are encapsulated in the char, beneath a layer of polymerized organic coke material that forms on the particles' surfaces. This layer, which is not present in incineration ash, strongly inhibits leaching of the metals, as shown in EP Toxicity and other tests [Pfeffer et al. 1985] that compared the char leachate with leachate from char that was subsequently incinerated. Total energy yields from the PAR technology would increase by 20% if the char was incinerated. However, this is not advisable because air pollution from the incinerator would increase, as would the leachability of the incineration ash.

No polychlorinated dibenzodioxins or dibenzofurans were detected in the char nor in any of the other solid or gaseous product streams in the DOE tests. The char adsorbs 90% of the chlorine and 30% of the sulfur present in the feedstock, so that much less acid gas is produced than even in starved-air incinerators.

Although activated carbon that is contaminated with heavy metals (say, after cleaning up a DOE site) may be sent to a hazardous landfill, it may be feasible to recover valuable heavy metals, for example, by using the Enviro-Clean process, which the Department of Energy has targeted for further industrial development [InnCon 1993 (Lewis)]. If VOCs and other hazardous organics are present, following clean-ups, the activated carbon can be recycled, i.e., regenerated by running it through the destructive distillator again.

(ii) Air Pollution

The Department of Energy [Pfeffer et al. 1987] tested emissions from a common stack serving the drying unit, the distillator and the boiler so including pollutants from burning of product gases. The stack had no pollution control devices. As shown in Table 3, very high reductions in pollution were found across the board, compared to uncontrolled emissions from a mass-burn incinerator tested by the California Air Resources Board.

Table 3: Results of Air Pollution Testing - Uncontrolled Emissions

Pollutant	Incinerator* Emission Rate (lb/ton)	Waste Distillator Emission Rate (lb/ton)	Percent Reduction by the Waste Distillator
Particulates	50.0	9.17	82
SO ₂	3.9	1.84	53
SO ₃	nr	8.40	
HCl	7.7	0.48**	94
CO	7.7	0.881	89
NO _x	4.4	2.66	41
VOCs:		0.284	
Condensable	0.21	0.163	22
Noncondensable	nr	0.121	
Formaldehyde	nr	0.0004	
Lead	0.370	0.007	98
Beryllium	0.00008	0.00002	69
Mercury	0.002	0.00002	99
Nickel	0.010	0.0006	94
Chromium	0.020	0.002	87
Arsenic	0.005	0.0001	97
Cadmium	0.040	0.0005	99
Dibenzodioxins	nr	nd	***
Dibenzofurans	nr	nd	***

Source: Pfeffer et al. (1985).

nr - not reported

nd - not detected

* Source: "Air Pollution Control at Resource Recovery Facilities"; California Air Resources Board; 24 May 1984.

** Obtained by material balance

*** Traces of dibenzodioxins and dibenzofurans have been identified in the emissions from several incinerators abroad and in the United States. Testing showed that neither pollutant was detected in the stack gases of the Waste Distillator.

The HydroSonic scrubber, developed and used by du Pont and DOE at Savannah River, was identified as the best available control technology, and is specified as standard equipment in the PAR system. Controlled emissions also are much lower for the PAR system than for both the California plant and a two-stage starved air Canadian incinerator tested by the U.S. EPA. The latter is considered to be one of the best-run incinerators in North America. [See Table 4, Comparison of Emissions]. The higher level of chromium for the PAR system reflects the fact that chromium-containing plastics were removed from the Canadian plant's feedstock before testing.

Table 4: Comparison of Emissions (Tons/yr) for 50 Ton/day Plant

Pollutant	*Incinerator/DD	*Ratio: Incinerator/DD	**Ratio: Incinerator/DD
CO	5.6/7.7	0.73	8.8
NO ₂	42.2/3.5	12.1	11
SO ₂	8.1/0.8	10	30
HCl	7.8/0.04	195	1590
PCDD	12 x 10 ⁻⁶ /nd	> 10 ⁵	
PCDF	15.8 x 10 ⁻⁶ /nd	> 10 ⁵	
Particulates	0.83/0.87	0.95	5.0
Cadmium	0.103/0.00005	2060	
Lead	0.78/0.0069	113	528
Chromium	0.00045/0.0011	0.41	200
Nickel	0.027/0.00025	108	300
Mercury	0.077/0.0000005	154,000	2000
Arsenic	0.0005/0.0001	5	1000
Totals	66.1/12.9	5.1	

Source: Pan American Resources (1993).

* Prince Edward Island Data, U.S. EPA

** Ca. Air Resources Board, 24 May 1984

DD = Destructive Distillation

Product gases have been flared at the 150 ton/day plant in Salzgitter, Germany, whose pyrolysis system is virtually identical to the Lantz converter. This plant principally converts waste plastics to product liquids that are converted again to virgin plastics. No dioxins, furans, PCBs, or other hazardous organic compounds were found in tests.

Net reductions in pollution would accrue from using activated char in the environmental applications noted above (particularly if the activated carbon is recycled), and from using products such as oxygenated gasolines, electricity, or new plastics, that substitute for conventional petrochemical-derived products. For example, virgin plastics derived from liquefied product gases would avoid some of the pollution generated by extracting, transporting, and refining petrochemicals. PAR estimates that a 250 ton/day destructive distillation plant that makes electricity would save the energy equivalent to 100,000 barrels of oil per year. Net reductions in pollution also might arise if pyrolysis diverts some wastes from other methods of waste management.

(d) Long Island/Regional/DOE Prospects

For existing collection systems for discards and recyclables on Long Island, targets of opportunity include low-grade and/or contaminated papers (including newspapers), plastics other than No. 1 and No. 2 containers (especially PP, PVC, PS, and HICs), and industrial plastics scrap (e.g., from Long Island electronics and plastics manufacturers). Existing plastics recycling programs reach at most 14% of all post-consumer plastic discards [Barlaz et al. 1993, Curlee and Das 1992, Swanson et al. 1993, Breslin et al. 1993]. When market conditions block their recycling, paper and other recyclables may be

obtained from MRFs. Institutional food wastes (and food wastes in MSW) and agricultural wastes also are primary targets of opportunity. Proximity to East End towns may attract agricultural wastes, depending on the success of MSW composting projects.

PAR's proposed design to co-process 88 tons/day of regional MSW with 12 tons/day of regional hospital wastes at the Pima Maricopa Indian Community (Arizona) could be a significant model for Long Island. The 160 or so tons/day of Long Island hospital wastes (including red-bag wastes) also can be processed with the Destructive Distillator, using the sealed system designed by PAR. It may be possible to develop an integrated system of sealed collection containers brought to sealed shredders, such as that under development in Bari, Italy, in cooperation with SUNY/Stony Brook's Marine Sciences Research Center.

The discarded tires in Kings Park, Long Island could be co-processed with MSW. Under conditions described in section II.5(b), these two million tires could be eliminated from within six months (at 100% tire feedstock) to within 2.5 years (at 20% tires, 80% MSW).

PAR's engineering development in this area makes landfill mining promising. PAR has submitted two landfill mining proposals in the United States and Canada; the design could be transferred to landfill mining in New York State. That approach could extend the lifetimes of landfills in the NEWME region: 80% of the landfills in the northeastern United States are scheduled to close by 2010. NYSERDA may be interested in exploring such a project. PAR has expressed an interest in tackling New York City's Fresh Kills landfill.

The industrial waste streams mentioned above (railroad ties, treated lumber, paints, inks) and liquid and solid hazardous or non-hazardous industrial organic chemical wastes also appear to be particularly well suited for the PAR system; these include wastes generated by Long Island electronics manufacturers who have applied for major federal funds to develop alternatives to CFCs and VOCs that minimize waste and prevent pollution. Here, there might be an opportunity to examine the possible use of pyrolytic carbon as a dispersant for foamed plastics, albeit that Long Island's electronics manufacturers have used CFCs mainly for cleaning circuit boards and other advanced electronic equipment, and not in connection with foam manufacture.

Wastewater sludges from paper mills outside metropolitan areas also have been proposed for treatment with the PAR system by a PAR stockholder and former officer [Fiorito 1993].

PAR has shown a strong interest in major operations on Long Island aimed at MSW, tires, plastics, hospital wastes, hazardous organics, and other industrial/commercial materials. A 50 ton/day and a 100 ton/day unit are available; the former could serve a "wasteshed" of 125,000 people if it were devoted to MSW only. If either unit meets expectations, PAR envisions the possibility of expanding with 50-ton/day modules to a distributed or centralized system appropriate to the scale of the region's waste stream -- 200 to 300 tons/day at a minimum.

A 100 ton/day unit that is available costs \$400,000 to \$500,000. A new one would cost upwards of \$1 million, and total "turnkey" system costs (including separation, shredding, steam and electricity generation) might run to \$10 - \$13 million. There are many ways to lower or parry some of these costs, so price information is somewhat premature before more specific discussions. For example, as with the other technologies discussed in this report, there may be opportunities to share existing waste-separation infrastructure. PAR officers have stated their willingness to develop a plant on Long Island as a loss-leader.

A crew of 28 (total, not per-shift) would operate the 100-ton plant on a 24 hour/day, 7-day/week basis. M3 has designed new, highly automated controls for the operating systems.

Capital costs for a turnkey 100 ton/day plant on Long Island are estimated to be \$13.5 million or less (a 50 ton/day facility could run \$9 - \$10 million). A site of two to three acres would suffice, but three to five acres would be desirable. PAR states that a tipping fee of, at most, \$60/ton, averaged over all feedstocks, would ensure profitability. Other revenues could be shared by PAR and towns. A 100 ton/day facility selling electricity for 6 cents/kwh (a low price for Long Island) would yield a revenue of from \$15/ton to \$60/ton, depending on feedstock, for a minimum income of \$1,500 per day (= \$540,000/year). At \$10 per 1,000 pounds, steam sales could return \$1.8 million annually. At 160 pounds of carbon char per ton of MSW, current market prices (70 cents/pound) would return \$112/ton of MSW. Another source quoted current prices for high-grade virgin activated-carbon as \$0.75 to \$1.50 per pound. The many grading subclassifications make comparisons elusive. Tipping fees would make up the difference.

Participation by LILCO or other utilities in financing may be worth discussing. A 250 ton/day MSW pyrolysis plant would generate between 2.5 and 10 megawatts of electricity. Some of the financial benefits discussed in section II.6 and elsewhere in this report may apply.

Potential revenue varies with feedstock. Hazardous wastes would command very high fees. To take another example, using standard tires, processing 20,000 tires/hour at 650°C yields 655 pounds of carbon. At \$1/pound for the particular grade of high-grade carbon that can be produced, revenue becomes \$655/hour. Markets for this material vary strongly with its quality, and it is unclear that this revenue is realistic, given the effectiveness and costs of current upgrading techniques. However, as noted, economics for the PAR system depend on tipping fees and sales of electricity or other energy products. Any revenue from char is regarded as an extra dividend.

Forecasts of income from sales of liquefied pyrolysis products (for fuel or plastics recycling applications) are not available in PAR's literature. While PAR has stated that it is prepared to make a careful regional assessment if NEWME is interested in exploring such options, all evidence suggests that prospects for sales of these products are similar to those for the liquid products of the Conrad/Tuttle Technologies system.

PAR owns a 4 ton/day demonstration Lantz Converter that ran for 30 years. It is in storage; some re-wiring would be needed to meet present-day specifications. PAR has stated its interest in making this unit available to SUNY/Stony Brook or Brookhaven National Laboratory for environmental engineering studies (gas chromatography, continuous emissions monitoring, materials studies). PAR also is interested in working with BNL and Stony Brook to obtain federal or state funds to develop computer models relating variations in MSW feedstock to changes in the makeup of the product gases.

PAR is interested in building upon earlier SUNY/Stony Brook and Brookhaven National Laboratory experience to develop and assess ways to use char in (a) concrete construction blocks, (b) sound barrier walls and other bulk infrastructure applications, and (c) containment barriers at contaminated waste sites.

BNL projects could concentrate on the performance characteristics of various DOE cleanup wastes in the PAR system, on the performance of char-derived carbon in those cleanups, and on decontamination and recycling methods for char. BNL and SUNY/Stony Brook also could play a role in the engineering of sorting and materials-identification technologies. PAR is strongly interested in working with national laboratories on the pyrolysis of waste streams from ammunition processing and destruction processes; they have significant expertise in this area.

PAR's Adelanto, California design for a 10,000 ton/day facility to handle waste shipped by rail from Los Angeles may be a model for wastes from New York, or other large cities. Three-quarters of this MSW would be pyrolyzed, one-quarter composted. While siting such a facility would be impossible

on Long Island, a less-populated location in the Eastern United States might serve as a mega-landfill/pyrolysis/recycling facility, as envisioned in Judd [1993].

II.2 Entropic Technologies Process

Note: information in this section is based on [Entropic Technologies 1993(a) and 1993(b)], and on discussions with Entropic personnel, regulators, and other parties.

The Entropic technology produces a synthetic coal by pyrolysis of organic components of shredded MSW. Pyrolysis occurs in a small, simple tube at very low temperatures generated entirely by friction from mixing augers that act as a kind of waste meat-grinder.

(a) Company Background

Entropic Technologies was formed in 1984 and has exclusive worldwide rights to patents held by the inventors. The key idea was the realization that twin screws, unlike a single screw, would generate enough heat for pyrolysis. Entropic's chief engineer was in charge of the design, construction, and operation of the \$2 billion Great Plains Coal Gasification facility, the first commercial synthetic fuels facility in the United States. Several other individuals and firms from the Great Plains and other coal gasification projects were instrumental in developing the Entropic system. The person in charge of Entropic's project development and financing has arranged financing of \$1 billion in environmental facilities during 10 years with the Ford Motor Company, and in other capacities. Equity financing was arranged for Huntington's Ogden-Martin incinerator, and several other East Coast incinerators.

Development of the technology was supported by \$2 million in grants from the State of Michigan and the federal government. The major plant equipment is made by APV (Saginaw, Michigan), a \$4 billion company that makes large industrial equipment for the National Aeronautics and Space Agency (NASA) and other major clients.

The Turkish government has expressed interest in the Entropic technology as an element of its national waste policy. Project opportunities are being pursued in Greece, Taiwan, Spain, South Korea, and the Philippines. Marketing and development capital is sought to help penetrate what the company sees as large markets in Eastern Europe, the Middle East, and Asia.

(b) Process Description

In the first stage of the Entropic process, a series of shredding, separation, and size fractionation steps remove metals, glass, and building materials from MSW and convert the remainder into a refuse-derived fuel (RDF) of sufficiently uniform consistency. This shredded material may be stored on-site for short periods as the logistics of production require. Next, a twin-screw conveyor continuously moves 8 tons of RDF per hour per screw through the pyrolysis reactor (called the "carbonizer" in company literature). The reactor is simply a 12-inch diameter cylinder 25 feet long. Friction from the screws' mixing action heats the feedstock to 290°C; no other source of heat is used. The RDF feedstock contains varying proportions and grades of plastic, paper, food scraps, cardboard, fabrics and other soft items, and fine inorganic solids. This feedstock also helps lubricate the extruder's surfaces. The process diagram is shown in Figure 3.

Off-gases (with a condensable oil) are burned on-site to produce energy to make the steam that drives the conveyor. Gases are removed as material travels down the screw, resulting in an odorless, greaseless syncoal. Burning the off-gases at 1,650°C destroys all hazardous organic compounds that may have been present in the original MSW. No detectable levels of hazardous organic substances

have been found in the condensable oil. Acid gases and particulates are removed from flue gases by a dry sodium-sesquicarbonate scrubber and a baghouse.

One ton of unprocessed MSW yields 1,513 pounds of RDF, which is pyrolyzed into 700 pounds of volatile gases and 832 pounds of syncoal. As noted in section 1.2, the lower the temperature of pyrolysis, the greater the proportion of char byproduct. In the Entropic system, the design goal of maximizing syncoal production dovetails with the low temperatures possible from the mechanical energy of mixing alone. The pyrolysis tube is oxygen-free except for remanent oxygen in small voids in the feedstock.

On average, of the 487 pounds (of the ton of incoming raw MSW) that is not made into RDF, 275 pounds are unprocessibles that are put into landfills, and 212 pounds are recyclables recovered in the separation steps (glass, 76 lbs.; ferrous metals, 118 lbs.; non-ferrous metals, 18 lbs.)

(c) Environmental Effects and Syncoal Properties

The heating value of the syncoal fuel is 9,500 or more Btu/lb. (70% of the heating value of the RDF). The syncoal has passed U.S. EPA's EP Toxicity test both as uncombusted fuel and as combusted ash; the ash has passed the TCLP Analysis test (this test apparently was not run on the coal). The concentration for virtually every element was very substantially below regulatory limits.

Moreover, U.S. EPA Tests Nos. 8240 and 8270 found no detectable quantities of potentially carcinogenic chemicals, such as dioxins, trichloroethylene, and other volatile organic compounds, among the one hundred or so compounds covered by these tests. Syncoal itself is formed at temperatures too low for dioxin formation, and burns at temperatures (1,370°C or higher) that destroy the hydrocarbon precursors of dioxins.

The syncoal is a low-sulfur (under 0.25%) coal and would not be a significant contributor to acid rain. It is chemically similar to Western sub-bituminous coal, but with virtually no moisture and with an ash content similar to that of Pennsylvania bituminous coal. Syncoal ash is nonhazardous under RCRA definitions, low in heavy metals, and appears to be far less prone to leaching into groundwater than is incinerator ash. Michigan's Department of Natural Resources determined that the ash may be disposed of in existing landfills without modification and with no need for new permits, and that the syncoal itself may be blended with coal. Detailed data are available on the chemical composition and combustion engineering characteristics of the syncoal, syncoal ash, and oil.

Entropic syncoal has been burned in several Detroit Edison tests, alone and mixed with varying amounts of coal. Co-firing with coal, particularly as a substitute for costly Western low-sulfur coal, is its major targeted market.

PROCESS DESCRIPTION

Front End

PROCESS DESCRIPTION

Carbonization

Figure 3: Entropic System

Source: Entropic 1993(a).

(d) Pontiac, Michigan Project and Earlier Waste Experience

The City of Pontiac, Michigan agreed to act as host community for a commercial, 630 ton-per-day plant, and has guaranteed access to the City's landfill for residues. The facility will handle 85 tons of MSW from Pontiac daily, at an average tipping fee under \$50 per ton. Entropic also has been negotiating long-term put-or-pay contracts to receive waste at this facility from other Michigan cities, and expects very shortly to be signed up very close to the 630-ton capacity. The initial, up-front capital costs for the system are \$45 million, plus the cost of the front-end separation system. In the full-scale design configuration, incoming waste is processed into fifty tons of RDF per hour in two shifts daily, 5.5 days per week. Three pyrolizers are run at 77% capacity. The twin-screw mixing technology has been a fixture for many decades in powder and paste compounding operations and other chemical industry applications, often with materials far less tractable for mixing than MSW. These machines are commercially available in a wide range of diameters and capacities.

Entropic has used the technology on RDF from many localities, including auto-shredder waste, on wastes spiked with PVC and crumb rubber, and on upholstery and foam padding. Many of these materials came from landfills without prior front-end separation, and included rocks and dirt. Results of the landfill mining were acceptable, but it is clear that much better results would be obtained with pre-treatment screening and trommelling. The same conclusion was reached in New York State-sponsored experiments with "mining" of old landfills by incineration and other techniques [NYSERDA 1992]. Proper pre-treatment also would reduce the ash content of the syncoal and raise its energy value. The syncoal from the metal-laden shredded landfill automobile waste passed EP Toxicity tests, as did the ash from the burned syncoal made from it.

Tires can be processed by mixing them with MSW to enrich the rubber content of the MSW from the baseline 2% to 4% or 6%. Rubber fractions above this level may be difficult to ram into the conveyor. The Entropic system also is highly suitable for hospital red-bag wastes. Company officials see the DOE environmental restoration and waste management programs, and federal cleanup operations generally, as an important market for them. The economic outlook for applications of the Entropic technology to Long Island/Northeast United States MSW is seen as particularly bright because waste-tipping fees are much higher than in the Midwest.

(e) Prospects for Long Island and Other Markets

This pyrolysis system has several distinctive, appealing features. The small physical scale of the pyrolysis units allow comparatively easy modularization, just-in-time expansion, and somewhat easier siting. The friction-only, low-temperature heating regime lowers energy costs, simplifies engineering, and maximizes syncoal production per unit feedstock. Another advantage is that all pyrolytic oils produced are used on-site. The low profile of the facility also may facilitate siting; the 20-foot off-gas flare stacks would be the highest part.

Syncoal would be marketed to coal-using utilities seeking alternatives to low-sulfur western coal in New York State (outside Long Island), New Jersey, Connecticut, and other nearby areas. Current prices in the midwest are \$1 per million Btus for syncoal, versus \$1.40 per million Btus for Western coal. Longer-distance markets may be available. The Long Island Rail Road could freight syncoal if a plant is built on Long Island. Emissions-trading aspects of the Clean Air Act Amendments also may render syncoal more attractive to utilities. Syncoal ash would be incorporated into existing management systems for a utility's coal ash. From a regulatory and environmental standpoint, syncoal ash is easier to manage than incinerator ash.

The company has targeted several waste stream components of concern to Long Island besides MSW *per se* (auto shredder residue, old landfills, hospital wastes, problematic plastic resins, and tires).

The company has operational experience with several of these components, and with MSW generally. The company's technical and managerial resources appear first-class.

Company officials have indicated that they are prepared to make substantial technical and capital resources available to develop a project on Long Island. Company partners include the multi-billion-dollar APV industrial equipment firm, and a major RDF equipment maker. Also, negotiations are near completion with major corporations whose names cannot be divulged as yet.

Capital costs for a 100 ton-per-day plant would be much less than for the 630 ton-per-day plant designed for Michigan. Much of the cost is for separation equipment. Costs of front-end separation equipment would be lowered considerably if arrangements can be made to share the considerable stock of separation equipment at existing Long Island incinerators and MRFs or at planned MSW composting facilities. Gains in efficiency could lower costs for all parties concerned.

With such arrangements, an Entropic system could be built cheaply on Long Island. One twin-screw system, including ancillary equipment, and pollution control systems could be installed on Long Island on a turn-key basis for \$5 to \$6 million in capital costs. If needed, an additional shredding unit to prepare the RDF would cost extra. A Long Island facility could process dedicated waste streams and also could provide standby or buffering capacity for other waste-management facilities.

Business opportunities appear quite promising in Eastern Europe, the former Soviet countries, China, and other heavily coal-dependent, polluted regions scouting for comparatively inexpensive, pollution-reducing coal substitutes made from wastes with basic industrial equipment.

An intriguing regulatory issue is posed by the Entropic technology. The New York State Department of Environmental Conservation classifies MSW pyrolysis as a thermal treatment technology, subject to the same rules as incineration (this does not apply to tire pyrolysis in New York State, which has been assigned a beneficial use determination). However, the Entropic system runs at temperatures not much higher than those generated in many conventional plastics recycling systems, such as the extruders used to make plastic lumber. So the rationale for treating plastics recycling as a form of mechanical treatment and plastics (and MSW) pyrolysis by the Entropic method as a form of thermal treatment seems debatable. The Ontario Ministry of Environment and Energy has just ruled specifically that this technology is not a form of incineration, following an extensive formal review. Michigan's Department of Natural Resources classifies the Entropic system as a "waste processing facility." The major formal criterion for membership in this regulatory category is that hourly Btu consumption fall below a cutoff value, as is the case for conventional recycling operations.

Entropic's Pontiac facility has received strong support from environmental and neighborhood groups.

As discussed in section II.5(d), no decision has been reached as to whether wastes that are pyrolyzed will count towards a Suffolk County New York Town's recycling goals, or qualify for tax or other advantages.

(f) DOE Opportunities

The small size of the tube would appear to make for easily transportable units for wastes in field locations not requiring prior sorting and shredding. Consequently, transportable Entropic units appear well-suited for handling some of the relatively homogeneous wastes created in cleanup operations at DOE sites. Other cleanup wastes may be too liquid or otherwise unsuited to frictional heating. Brookhaven National Laboratory might study (1) what kinds of DOE cleanup wastes have physico-chemical characteristics conducive to pyrolytic heating by mixing friction (perhaps supplemented by some externally applied heat), and (2) what sizes of tube and screw work best with those wastes

(diameters of commercial models run from 0.5" to 36"). Experience with paste and powder mixing in the chemical industry might shed light on these questions. Also, Entropic has been discussing possible projects involving the handling of automobile shredder waste with Argonne National Laboratory; the company has stated that should these discussions bear fruit, there would be many opportunities to dovetail projects at Brookhaven.

II.3 Hynol Corporation, New York, New York

Note: this section is based on Hynol [1993], Steinberg and Dong [1993], Steinberg et al. [1990, 1991, 1993], Steinberg [1987, 1991], Steinberg and Cheng [1987], Kobayashi and Steinberg [1992], Grohse and Steinberg [1987], and on conversations with Hynol personnel, regulatory officials, and other interested parties.

(a) Background

Like the other pyrolysis systems sketched in this study, the Hynol system converts a flexible range of waste feedstocks into a multipurpose product, namely, methanol as a liquid fuel in power plants and motor vehicles, as an ingredient in reformulated, less polluting gasolines, and as a basic industrial chemical. The power production and transportation applications comport strongly with requirements for pollution reduction of the Clean Air Act Amendments [CAAA] and other legislation, especially in CAAA noncompliance regions like New York City and Long Island, where increased use of oxygenated fuels is mandatory.

REM Capital Corp. of Arlington, Virginia, which has significant experience dealing with MSW technologies, has acquired a half-interest in Hynol, and has formed a new company vested with exclusive worldwide rights to MSW applications of the patented Hynol process. Two Hynol principals are BNL chemical engineers with extensive, world-class experience (a third handles management and finance). A national commercialization effort has been mounted by the Hynol Waste-to-Methanol Consortium, recently formed by REM Capital (finance and project development), Hynol (technology supervision), John Brown Inc. (facility design and engineering), Acurex Environmental, Inc. (environmental engineering), and Verner, Lipfert, Bernhard, McPherson, and Hand (legal and regulatory affairs). These are top-flight financial and scientific resources.

(b) Process Description (Figure 4)

The Hynol system amalgamates three processes -- a hydrolysis step (also called hydrogasification, this refers to pyrolysis in a hydrogen, or largely, hydrogen atmosphere), a steam pyrolysis step, and a methanol synthesis step.

The Hynol process and its relative, the Hydrocarb process, were invented and developed at Brookhaven National Laboratory. Hydrocarb originally was engineered to produce, as its primary product, a clean carbon by hydrogenating and then pyrolyzing coal. The carbon can be used as fuel or as an ingredient in tires, paints, and inks, or simply stored to mitigate potential greenhouse effects by reducing levels of carbon dioxide in the air. Depending on the system's configuration, hydrogen, methane, methanol, or water are co-produced. Later engineering design turned to wood and other biomass, and then to MSW feedstocks. In the Hynol technology, methanol becomes the primary marketable product, and the carbon-containing ash residue is destined for landfills or incorporated into secondary materials. Hydrocarb (unlike Hynol) appears to require additional engineering development before commercialization.

As are other pyrolysis systems, Hynol is suited to a broad range of carbonaceous feedstocks: wood, agricultural waste and other biomass, used oil, hazardous organic and other industrial wastes, plastics, tires, old landfills, and MSW with or without certain components removed.

Step 1: The carbonaceous feedstock is reacted at high temperatures with a hydrogen-rich gas (recycled from step 3) and high-pressure steam in a fluidized-bed hydrogasifier (HGR), yielding a mixture of carbon monoxide, methane, and nitrogen gases. The exothermic reaction that forms the methane supplies the energy for the two endothermic reactions that form the carbon monoxide. Operating conditions would be adjusted according to the feedstock: for example, 800°C at 30 atmospheres for biomass; 900°C for feedstock high in sulfur to allow its full removal by adding limestone.

Not all carbon is converted to carbon monoxide or methane: some of the feedstock would end up as char (approximately 18% in the case of a biomass feedstock, perhaps 20% of wet weight for MSW).

Step 2: After particulate and gaseous impurities are removed, the gas mixture from Step 1 is combined with natural gas and reacted with steam in a steam pyrolysis reactor (SPR) at (for biomass feedstock) 1,000°C and 30 atmospheres, making carbon monoxide and hydrogen. The energy in the exit gas is used to heat the hydrogen-gas mixture from Step 3 for use in Step 1, and to make the high-pressure steam used in the HGR and SPR. The fraction of natural gas co-feedstock is expected to vary between 40% and 70%, as dictated by the composition of the feedstock. For instance, more plastics in the feedstock means less methane; some mixed MSW feedstocks without plastics may require 70% methane.

Step 3: Most of the carbon monoxide/hydrogen gas from Step 2 (now at 260°C, 30 atmospheres) is converted to methanol in a conventional methanol synthesis reactor (MSR). Heat from this exothermic reaction can be used to remove feedstock moisture before Step 1. The rest of the carbon monoxide/hydrogen mixture is recycled to Step 1.

The key to the Hynol system is its integrated design. For example, energy for endothermic reactions is provided by exothermic process reactions. The Hynol system is self-sufficient in energy, hydrogen, and steam. Such synergies mean that methanol yield for the process as a whole is estimated to be 12% higher than it would be for the sum of the individual conventional processes. The methanol yield also is higher per unit biomass and per unit methane co-feedstock than an advanced fluidized-bed biomass gasification process developed by the Institute for Gas Technology that has drawn DOE's attention.

The self-sufficiencies and the high efficiency of methanol production lower capital and operating costs. Closed materials-loops also lower expected emissions. Net emissions of carbon dioxide are estimated to be about 41% lower than for standard methanol production using steam reformers. As noted, the proportion of methane co-feedstock can vary to compensate for variations in the composition of incoming MSW or other feedstocks.

The Hynol technology appears ready for large-scale commercialization. Their literature notes that the reactors in each step are commercially available or have been demonstrated at large scales. Some design engineering is advisable to tailor the hydrolysis equipment to MSW feedstocks, and to improve systems for removing impurities from gases.

Carbon Efficiency	67.9%
Thermal Efficiency	69.0%
CO ₂ Emission	106.8 lb/MMBTU

Figure 4: Hynol System

Source: Steinberg and Dong (1993).

(c) Environmental Effects

The benefits of reducing or avoiding pollution depend on what the Hynol system is being compared to: conventional systems for making methanol from natural gas, naphtha, petroleum residues, or coal; other MSW disposal systems; emissions from combustion of conventional or alternative fuels; or emissions associated with electricity generation from oil- or coal-fired plants. In these comparisons, carbon dioxide, nitrogen oxide, sulfur, and dioxin/VOC emissions appear to be much lower for the Hynol technology, although more careful assessments are needed that pay detailed attention to the often tricky system boundaries and methodologies used to quantify these comparisons [Reaven 1984, 1985, 1986, 1987(a), 1987(b), 1987(c), 1993(a), 1993(b), 1993(c)].

Fundamental physico-chemical principles and emissions data from pilot or full-scale analogues of Hynol system components persuasively argue that emissions of acid gases, sulfur compounds, nitrogen oxides, dioxins and other VOCs would be zero to extremely small (and, in any event, smaller than those from conventional methanol-production facilities, and from conventional incinerators). Heavy metals in the char are in a less-leachable, reduced form. Detailed information on expected chemical composition and physical characteristics of the char is not available.

Methanol used as automotive fuel reduces overall emissions of carbon dioxide by 41% on a per-mile basis (1.5 to 2 gallons methanol substitute for 1 gallon of gasoline, depending on the engine's efficiency). Nitrogen oxides are not generated. The Hynol plant would produce sulfur-free methanol that satisfies all U.S. EPA regulations on its use as a utility or transportation fuel. In noncompliance areas, the Clean Air Act Amendments require increased use of alternative fuels, including methanol, in vehicles (either directly or as MTBE or other oxygenated gasolines) and utilities (alone or co-fired with oil). Methanol's advantages over natural-gas fueled vehicles are that as an easily transportable liquid, it meshes well with existing fuel distribution systems and engines, and that there are no emissions of methane.

(d) Long Island/Regional/DOE Prospects

The Hynol Waste-to-Methanol Consortium has prepared a project summary to solicit funding for a large Long Island facility. Long Island is a major target of their efforts. Preliminary calculations support very attractive returns to potential investors. The Consortium has discussed this proposal with several LI towns, with suppliers of natural gas to the utilities, and with those utilities that are potential methane users (Brooklyn Union Gas, Con Edison, LILCO). The Consortium is willing to consider any potential sites, sources and kinds of garbage, and institutional arrangements.

One scenario is to build a facility that would accept 3,450 tons of raw MSW daily (wet weight, including yard and kitchen wastes) at \$40 per ton. After unspecified steps to remove paper, plastic, and moisture, some 1,725 tons would be processed with 1,061 tons of natural gas, producing 2,500 tons of methanol and 690 tons of char ash daily. The reduction in volume is projected at 80% or more, although it is not clear whether this refers to MSW accepted by the facility as a whole or the MSW processed by the Hynol reactors. Capital costs are estimated to be \$250 million or less for a municipally owned, privately operated plant.

Methane would be sold to utilities for co-firing in oil-fired electric generation plants (especially for peaking power), operators of methanol-fueled fleets, and refiners as an ingredient in MTBE. A preliminary analysis suggested an effective price (on an equivalent gasoline-miles basis) of \$0.66/gallon, compared to refinery gasoline prices of \$0.73/gallon for oil priced at \$20/barrel. If world oil prices drop significantly and drive down methanol prices, the revenue losses could be offset by increased, but still competitive, tipping fees. To some degree, prospects for methanol also depend on mileage improvements in automobiles.

The Environmental Protection Agency is proposing regulations on tax credits for producing MTBE and other oxygenated fuels under section 211(k)(1) of the Clean Air Act. The status of fuels from wastes has not been settled.

A preliminary calculation for a \$150 million, 4,400 ton/day (dry) wood-to-methanol plant that would make more than 100 million gallons per year showed a methanol production price of \$0.43/gallon, against 1993 market prices of \$0.45/gallon [Steinberg and Dong 1993]. Operating costs were estimated to be \$1.1 million per day. A 15% return on investment was assumed.

Hynol has indicated that landfill mining, hospital wastes, and industrial wastes (including hazardous organics) are regional markets of particular interest to it. Present expectations, though, are that MSW would be the likely linchpin of any Long Island operation. Hynol's degree of interest in targeting tires is not known, but the company hopes to process sewage sludge with other wastes in California.

Few details are available on the types and sources of MSW that would be sought, or the collection, sorting, shredding, size fractionation, and other pre-treatment regimes that might be employed. Partly, this reflects an open-endedness: many options could be designed, picking one would be premature in advance of discussions and negotiations with the region's waste management community. The Consortium has cited as examples of possible waste sources MSW now landfilled in the Town of Brookhaven and in New York City. (The amounts cited are questionable). However, acceptance of waste from outside Long Island may be unpopular politically.

The Consortium's next step should be to clarify its front-end options for the waste stream. There are many questions. The Consortium indicated that one option is to process MSW from which paper and plastics have been removed. Removing much more than is captured in (separately collected) curbside recycling programs is a challenge, a "dirty MRF" approach may be required. The rationale for removing these materials at all is unclear because they are fully pyrolyzable, their recyclability is problematic, and most recyclers will not accept them due to contamination or their low value. Presumably metal and glass would be removed, at least above certain sizes. Would all the materials not destined for the Hynol reactors be removed at the Hynol plant, or elsewhere beforehand? What shredding, size fractionation, control of contamination, and possible upgrading by salting with specialized homogeneous wastes would maximize the reactor's performance? These are particularly important engineering issues for landfill mining. Would wastes be sought from Towns or private haulers, especially for commercial waste? What role would be played by specific institutional and commercial waste streams, e.g., restaurant, auto shredder residue [Reaven 1990, Reaven and Tonjes, 1991]? How would the expected waste flows complement existing incineration facilities, recycling programs, including existing contractual arrangements concerning waste flows? How would state-mandated goals of 10% source reduction and 40% recycling (more for Long Island) be advanced, and how would Hynol processing be counted in Solid Waste Management Plans (as fuel recovery or energy recovery)? How would use of the Hynol system affect towns with ash-for-trash or other exchange arrangements, and landfilling with incinerator ash?

It bears emphasis that these are all solvable problems, well within current engineering capability and the envelope of what can dovetail with the existing intricate, highly differentiated regional system of waste management. As with the other pyrolysis systems, the general problem is to obtain the maximum amounts of pyrolyzable wastes with the minimum amounts of nonpyrolyzable wastes, and, at the same time, to handle as much as possible of the MSW (and other wastes) that is not being managed viably by other means, such as recycling. There are tradeoffs of contamination, containerization, grade, energy value, cost, and many other factors. The Consortium includes companies with the necessary experience to complete the required system design and analysis of the waste stream.

The most promising option for char disposal appears to be incorporating it into secondary materials, such as the construction blocks made with incinerator ash, developed by the Waste Management Institute at SUNY/Stony Brook. This option should be explored with a view to conducting the necessary materials tests.

The Hynol system can process a very wide range of wastes generated in DOE and other federal (and state) environmental cleanup projects. Much of the equipment and personnel resources for implementation tests and studies is in place at Brookhaven National Laboratory.

Like the Tuttle Technologies/Conrad and Pan American Resources systems, Hynol produces a keystone, multipurpose industrial chemical. An advantage of the Hynol process is that no additional refining or significant blending steps are required. Moreover, unlike the Entropic, PAR, and Tuttle/Conrad systems, Hynol can run on 100% natural gas to ride out any periods when MSW is not economically obtainable. On the other hand, unlike PAR or Tuttle/Conrad, the principal product of the facility cannot be recycled into new materials, rather than fuels.

Apart from its environmental benefits, a large-scale Hynol facility would be a major economic windfall for Long Island. The considerable ripple effects in construction jobs and supplier orders would be magnified by the fact that much of the money involved would remain in regional circulation -- for example, by purchasing natural gas from regional utilities, or by converting the former Shoreham Nuclear Power Station to run on methanol. Perhaps the Grumman Corporation could run the Hynol plant, or provide a site.

The five large Suffolk County towns recently broached the possibility of creating some sort of joint waste-management authority in the coming years. The Hynol system could be an ideal project for any such regional authority. Siting prospects for a facility billed as a maker of safe, environmentally clean, easily transported, alternative fuel would be brighter than for a facility packaged as a waste disposal operation. A Hynol facility could very well attract national attention for making a tangible dent in automotive pollution in one of the nation's most congested traffic complexes, and for doing so with the region's own resources. That kind of attention would help national and international marketing efforts.

II.4 The Conrad/Tuttle Technologies Process

Note: information in this section is obtained from Tuttle Technologies [1993], U.S. EPA [1991], American Plastics Council [1993], and from discussions with officers at Tuttle Technologies, Conrad, regulatory agencies, trade associations, and environmental organizations.

(a) Process Description (Figure 5)

This technology is a variation on the plastics-industry- supported Conrad system for pyrolysis of post-consumer plastics wastes (with and without tires) now undergoing testing in Chehalis, Washington, in preparation for commercial operations. That process evolved from the Conrad tire pyrolysis technology that was the subject of a major U.S. EPA assessment [U.S. EPA 1991].

In what here is referred to as the Conrad/Tuttle Technologies process, a 100 ton/day MSW-feedstock pyrolysis system produces an alternative fuel with the same properties as low octane (86) unleaded gasoline. This fuel, which runs "as is" in automotive engines, is made by blending alcohols created by the pyrolysis with stripped natural gas liquids (SNGs). More than seventy percent of MSW is suitable for the pyrolysis process.

The plant would receive 145 tons/day of MSW and sort it to extract aluminum, ferrous metal, and glass (by color) recyclables, and to remove dirt and oversize items. These operations should leave perhaps 100 tons of feedstock, primarily paper, organics, and plastics, to be shredded into 2-inch

pieces. After removing moisture, this material would be stored in silos equipped to prevent any buildup of gases.

The shredded feedstock is fed continuously to a 540°C Conrad pyrolysis unit where it is converted to product gas and carbon char (6% - 8% of the original volume). Some of the gas mixture is used as a heat source for the system, some is sent to the alcohol synthesis unit, and some is condensed to oils which in turn are sent to the alcohol unit. Energy is supplied by a second, smaller pyrolysis unit that can run on tires, wood waste, and other materials.

The alcohol conversion plant is a standard cracking tower that produces 15,000 gallons of mixed alcohols, primarily methanol, per 100 tons of MSW entering the pyrolyzer. It receives, at a pressure of 1,200 pounds per square inch, the gases and oils from the pyrolyzers, stack gas, and compressor off-gas. These gases are cooled, scrubbed twice, and compressed, reheated, and steamed (providing H₂ to make alcohols), catalytically vaporized, and condensed. Compressors are powered by a dedicated second pyrolyzer that would most likely be fed with tires and wood waste.

In Conrad/Tuttle Technologies' design-basis scenario, the mixed alcohol is stored for one week to accumulate 100,000 gallons for mixing with SNGLs (the system design also drives short-chain molecules into longer-chain, less volatile molecules). A site with rail, pipeline, or Interstate access is preferred, to receive SNGLs and to ship the final fuel.

Depending on the chemical makeup of the MSW, the char can be placed in a landfill or an ashfill, used in a fertilizer, or converted to activated carbon and sold.

(b) Environmental Effects

Process parameters and environmental impacts for the steps up to and including pyrolysis are expected to be very similar to those for the earlier Conrad systems. The company has not given detailed information on characteristics of the char. U.S. EPA [1991] measured particulate, VOC, and other air emissions at the Conrad tire facility, as the centerpiece of a broad study of tire pyrolysis, and concluded

"Pyrolysis units are expected to have minimal air pollution impacts because most of the pyro-gas generated in the pyrolysis process is burned as fuel in the process. During burning, the organic compounds are destroyed. Assuming complete combustion, the decomposition products are water, carbon dioxide, carbon monoxide, sulfur dioxide, and nitrogen oxides."
[U.S. EPA 1991, p. 8-13]

The facility did not require special equipment for pollution control other than the standard equipment to capture excess gas at the flare stack, nor equipment for continuous emissions monitoring. Emissions were well within state limits (Table 5). The U.S. EPA also found that "...water pollution problems should be minimal," with the use of non-contact water-cooled condensers [U.S. EPA 1991, p. 8-20]. Regulatory compliance was straightforward (an annual state inspection). Fugitive VOC emissions from a "generic" pyrolysis plant, and fugitive dust from char-handling operations, also were estimated (Table 6), and were found to be a decidedly minor, controllable matter [U.S. EPA 1991, pp. 8-14 to 8-16]. The U.S. EPA also found that char from scrap tire pyrolysis "...does not indicate a problem with hazardous materials" [U.S. EPA 1991, p. 8-16].

As with the Hynol system (and, in certain respects, the Entropic and Pan American systems), the "alternative fuel" configuration is associated with "total system" reductions in pollution and energy when compared to pollution generation and energy use associated with current automotive fuels. Similar Clean Air Act Amendments incentives would apply.

Figure 5: Conrad/Tuttle System

Source: Tuttle Technologies

Table 5: Emission Estimates from Pyrolysis Facility, Conrad Industries^a

	Concentration (mg/l)	Emission Rate ^b (lbs/MMBtu)
Particulates	2500	1.0×10^{-4}
Metals		
Aluminum	1.51	6.7×10^{-8}
Chromium	0.82	3.7×10^{-8}
Iron	9.89	43.9×10^{-8}
Magnesium	0.45	2.0×10^{-8}
Manganese	0.09	0.4×10^{-8}
Mercury	0.05	0.2×10^{-8}
Nickel	2.95	13.1×10^{-8}
Potassium	1.84	8.2×10^{-8}
Sodium	18.62	82.7×10^{-8}
Zinc	0.65	2.9×10^{-8}
Semivolatile Organics		
Bis-(2-ethylhexyl) phthalate	10.2	45.3×10^{-8}
Butyl Benzyl phthalate	1.7	7.5×10^{-8}
Di-n-butyl-phthalate	0.9	4.0×10^{-8}
Naphthalene	2.87	12.7×10^{-8}
Phenol	1.4	6.2×10^{-8}
Volatile Organics		
Benzene	20.2	c
Ethylbenzene	24.1	c
Toluene	30.8	c
Xylene	16.2	c
Sulfur Dioxide	310,500	7.7×10^{-2}
Nitrogen Oxides	210,000	9.7×10^{-3}

Source: U.S. Epa [1991].

- ^a These emission estimates reflect the composition of the pyro-gas, which is either burned in the process as fuel or vented to the facility's flare. These estimates do not reflect atmospheric emissions.
- ^b These emission rates were calculated by taking the average concentrations reported for the compound and multiplying it by the average flow rate for the test runs. An energy input of 31 MMBtu was used to calculate lbs/MMBtu.
- ^c Flow rates were not reported. Thus, pounds of emissions per hour could not be calculated.

Table 6: Estimated Fugitive VOC Emissions from a "Generic" Pyrolysis Plant

Fugitive Emissions Source	No. of Sources in Process	VOC Emissions (kg/day)	VOC Emissions (lb/day)
Pipe Flanges	47	2.72	6
Valves	12	30.84	68
Pump Seals	4	5.90	13
Compressors	1	5.00	11
Pressure Relief Valves	1	2.27	5
Open Drains	7	4.54	10
Total		51.27	113

Source: U.S. EPA [1991].

(c) Long Island/Regional/DOE Prospects

In its tire-pyrolysis phase, Conrad did not remove benzene and toluene from pyrolytic liquids because this was too costly. Instead, the pyrolytic liquids were sold as a substitute for No. 6 fuel oil. U.S. EPA [1991] found that these liquids had a promising, untapped market as a blending oil for commercial fuels. The Conrad/Tuttle system extended this idea of blending by introducing the alcohol step and by concentrating on MSW rather than tires. Pyrolytic liquids obtained from MSW feedstock would have much lower fractions of sulfur, benzene, and other pollutants than liquids obtained from tire feedstock.

Each year, 38 million gallons of SNGLs would be purchased (prices have remained stable at \$0.42 per gallon) for blending with the alcohols. Independent (i.e., unbranded) distributors and distributor associations would market the resulting "syngas" to local fleets, especially government fleets complying with mandates to increase use of oxygenated fuels, and local, independent gasoline distributors. The production cost of the mixed alcohol is estimated to be \$1.29 per gallon. At the \$0.42 per gallon price for the SNGLs, the production cost of syngas is estimated to be \$0.55 per gallon. The sale price of syngas is at least \$0.60 per gallon. This profit is apart from significant tax incentives for creating alternative fuels. Alcohols were chosen because they were seen by Conrad and Tuttle Technologies as the highest-value product that could be made readily from the output of the Conrad pyrolyzers. Apparently, the existing Buckeye pipeline could be used to transport materials for the Conrad/Tuttle system.

Tuttle Technologies, Conrad's representative for the eastern United States, has begun an effort to sell the system in the eastern United States. The effort has led to collaboration with a major national waste hauler and other partners who would transport MSW by railroad from several locales in the region to a large-scale pyrolysis facility that would be built in Michigan. The City of Newark expressed interest in examining options for pyrolysis of its MSW, since nearby refinery complexes, a source of SNGLs, and the allied concentration of fuel-blending and distribution facilities, make the Conrad/Tuttle process attractive. The City of New York has shown an interest in examining options for pyrolysis of commercially collected papers.

Marguerite Tuttle, President of Tuttle Technologies, stated that the firm is strongly interested in developing a project on Long Island or elsewhere in the region, and in building a turnkey facility, and either operating it or training others to do so. Arrangements as to ownership, leasing, and financing are said to be very flexible. The plant would employ 29-33 persons.

The recyclables obtained for the sorting operations could proceed to a MRF, if the degree of contamination is compatible with the tolerances of the particular MRF. As with the other pyrolysis technologies discussed in this report, potential synergies with existing waste management facilities include use of their baling and crushing equipment and pyrolytic processing of their rejects. MSW could be obtained from most of the sources identified in section II.5(a).

A spreadsheet provided by Tuttle Technologies promises a 27% return on investment in year 1, 35% in year 5, and 44% in year ten. The total 10-year capital costs are given as \$35 million (approximately \$4.2 million in year one, \$3.4 million annually thereafter). The total 10-year operating expenses are \$278 million; these rise annually from approximately \$20 million in year one to \$29 million in year ten. Most of the operating costs are for purchasing the bulk SNGLs. Total 10-year revenue is given at \$382 million, for a total net revenue of \$102 million.

Capital costs per installed ton of capacity are higher for the Conrad/Tuttle system (\$350,000) than for the Hynol 3,450 ton/day system (\$72,500), the 100 ton/day PAR system with a new Lantz Converter (\$100,000 - \$130,000), and the 100 ton/day Entropic system (minus a shredder) (\$60,000). However, this preliminary calculation ignores (i) the absolute size of the plant that is wanted, (ii) amortization and other financing packages, (iii) significant differences in operating costs, (iv) distinctions between costs for wastes that arrive ready for pyrolysis with minimal screening, separation, or pre-treatment and costs for wastes that significantly require such measures. The comparisons of capital costs per installed ton of capacity also do not consider whether recalcitrant wastes commanding higher fees are processed, such as hospital, hazardous, or old landfill wastes.

Quoted prices are likely to come down in negotiation because representatives of the four companies have said that their firms want to crack the Long Island market with its dense concentration of wastes, waste facilities, and infrastructure, and so see a plant in this region as a loss-leader. Furthermore, there are many ways to share direct and in-kind costs, and benefits, among the participants (towns, DOE, fuel companies, utilities, universities, fuel distributors, recyclers, and so on).

Waste stream targets for the Conrad/Tuttle system, besides MSW per se, are similar to those for the other pyrolysis systems but with somewhat greater emphasis on post-consumer plastic wastes, and, presumably, less emphasis on tires or old landfills. The Conrad/Tuttle approach shares several of the features of the Hynol approach. Both are large operations (compared to the Entropic or Pan American Resources systems) that seek to tap the regulation-driven demand for alternative transportation fuels, both dovetail with the existing infrastructure for fuel preparation and distribution, and both may need significant on-site storage.

The LIRR or other regional railroads may be able to develop a railhaul arrangement similar to that planned in Michigan. This concept might underlie a large pyrolysis facility designed to accept wastes from the entire metropolitan area, including New York City, and beyond. Siting any such mega-operation on Long Island would be logistically inadvisable and politically impossible.

II.5 Regional Waste Applications

(a) Municipal Solid Waste

(i) Pyrolyzable Materials in Long Island's Waste Stream

There appear to be ample opportunities for using pyrolysis to treat Long Island municipal solid wastes. About 2.25 million tons per year of MSW that is not now, or soon likely to be, recycled is appropriate for pyrolysis. Not all of this catchment is available practically, however. One-third consists of materials for which pyrolysis is a clear improvement over current practices; this is the easiest target

of opportunity for pyrolysis, which would provide a backup to other waste management and recycling systems. Penetration into the second third would establish pyrolysis as one of the stand-alone, anchor, waste-management technologies. The remaining third (0.75 million tons) would be available for pyrolysis only if there is a significant move away from the existing incineration capacity.

Realizing these opportunities calls for careful systems design that takes into account the variegated collection, processing, and disposition arrangements for wastes and recyclables across Long Island. While there are several specific kinds and sources of wastes that are attractive targets to get pyrolysis off the ground, the full potential of pyrolysis best can be realized if regional, multi-town arrangements are worked out.

Some background on area MSW circumstances helps clarify these points. Of approximately 20.16 million tons of municipal solid waste reported in New York State in 1992, approximately 49% was placed in landfills, 17% was burned in waste-to-energy plants, 4% was burned without energy recovery in New York City municipal and apartment incinerators, 19% was shipped out-of-state, and 10% was recycled [New York State LCSWM 1993].

The 49% in landfills consisted of MSW (74%), industrial wastes (10%), incinerator ash (6%), construction and demolition debris (4%), and other materials (6%). The principal components of the recycled 10% were paper of all types (37%), metals (16%), glass (4%), plastic (1%), mixed recyclables including some plastics collected among mixed recyclables, yard waste (21%), and construction and demolition materials (8%). Other states in the Northeast report similar overall percentages.

Long Island departs from this pattern. As shown in Table 7, incinerators burn more than 45% of Long Island's MSW; 25% is sent off the island, perhaps 20% is recycled, and 10% (all in Suffolk County) is put in landfills [Tonjes and Swanson, 1992; Swanson, et al., 1993]. County- and island-wide statistics may camouflage significant variations among the towns. Estimates of waste generation, composition, and disposition for individual towns may be found in Tonjes and Swanson [1992], and in the Solid Waste Management Plans (SWMPs) each town must prepare pursuant to ECL 27-107 and 6NYCRR Part 360-15.

Table 7: Fate of MSW Generated on Long Island in 1992 (Thousand Tons/yr)

	Total	Incinerated	Recycled	Transported	In Landfills
Suffolk	1,825	650	350	475	350
L. I.	3,500	1,650	675	875	350

The Island's strikingly lower fraction of landfilled wastes reflects the stringent Long Island landfill closure law. The higher rates of incineration and recycling reflect the concentration of wastes on Long Island, and the impetus to recycling in the aftermath of the garbage barge fiasco [Reaven 1987(c)].

Guidelines set by the New York State Department of Environmental Conservation require a 50% reduction in net waste generation by 1997 (40% from recycling, 10% from source reduction). What would constitute meeting these numerical goals is a matter of thoroughgoing debate. The seeming precision of the numbers belies many fundamental questions about what wastes to count, and even how to measure them [Reaven 1994].

Seven and one half pounds of municipal solid waste discards per capita enter the Long Island waste stream every day; this figure includes residential, commercial, and some industrial wastes. It does not include construction and demolition wastes [Lambert and Domizio 1993], and certain other wastes usually accounted for separately.

However, despite all the attention paid to recycling and waste management in recent years, our detailed knowledge of the quantities, compositions, and dispositions of MSW and other wastes is surprisingly shaky. Federal (U.S. EPA), State (Department of Environmental Conservation and the Office of Recycling Market Development of the Department of Economic Development), and town figures inconsistently define waste components, group the components into incommensurable categories, and tabulate the results according to incompatible accounting methods. The information often is too aggregated to break down suitably. Figures reported by sources of questionable reliability are taken at face value, and large amounts of waste sometimes elude tabulation altogether.

Tonjes and Swanson's [1992] survey is the most careful one available of the Long Island waste stream, precisely because that study was undertaken to disentangle the methodological confusion. The Town of Brookhaven's Updated Solid Waste Management Plan [Tonjes, September, 1993] is the only reliable recent analysis of a town's MSW that breaks down the waste stream into sufficiently detailed categories for the purposes of the present study. Therefore, the waste stream composition, generation, and disposition data reported in these two documents were the two primary sources used to gauge the local potential for pyrolysis; these data were supplemented by, and cross-checked against, other sources. The conclusions on the quantities of pyrolyzable wastes then were scaled up from the Town of Brookhaven to Long Island according to their respective populations. The practical availability of those wastes varies from town to town, depending on each town's waste management program.

Recyclables collected in existing and imminent recycling programs are unsuitable for pyrolysis because state and federal policy gives clear priority to waste reduction and to conventional recycling programs. However, recyclables that are not processed for recycling, or that cannot be recycled due to economic or technological conditions, are assumed to be eligible for pyrolysis.

Table 8, derived from Tonjes [1993], shows the estimated amounts of pyrolyzable wastes generated in the Town of Brookhaven that were not collected in recycling programs. The Town's own MSW operations handle 1,062 tons of largely residential waste daily. Private collectors handle 590 tons/day of almost entirely commercial wastes. Another 200 tons of construction and demolition wastes is generated daily.

The Town of Brookhaven sends 200,000 tons to the Hempstead incinerator and, in return, puts 244,000 tons of ash from this incinerator into the Town landfills. Town plans also call for the construction of a private MSW composting plant with an annual capacity of 109,000 tons of MSW and yard wastes, of which perhaps 90% would be pyrolyzable. Wood wastes, for example from storm damage, collected by the town's highway department are not included in the Table 8; this material is chipped and made available to citizens. Table 8 also does not list automotive "car fluff," a prime candidate for pyrolysis (31,590 tons/year are placed in the Town's landfill).

Table 8: Residential and Commercial Pyrolyzable Wastes Not Collected in Recycling Programs, Town of Brookhaven, 1992 (Tons/yr)

	Residential	Commercial	Total
Paper	68,275	69,295	137,570
Newspaper	11,300	7,523	18,823
Magazines	436	230	666
Corrugated Cardboard	19,323	39,958	59,281
Kraft Paper	2,540	1,344	3,884
Boxboard	7,603	4,698	12,301
Office Paper	9,945	6,113	16,058
Books	867	459	1,326
Other	16,261	8,970	25,231
Plastics	27,019	17,286	44,305
HDPE	1,123	473	1,596
PET	1,996	1,158	3,154
Other rigid	14,612	9,418	24,030
Other flexible	9,288	6,287	15,575
Food	23,145	30,000	53,145
Textiles	16,145	6,891	23,036
Wood	21,143	20,088	41,226
Rubber	3,799	2,917	6,718
Diapers	6,294	3,319	9,613
Yard	22,573	6,076	28,649
Leaves	1,310	207	1,517
Grass	15,394	4,525	19,919
Brush	5,869	1,344	7,213
Total Pyrolizable	188,393	155,872	344,625
Total not collected for recycling	207,853	171,603	379,456

Source: derived from Tonjes [1993].

Table 8 suggests that nearly 91% of the town's residential and commercial wastes now collected apart from recycling programs, nearly 950 tons/day, could be pyrolyzed. This value is a maximum. More realistic assays must take several other factors into account. One is the expected expansion of residential recycling programs. For the present analysis, it is assumed that, at most, collection programs will only improve to the degree that 25% of the paper and 25% of the plastics listed become collected. These improvements reflect wider, better residential participation, and the possible addition of certain kinds of paper and plastics to the list of materials collected for recycling.

A second factor is the extent of existing and future recycling by commercial operators. Of the pyrolyzable materials, this is almost entirely corrugated cardboard of sufficiently low contamination. It is assumed that 50% of the commercially collected corrugated cardboard is or will be recycled.

Higher levels of commercial and residential waste recycling and waste reduction are called for in town projections for 1997 and 2009, pursuant to requirements imposed by NYSDEC in 1993 mandating increased commercial recycling, including on-site source separation at businesses. However, it is unlikely that these goals will be met. Concrete, economically realistic plans for meeting them are not in sight. In any case, businesses are reluctant to shoulder any added costs, and volatile markets for recyclables make carters suspicious of commercial source-separation. The waste industry prefers to rely on post-collection sorting (including front-end separation at an incinerator, MSW composting facility, "dirty" MRF, or a pyrolysis plant).

Taking the above factors in consideration, some 300,000 tons/year of pyrolyzable wastes could be available for pyrolysis, roughly 90% of some 335,000 tons that would be collected apart from existing and prospective recycling programs. The Town of Brookhaven's waste stream is reasonably similar to that of other Long Island towns [see, Tonjes and Swanson, 1993]; many of the variations among towns cancel one another out. The Town of Brookhaven includes approximately one-seventh of Long Island's population. It is reasonable to assume that about 2.25 million tons of Long Island municipal solid wastes not captured by current or planned recycling programs is pyrolyzable. This estimate includes some New York City-generated commercial wastes that come to Long Island, but does not include other pyrolyzable wastes, such as the bulk of New York City MSW, tires, old landfills themselves, and pyrolyzable industrial and DOE cleanup wastes.

How much of the three million tons is available practically? Answers vary from town to town. Wastes shipped off-island, by towns or by private haulers, are available for pyrolysis if the haulers find the tipping fee at the pyrolysis plant competitive. Table 9 shows these exports. The range of tipping fees given in sections II.1 - II.4 is competitive with current off-island disposal rates, and is significantly cheaper than charges for incinerators and MSW composting plants on the island.

Table 9: 1993 MSW Incinerated In and Exported From LI Towns and NYC

Town	Tons incinerated	Tons exported
Babylon	217,000	
Hempstead	914,000	114,400
Huntington	268,000	13,700
Islip	156,000	
Long Beach	62,000	13,500
Glen Cove		21,700
Oyster Bay		264,200
North Hempstead		184,000
New York City		2,900,000

Source: Swanson, R. [1993].

In some towns, significant fractions of the pyrolyzable wastes may be unavailable due to contractual commitments to send wastes to incinerators. Then again, many incinerator operators may accept arrangements to divert pyrolyzable wastes that reduce the efficiency of incinerators, such as food wastes and an oversupply of plastics. Other towns have either decided not to build or rely upon

incinerators, or seek to reduce reliance on them, and are in a better position to entertain alternatives such as pyrolysis.

The agreement between Brookhaven and Hempstead allows Brookhaven to divert wastes from the Hempstead incinerator to support recycling and composting activities. Inasmuch as nothing is said one way or the other concerning pyrolysis, state regulatory decisions on the recycling status of pyrolysis may be crucial on this score.

Some towns, such as Riverhead, plan to rely on MSW composting as the anchor MSW management technology. However, the prospects for such operations have dimmed during the past two years, and composting may play a smaller role than originally envisioned. OMNI company plans to build an MSW composting facility in Riverhead, LI, NY. The design capacity for this plant has dropped significantly in view of difficulties in negotiating waste commitments from nearby towns. Towns (e.g., Islip) that had mounted large, regular (leaf/yard waste) composting operations have encountered increasing public opposition, relating to odor and perceived health risks, and some operational glitches, and are examining alternative treatments for such materials.

Even where MSW composting and incineration lay prior claim to large portions of the waste stream, significant quantities of wastes appear available for pyrolysis. The Town of Brookhaven's commercially collected wastes are an example. These wastes often have higher pyrolyzable fractions than residential MSW, because of the high fractions of (contaminated) corrugated cardboard, institutional food wastes, office paper, and comparatively homogeneous manufacturing discards, such as plastics.

Tires, some commercial plastics, auto shredder residue, food, textiles, and certain other pyrolyzable wastes could be brought to the pyrolysis facility already separated into homogeneous loads. This separation could be accomplished either by existing collection and delivery arrangements, or by expanded, dedicated commercial recycling routes, for example, for restaurants, supermarkets, hotels, and institutional cafeterias [Reaven and Tonjes 1991]. The latter option may be attractive to towns searching for ways to comply with the Department of Environmental Conservation's requirements that towns mandate commercial recycling.

Other wastes, including bulk MSW, would require separation of pyrolyzable materials (up to 90%) from non-pyrolyzable materials which could be done at the pyrolysis plant, or at existing or planned separation facilities at incinerators, MSW compost facilities, transfer stations, so-called "dirty" MRFs, or at the residential level.

In other words, there are many design options for accommodating existing waste separation, collection, and processing infrastructure to pyrolysis. This is particularly so in view of Long Island's advantages of short transportation distances, a concentrated supply of wastes, well-articulated network of brokerage services and value-added processors, and ready access to marketing and distribution networks [O'Neill and Sheehan 1993].

Long Island's MSW stream has the potential to support large-scale pyrolysis projects. It seems safe to say that arrangements could be made to obtain 750,000 tons per year of pyrolyzable MSW materials fairly readily as bulk MSW or individual MSW components. These wastes correspond to the backup option discussed below.

A second 750,000 tons per year would be available with significant additional effort, such as coordination with regional cooperation mechanisms, carter negotiations, reclaimer specifications, and collection vehicles and logistics.

The remaining, third 750,000 tons of suitable MSW materials could be obtained only in the unlikely event that incineration ceases to be a major element in municipal solid waste management on Long Island. These conclusions assume that tipping charges at pyrolysis plants stay within the competitive envelope projected in sections II.1 - II.4.

NEWME could play a major effort in facilitating regional or multi-town arrangements to obtain wastes for pyrolysis and for concomitant separation or other pre-processing. With Stony Brook's Waste Management Institute, the five major Suffolk County towns have begun to explore opportunities for regional cooperation in waste management, including forming a regional waste-management authority. Driven by economies of scale and from avoided duplication of facilities, several towns have institutionalized exchange of waste materials and recyclables, and access to landfills, MRFs, or incinerators.

The Department of Environmental Conservation has strongly encouraged such efforts, and inter-municipal agreements, generally. U.S. EPA's new Subtitle D rules for MSW landfills also encourage the formation of regional, multiple-municipality waste authorities and coalitions [Gambler 1993, Dunson 1993]. Other regional instrumentalities, such as the Long Island Recycling Cooperative, also could contribute to developing an integrated regional approach to waste management. Although issues about controlling the waste flow remain outstanding, major regional agencies have begun operation in Connecticut, Rhode Island, and Massachusetts [Redd 1993].

The waste management picture on Long Island remains in a state of flux. Answers have been elusive: the optimism in many quarters that greeted incineration, composting, MSW composting, and even recycling has faded. What has happened is that each of these technologies has carved itself a niche, but one that is smaller than was foreseen. It is precisely this development that creates an opportunity for pyrolysis.

While the practical niche for pyrolysis, too, may prove narrower than its estimated potential, it seems clear that a significant niche exists. Even if it does not develop as a stand-alone, "anchor" technology in MSW management, pyrolysis could play at least a complementing or backup role in an integrated scheme for waste management. This role would claim the first of the 2,250,000 tons per year of Long Island MSW appropriate for pyrolysis.

In this role, pyrolysis would serve as a backup technology that processes various wastes that, for one reason or another, are not being managed acceptably. These wastes include the landfilled pyrolyzables, pyrolyzables shipped off-island, plastics that are not being recycled because of severe economic or technological constraints, contaminated papers and plastics, and specialized wastes such as auto fluff and tires, and "recyclable" materials obtained from MRF's or front-end separation operations at incinerators and MSW compost plants. A backup strategy also will seek to obtain wastes that lower the operational and economic efficiency of incinerators, so that incinerator operators prefer not to process them. Landfill mining and pyrolysis of old tires also belong to the backup scenario.

Pyrolysis would become a stand-alone or anchor (instead of a backup) waste management technology insofar as it makes inroads into the second 750,000 tons per year of Long Island wastes appropriate for pyrolysis. Pyrolysis can be a critical pillar of integrated waste management in either role. In any event, the key public policy justification would be that pyrolysis moves the wastes one or more steps up the ladder of waste-management preferences.

(ii) Recommended Target Wastes for Pyrolysis

The specific materials that are targets of opportunity in the MSW stream are as follows (tires are discussed in the following section).

1. Residential and commercial plastics not collected or likely to be collected for recycling. Eighty per cent of post-consumer plastic waste is LDPE, HDPE, PVC, PP, PS, PET, or ABS. Post-consumer plastics make up nearly 10% by weight of Long Island's MSW [Swanson et al. 1993]. More than 85% of these plastics between 123,000 and 148,000 pounds per year in Suffolk County are appropriate for pyrolysis. The three components of post-consumer plastic waste sought by conventional plastic recycling programs, beverage containers (PET and HDPE), milk containers (translucent HDPE), and certain other household containers (mostly colored HDPE), comprise 14% of such discards and but 1.1% of MSW [Barlaz et al. 1993]. Almost all plastics collected for recycling are PET or polyethylene containers. Recycling of polyethylene grocery sacks, foamed and rigid polystyrene food service-ware (rigid and foamed), and PP bottles is negligible by comparison. A survey of the recycling programs of the 40 biggest American cities discovered that (a) fourteen collect PET and HDPE bottles only, (b) four collect HDPE plastic milk jugs and all plastic soft drink bottles, (c) two collect all plastic soft drink bottles, (d) one collects plastic milk jugs only, (e) four collect all plastic bottles, and (f) fifteen collect no plastics for recycling [Apotheker 1993]. Manufacturers of plastic lumber use commingled plastics obtained mostly from residential collection of post-consumer plastics and commercial collection of pre-consumer (largely polyethylene) scrap [Breslin et al. 1993].

Pyrolysis would aim at PE and PS products not collected for recycling, PP, PVC (keeping this material with a 50% chlorine content out of incinerators), rigid and flexible nylons, ABS, industrial plastic scrap, fibers and strappings, and miscellaneous engineered plastics, food-contaminated plastics of all resins, and multi-resin and multi-material laminates and composites. These materials could arrive for pyrolysis mixed with MSW or wastes, or in source-separated or otherwise pre-separated batches.

Plastic wastes from Long Island manufacturers of printed circuit boards and ABS computer cabinets are concentrated sources of plastics that are not being handled acceptably by any other technology.

Mechanical recyclers worry that pyrolytic recycling of plastics will drive feedstocks towards lower-end uses by creating low-cost liquid chemicals for refining, fuel use, or repolymerization. This is unlikely because pyrolysis targets hard-to-recycle plastics that are virtually unrecyclable in practice, for example, food-contaminated plastics, and multi-material tailings. The recent worldwide drop in virgin resin prices has meant that mechanical recycling is not competitive except at the highest value-added end. The only recycled resin for which demand holds strong is PET [Modern Plastics, Jan. 1994, pp. 45 - 85]. Some Long Island plastic-lumber manufacturers have closed or reduced operations due to high electricity and other operational costs.

Long Island incineration plants seek to reduce the amounts of plastics processed because their high heating value leads to operational difficulties and reduces efficiency.

2. Residential and commercial papers not collected or likely to be collected for recycling. These are largely lower-grade, often contaminated materials. Recycling programs emphasize cardboard, newspaper, and office paper.

3. Pyrolyzable rejects, bypass wastes, and processing residues from materials recovery facilities. These comprise approximately 10% of materials collected for recycling and delivered to the MRF.

4. Materials that are collected in recycling programs but never recycled. Such items are processed by a MRF, but are never made into new products because of bottlenecks in production capacity or prohibitive costs. Instead, the recyclables end up "stored" in landfills or "temporary" warehouses, and they deteriorate.

This surfeit of recyclables has become a major problem for Long Island recycling programs. At the end of 1993, the volatile markets for many recyclables, especially newsprint and other low-grade

papers, were near all-time lows. For example, in 1993, the price of old newspaper (ONP) rose from negative values to \$25-\$35 per ton and then to negative values again [Rabasca 1993]. Although some new paper-recycling facilities opened, to stanch severe losses, several other large paper-recycling mills closed, others reduced capacity, and plans for others were dropped or delayed. German and Asian recycled and virgin plastics inundated the world market and rocked the economics of all but the largest, vertically integrated plastics recyclers. The outlook remains promising only for PET and HDPE.

Circumstances may improve as the worldwide recession ends. But the economic volatility of paper recycling and mechanical plastics recycling is expected to continue for the foreseeable future. Pyrolysis can help paper and plastics recycling ride out periods of oversupply by providing backup capacity. Furthermore, electricity generated from pyrolysis could be earmarked for use by mechanical plastics recyclers at rates that would allow these manufacturers to stay on Long Island, instead of moving South in search of affordable electricity [Breslin et al. 1993].

5. Unwanted "front-end" materials received from MSW composting plants and incinerators. An MSW composting plant may send to the recyclers plastics that are separated at the front-end but are not suitable for mechanical recycling. The kind of available material would vary with the type of facility and depend on the attractiveness of options for those materials, other than pyrolysis.

6. Food wastes, especially from institutional cafeterias, supermarkets, agricultural processors, and restaurants and hotels. Constituting some 10% of MSW, these wastes include residential, institutional cafeteria, supermarket, hotel, restaurant, and agricultural and food processor wastes. Very little food waste composting is attempted on Long Island because of inherent process difficulties. Institutional food wastes are collected in compactors or other concentrated forms outside most large cafeterias, making these wastes particularly outstanding candidates for pyrolysis. Diversion of food wastes from MSW reduces contamination and improves the performance of incinerators and landfills, while diversion of food wastes from restaurant and cafeteria recyclables, especially cardboard, increases the quantity that reclaimers will accept. This effort could be enhanced by using hydropulpers or other equipment for squeezing water from food wastes.

The 1,500 tons/day of restaurant and institutional food wastes generated in New York City may be an attractive supply for pyrolysis. Composting the food waste would not be acceptable within New York City.

East End agricultural wastes also may be an opportune source of materials, depending on the fate of plans for composting and MSW composting.

7. Textiles. There is little competition for textiles -- only two of the forty largest American cities collect them at all. Food-, grease-, oil-, and hazardous-organic contaminated textiles are no problem for pyrolysis plants. Institutional maintenance (e.g., wiping cloths), Goodwill rejects, the garment industry and textile exporters are significant sources for which dedicated collection mechanisms could be leveraged from the existing distribution infrastructure.

8. Pyrolyzable commercially collected New York City wastes brought to Long Island. Commercial carters collect 11,000 tons/day in New York City. The city's Department of Sanitation now requires source separation and separate collection of recyclables for all businesses. Major national companies, such as WMX, hope to acquire some of this market. Privately run sorting operations skim the high-value recyclables, leaving 20% to 80% of the original garbage to be landfilled or incinerated. Some of the shipments cover long distances, with high costs -- 2.9 million tons of commercial and residential MSW were exported from New York City in 1992. Other shipments come to Long Island. Pyrolysis may be attractive for relatively homogeneous shipments obtained from certain commercial sectors. Carters may be able to offer longer-term, fixed price contracts that will be more attractive to commercial waste generators than current contracts.

9. Some wood and yard wastes. Treated wood and most non-treated construction wood wastes are not chipped or otherwise recovered. While the market for chipped wood remains strong, pyrolysis may play a backup role when there is excess storm damage. In many towns without home mulching programs, odor, health, and operational issues have made composting less attractive. Some towns may wish to consider pyrolysis for leaves, grass, and similar materials.

10. Automobile shredder residue. The Town of Brookhaven landfilled 31,590 tons of this material in 1992. No information was found for other towns. Pyrolysis is the clear treatment of choice for this material.

11. Used oil. Some towns send used oil to re-refiners. The ultimate fate of these materials under pyrolysis is much the same. Which option is most attractive will vary with individual economic and logistical conditions.

12. Raw residential and commercial MSW that either now is landfilled on Long Island, shipped off-Island, or that exceeds the capacity of available incinerators.

13. Pyrolyzable materials obtained from waste exchanges. The Chicago Board of Trade and the National Recycling Coalition's Recycling Advisory Council have developed a demonstration project to set up a secondary-materials electronic trading market and information exchange. This is an appealing idea for the New York City metropolitan region, and would complement the existing industrial-waste exchanges in the Northeast.

Tires, hospital wastes, landfill mining, industrial wastes, and federal cleanup wastes are discussed in the sections that follow.

(b). Old Tires: Kings Park Tire Pile

Waste tires on Long Island fall into two groups. The first consists of tires discarded as worn ones are replaced, and as old cars are junked. Most of these tires flow through service stations, tire dealers, institutional fleets, and used car/junk car dealers. Some are discarded in roadside areas and collected by highway departments, and, in some cases, put in landfills or incinerated -- inadvertently, or accidentally-on-purpose, or in approved tests. Burning tires in MSW incinerators is forbidden by the NYS Department of Environmental Conservation except for permitted tests.

Tires of this first type are not recommended targets for NEWME because existing commercial networks handle them well now, and because a commercial tire-pyrolysis plant is planned. These tires now are collected and sent off the island, where they are burned or shipped overseas. Proposals for scrap-tire recycling and pyrolysis submitted to Suffolk County in 1992 were not acted upon, in part because the County determined that ongoing discards no longer were a significant problem. (Regional tire processing and brokerage firms are detailed in NYS Department of Economic Development [1990].)

If the privately owned and operated Envirotire plant materializes, about 1.5 million tire discards in Suffolk County will be pyrolyzed annually in the Town of Riverhead, rather than taken off the Island. Tentative collection arrangements are said to be in place with area waste-tire generators. There may be an opportunity for NEWME to play a role in assessing environmental impacts associated with the facility, designing options for front-end separation equipment, and defining requirements for regulatory approval. However, Envirotire is not interested in pyrolyzing either piles of old tires or non-tire wastes.

The second group of waste tires may be referred to as "old tires," that is, accumulations of previously discarded ones. By far the most intractable of these is a private, illegally accumulated pile of some two million tires (15,000 tons) in Kings Park, Long Island, within the Town of Smithtown.

This pile recently has been a fire hazard and source of frustration to the public and to town and state agencies.

In July, 1993 the Town of Smithtown solicited proposals for environmentally acceptable removal of the tires, with energy and/or product recovery if possible, on condition that any facility built on-site was a temporary one [Town of Smithtown 1993]. Eleven proposals were received; bids ran roughly from \$ 800,000 to \$.11.7 million. The low bid was rejected as it was not responsive to the terms of the request for proposals (RFP). The one pyrolysis proposal received was submitted by Horizon Unlimited of Lincoln, Nebraska, which offered to make a powdery char from the tires. The proposal was rejected because the proposed on-site storage of pyrolytic oils was incompatible with the Town's conditions. Four (non-pyrolysis) proposals remain as finalists, at prices roughly between \$2.5 million and \$7.5 million. The Town Board is continuing to review them. It is said that a decision is not expected to be reached soon. One consideration for Smithtown is obtaining recycling credit towards the 50% - 60% 1997 NYSDEC mandates.

Town officials contacted indicate that the Town's fundamental interest is in disposing of the Kings Park tires in the best manner possible, economically and environmentally, and that the Town reserves the right to consider any better idea than those received so far. It would welcome any proposals growing out of NEWME's efforts.

The pyrolysis systems discussed in this report would be well-suited to the task. It is recommended that NEWME explore with the Town avenues for establishing a pyrolysis facility, perhaps at BNL itself, that would process the Kings Park tires alone or with other wastes.

For example, a PAR 50 ton/day Destructive Distillator using its standard feed and air lock devices can process feedstocks containing up to 20% tires. Further, a 100% tire feed stream could be handled with a modified feed and airlock system; see section II.1. The tire pile would be gone in approximately 1/2 year at the 100% rate, and 2.5 years at the 20% rate. The likely yield per ton of tires would be 600-650 pounds of carbon black, 9000 cubic feet (40 therms) gas (of which 15% or so would run the plant), 90-110 gallons oil, 85-100 lbs steel, and 70-80 lbs fiberglass. The steel, oil, remaining gas, and carbon black, and perhaps the fiberglass, would be sources of revenue.

The significant regional market potential for pyrolysis of stockpiled tires may be gauged from a computation that a single 250 ton/day Pan American Resources Destructive Distillation plant would eliminate all tire stockpiles in California in 24 years. Such a plant would generate from 2.5 to 10 megawatts, depending on how much MSW is processed with the tires.

The regional potential is enhanced by the generic beneficial use determination (BUD) that the NYSDEC has accorded to tire pyrolysis, exempting this technology from solid waste regulations affecting incinerators and other thermal treatment technologies. The exemption was triggered by a petition from the New York State Electric and Gas Company to generate energy from pyrolysis of tire chips with coal. This option may be attractive to other utilities in the NEWME region.

National legislation confers economic benefits on utilities that burn or pyrolyze tires in power plants of up to 25 megawatts of capacity -- a size that requires a large metropolitan area's tireshed. It is unclear if these benefits apply to pyrolysis of a mixture that is 80% MSW and 20% tires.

Although the exemption does not apply to air-emissions regulations, the Environmental Protection Agency determined that "there are essentially no process emissions from pyrolysis units" [U.S. EPA 1991, p. ES-7]. Char handling, screening, and packaging can generate some fugitive particulate emissions, but any such dust "does not appear to be hazardous" and can be handled with standard equipment, such as canopy hoods [op cit., p. ES-7]. Proper design and maintenance minimizes any fugitive VOC emissions from leaky valves and joints.

State officials contacted noted that, in the past, the revenue from sales of char from tire pyrolysis was overestimated. These opinions tend to reflect experience with particular plants -- many sources contacted said that they had not had an opportunity to study many recent developments in pyrolysis technology and plant performance. Significant strides have been made in separating the char into grades, and in upgrading. The value of char and its marketability has been acceptable in plants where some of these improvements have been installed. Still other advances are being readied for commercialization [e.g., InnCon 1993].

Annual tire discards are, perhaps, one percent of MSW by weight [*Waste Age*, July 1993(b), pp. 113-114]. Twenty-eight per cent of the 240 million tires discarded in the United States in 1992 were recycled or reused in some fashion, burned whole, or as tire-derived fuel (TDF) by utilities, cement manufacturers, and pulp and paper companies [Lynch 1993(b), Blumenthal 1993(b)]. Few of the two to three billion old tires stockpiled in the United States are being subjected to these options.

Many of these options are consonant with the terms of the Town of Smithtown RFP, but may be inadvisable or noncompetitive:

A 1991 Environmental Protection Agency study concluded that products such as floor mats, sandal soles, athletic tracks, mud guards, and fish barriers made with crumb rubber reclaimed from scrap tires "have very limited demand and at best could assemble [sic] only a small fraction of the available scrap tires" [U.S. EPA 1991, p. ES-1]. Competitive prospects for recycling crumb rubber tire since have worsened, owing to high processing costs and dropping prices of crude oil [Powell 1993(e)].

Crumb rubber from scrap tires also can be used in highway paving materials, in aggregate and in binder/sealer applications. Theoretically, yearly asphalt requirements could accommodate rubber from ten times as many tires as are discarded annually. Section 1038 of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) requires that rubberized asphalt is used for 5% of 1994 highway construction in states receiving federal highway aid. The fraction rises to 20% by 1997, which would consume 80 million scrap tires each year. However, this provision has become controversial because of concerns about the environmental and health impacts of rubberized asphalt, its own recyclability, long-term performance, and, above all, its cost. Congress accordingly enacted a proviso in October, 1993 prohibiting the use of federal funds to implement or enforce the ISTEA mandates. This confrontation continues, and the outlook for rubberized asphalt under ISTEA is anyone's guess.

Whole or sliced tires can be used as highway underbedding and in artificial reefs. Artificial reefs may play a role in Long Island's future, but are not a viable possibility at the moment. Cement kilns appear to be a growing market for this material [Blumenthal 1993(b)].

Incineration of tires for energy generation (they yield 12,000 to 16,000 Btu/lb) has fallen on hard times. The touted Oxford Energy Company operation in Modesto, California, the media darling of tire recyclers, filed for bankruptcy in 1993 after posting \$23.8 million losses on revenues of \$33.8 million [*MSW Management*, March/April 1993]. Other sources contacted said that Oxford's ten million tire/year plant in Sterling, Connecticut is likely to close soon.

The shaky economic environment for recycling and incinerating scrap tires creates an opportunity for pyrolysis.

(c) Other Waste Targets

(i) Hospital Wastes

As noted in sections II. 1 - II.4, hospital wastes are sought by the four companies whose pyrolysis systems meet the criteria for further consideration by NEWME. Long Island hospitals generate roughly 160 tons of hospital wastes per day, including red-bag wastes. A high fraction consists of paper and plastic medical, sanitary, and food service products suitable for pyrolysis. Costs of waste disposal have been rising steeply for hospital wastes. Current methods of disposal include incineration, sterilization, putting in landfills, and shipping off-island. The closed-container systems (see section II.1) integrated from point of generation, through transportation, to shredding and pyrolysis are a particularly attractive business opportunity.

(ii) Industrial Waste and Waste Minimization

Note: this section covers pyrolysis of hazardous and non-hazardous wastes generated by ongoing industrial activity. Opportunities for pyrolysis of contaminated industrial property remediation wastes, as from cleanup of old spill sites, are discussed in section II. 7.

Industry accounts for ninety-two per cent of the roughly 300 million tons of RCRA hazardous wastes generated annually in the United States. Ninety-five per cent of the generators use only off-site hazardous-waste management services. However, ninety-six per cent of the volume of hazardous wastes is managed on-site; this is due, mainly, to wastewater treatment by large generators. Perhaps 500 million gallons of liquid (mostly organic) industrial hazardous wastes are incinerated annually. Hazardous waste incinerators must maintain high temperatures, sustain turbulent mixing regimes, and provide sufficient residence time. Storage, treatment, and disposal costs have risen steadily in recent years. Pyrolysis is an attractive alternative to incineration because it offers lower costs without the concerns on air emissions and the control challenges associated with incineration.

Industry also generates 7.6 billion tons of non-hazardous or minimally hazardous solid wastes that require disposal; this includes recycling and re-use on-site or via industrial waste exchanges [Gruder 1993]. Prompt plastics and paper scrap, railroad ties and telephone poles, used oil, and bulk non-hazardous chemicals are examples. Most non-hazardous industrial waste is not tabulated in MSW statistics because collection usually is not under municipal aegis. Instead, these wastes are usually managed within existing trade networks (e.g., scrap iron) or by private collection services.

Many hazardous and non-hazardous industrial wastes used in large quantities by regional industry are pyrolyzable: solvents, coatings, paints, treated wood, plastics, and agricultural chemicals. Hazardous organic chemicals from remediation treatments also are found in the industrial waste stream. Long Island electronics, aviation, plastics, utility, transportation, and metal finishing industries appear to be targets of opportunity.

There is growing industrial demand for better, cheaper, faster treatment, storage, disposal, and recycling technologies for these wastes. This need is driven by the far-reaching requirements to develop, monitor, implement, and report comprehensive waste prevention and minimization programs for the key industrial chemicals listed in the Toxic Release Inventory (Form R) (TRI) guidelines authorized by the Emergency Planning and Community Right-to-Know Act/Superfund Authorization Renewal Act. New York State has imposed somewhat tougher waste reduction requirements (section 378). The Clean Air Amendments Act, Resource Conservation and Recovery Act, and other legislation also drives industry's efforts in waste management.

On- and off-site pyrolysis (there are significant regulatory differences) could be a key component of many integrated industrial-waste management systems. Pyrolysis should be attractive to large

generators who may be able to support small on-site pyrolysis units. The lower transportation cost is as much of a consideration as lower processing cost. The trend is towards treatment on-site or as near as possible to the point of generation [MacMillan 1993]. Pyrolysis would sharply reduce the quantity of wastes requiring long-distance shipment, for example, to the only licensed hazardous-waste landfill in New York State, near Buffalo. There may be additional dividends if pyrolysis helps reduce interstate movement of hazardous waste, because of pending legislation that restricts or taxes such movement.

Industrial waste management increasingly involves re-use, recycling, processing redesign, energy recovery, and substitution of materials that are friendlier to the environment. In this regard, pyrolytic recovery of fuel and industrial chemical hydrocarbons is attractive.

Pyrolysis also can be integrated with industrial waste exchanges. Eleven million tons of industrial wastes are traded through waste exchanges for reusing and recycling as raw material feedstock or chemical agents. Industrial and commercial waste exchanges have been created across the United States in the last few years. These clearinghouses allow companies seeking markets for their manufacturing wastes to find other companies willing to purchase or trade for the wastes. The exchanges are spreading; there are 42 in the United States, including two in New York State, and there are broker networks in place. Exchanges offer lower costs of storage and disposal, and of packaging or feedstocks.

Among the materials traded are solvents, other organic chemicals, oil and wax, plastic and rubber, textiles and leather, wood and paper, paints and coatings, unwanted hospital linens, fishheads, diskettes, paints, circuit board wastes, and other pyrolyzable wastes. A pyrolysis system could be linked to a waste exchange, such as the Northeast Industrial Waste Exchange, and serve as buffer or backup option for materials that find no outlet. The Northeast Industrial Waste Exchange, in Syracuse, New York, is a non-profit organization sponsored by the states of Ohio, Pennsylvania, and Maryland (New York State financial support ended in 1990).

There are many opportunities to use the carbon byproduct of pyrolysis as an adsorbent to sequester heavy metal and VOC contaminants from industrial process and lubricant streams.

There may be business opportunities for selling pyrolysis systems and services for on-site destruction of chemical warfare agents and munitions in Eastern Europe and in former Soviet States.

Long Island development of industrial applications of pyrolysis should be conceived as an integrated recovery services industry, one that recovers useful energy and materials and sequesters hazardous materials from a broad range of industrial waste streams. Such an industry would spin off related entrepreneurial activity in monitoring, separation, and processing technologies, including the emerging technologies of high-capacity VOC separation and recovery.

(iii) Landfill Mining

Landfill mining's principal benefit is that it would eliminate unsightly, malodorous landfills altogether and/or greatly extend their service lives, so deferring or avoiding the high cost of landfill closure and post-closure. Landfill mining opportunities are among those sought for the Entropic, Pan American Resources, and Hynol technologies. For example, The Pan American Resources and Entropic systems appear to have a high tolerance for inert materials compared to incinerators and to other pyrolysis systems.

New York State has been conducting significant research and development on using incineration in landfill mining. These efforts have encountered many operational difficulties [NYSERDA 1992]. The landfills may be too contaminated for recycling or incineration. Possibly, similar state sponsorship may

be obtained for trials of pyrolysis in landfill mining. New York City is considering options for mining the brontosaurian Fresh Kills landfill. Pyrolysis companies may wish to submit proposals.

Some of the engineering development needed for pyrolysis of old landfills is similar to that for pyrolysis of contaminated soils at DOE remediation sites. Brookhaven National Laboratory may wish to cooperate in developing smaller twin screws for the Entropic system, air-classification and washing systems. The laboratory's own landfill site might afford a demonstration.

(d) Regulatory, Public Acceptance, and Siting Considerations

Pyrolysis occupies a regulatory gray area ignored until 1993. Public support of, and opposition to, pyrolysis cuts across the usual fault lines dividing concerned stakeholder groups, environmental organizations, neighborhood associations, elected officials, regulatory agency administrators, and the several affected industries – plastics, oil, recycling, carting, and utilities. Although siting almost anything anywhere now entails treading through a minefield of controversy, several factors about a pyrolysis facility may be assets in finding an acceptable site. The regulatory, public acceptance, and siting issues are complicated by the fact that many are quite unfamiliar with current pyrolysis technology or hold misconceptions about it.

(i) Current Regulatory Status of Pyrolysis

A 1989 ruling by the New York State Department of Environmental Conservation (NYSDEC), in response to an inquiry from the Town of Southold, held that pyrolysis is to be regarded as a form of "thermal treatment," subject to regulation as incineration, and, therefore, that disposal of char would be considered as a form of ash disposal, and would be governed by 6NYCRR Part 360, Subpart 3.5. NYSDEC also stated that char is exempt from RCRA 3001(1).

However, tire pyrolysis, specifically, has been accorded a blanket exemption from these solid waste regulations due to a beneficial use determination (BUD) that was made when New York State Electric and Gas Company applied for permission to pyrolyze tire chips and coal together for energy recovery; energy recovery is the primary basis for the BUD. (Recycling MSW combustor ash into construction blocks also has a BUD). The BUD exemption applies to solid waste regulations; air and water emissions regulations still hold.

NYSDEC has not taken a position one way or the other with respect to issuing a BUD for plastic or MSW pyrolysis. At the time of the rulings, the option of turning pyrolysis byproducts into new plastics or other materials, or into alternative, pollution-preventing vehicle fuels, was not considered.

NYSDEC has not addressed whether towns can count tires, plastics, or any other wastes pyrolyzed for energy recovery towards satisfying the 1997 recycling goals. Remarkably, the State itself does include these wastes in measuring progress towards statewide recycling goals. Nor has NYSDEC addressed the possibility of allowing recycling goal credits for wastes that are pyrolyzed and then turned into new plastics.

The pyrolysis options assayed in this study, then, lie in open, unclaimed regulatory territory. The sudden revival of interest in pyrolysis around the world has led to regulatory changes in other states, and has now caught NYSDEC's attention. Several officials contacted in Albany and on Long Island stated that DEC viewed pyrolysis very favorably and wanted to encourage its development. They stated that current Long Island recycling programs could meet state recycling and waste management goals only if the more difficult waste stream components could be reached – the easy measures, such as curbside recycling, had been taken – and that pyrolysis appeared ideally positioned to fill that bill. They also said the energy, materials recovery, and pollution prevention benefits of pyrolysis were viewed as substantial within NYSDEC.

In 1993, Washington State's Department of Ecology determined that plastic pyrolysis does not fit neatly into its hierarchy of waste management technologies, which was devised before pyrolysis came up for consideration in the first place. The state's present policy is to consider pyrolysis to be a process for recovering materials and fuel products; it is considered to be energy recovery only if the process actually produces energy. The state lists pyrolyzed tires in its annual recycling survey, and plans to list pyrolyzed plastics, but does not count either in calculating the recycling rate [WSDOE 1993]. The policy is under review. California and Oregon also are wrestling with the matter of whether pyrolysis conforms to their specific regulatory requirements for being a "recycling technology" [Powell 1993(b)].

In 1993, the Ontario Ministry of the Environment ruled that pyrolysis was not as form of incineration, and the Michigan Department of Natural Resources classified the Entropic pyrolysis system as a waste processing facility along with conventional recycling (see below).

The Entropic pyrolysis technology (section II.2) poses an intriguing regulatory puzzle of its own. The reactors run at temperatures not significantly greater than those generated in many conventional plastics recycling systems, such as the extruders used to make plastic lumber. So, the regulatory justification for treating plastics recycling one way and pyrolysis of plastics (and MSW generally) by the Entropic method in another way would appear to collapse. These considerations suggest a strong case could be mounted for counting wastes pyrolyzed with the Entropic technology as a form of recycling. Independent arguments would be required for treating other pyrolysis systems as recycling.

Pyrolysis of hazardous organic materials is permitted and regulated under NYCRR Part 373 Subpart X (Miscellaneous Units for Treatment of Hazardous Wastes), which incorporates the corresponding sections of the federal Resource Conservation and Recovery Act. This regulation covers performance standards for boilers and industrial furnaces in a general manner. As discussed in section I.4(a)(ii), one arc pyrolysis plant was given a permit to operate near Buffalo to handle PCB capacitors from Love Canal and other hard-to-destroy hazardous organics. Refractory materials did not hold up, and the project was scrapped by the company before commercial operation began. The pyrolysis systems recommended in this report operate at far lower temperatures.

(ii) Is Pyrolysis Recycling?

The status of this question in regulatory agencies in New York, Washington, California, Oregon, Michigan, and Ontario is summarized above. Trade and environmental organizations have weighed in, too. The American Plastics Council urged the National Recycling Coalition to endorse plastic pyrolysis as a recycling technology. APC literature refers to pyrolysis as "advanced recycling technology."

One longtime recycling expert replied [Plastics Recycling Update, October, 1993] that pyrolysis is not recycling in the same sense as aluminum, glass, or paper recycling, on the grounds that plastic discards are pyrolyzed to "gases and hydrocarbons, not into plastics." He claimed that calling pyrolysis "recycling" would be like "recycling" ferrous scrap into iron ore, aluminum into bauxite, and paper into wood chips. A grassroots environmental organization leveled a related charge, saying that pyrolysis could not be recycling unless the products are used to make a new plastic container or other durable good [Californians Against Waste et al. 1993]

This line of argument is not compelling for several reasons. One is that the argument draws arbitrary system boundaries of the recycling process. Many conventional plastics-recycling processes take place in two or more steps at different locations. It would be arbitrary to say that pelletization followed by product fabrication elsewhere counts as recycling but pyrolysis followed by manufacture of virgin resin and a new product elsewhere cannot.

In the example above, the oddness of saying that converting ferrous scrap into iron ore is recycling stems from the fact that this conversion is, unlike the situation with plastics pyrolysis, impossible or at least outlandishly expensive. If one of the cheapest, easiest ways to recycle ferrous scrap were to convert it to iron ore and back again to new iron products, analogous to the situation with plastics pyrolysis, one might very well want to call it recycling. Moreover, pyrolysis does not convert plastics into crude oil, as the "ferrous" analogy might suggest.

For that matter, a stronger analogy is that between pyrolysis and composting. In composting, organic materials biodegrade to basic components that then are reconstituted in new materials. From this point of view, pyrolysis is a renewable resource process analogous to what has been called "nature's own recycling." It is far from obvious why physical, as opposed to chemical or biological, transformation should be the *sine qua non* of recycling, especially in light of the fact that many conventional recycling technologies, such as paper recycling, involve all three kinds of transformation.

The feedstocks created by pyrolysis put plastics and other pyrolyzable materials back into existing commercial commodity streams that require little marketing or product differentiation. This turns the argument that plastics pyrolysis should not count as recycling on its head, inasmuch as the recycling community has long insisted that "it isn't really recycling unless a recycled product is actually made and used."

Furthermore, the net fuel, energy and other nonrenewable resource expenditures associated with mechanical plastics recycling may exceed those associated with the pyrolysis of plastics [Reaven 1993(a), 1993(c), 1984, 1985, 1986, 1987(a), 1987(b)].

One of the most commonly repeated arguments against plastics is the contention that they deplete nonrenewable, dwindling fossil fuel resources [see Reaven 1993(c)]. Pyrolysis could conserve these resources by substituting for virgin products and avoiding the environmental costs of extracting natural gas and petroleum.

There is yet another difficulty with the argument that plastics pyrolysis that yields new plastics cannot be pyrolysis. Nothing forbids viewing pyrolysis as a form of recycling not of the actual discards but of the starting materials. That is, pyrolysis could be considered as part of a cyclical process of making raw materials (e.g., monomers) into polymer products and recycling these back into the raw materials. The point of entry into the cycle need not be decisive. This could also be thought of as fuel recycling.

Finally, it seems inconsistent to call re-refining of used oil recycling but to refuse to do the same for the pyrolysis of used oil followed by upgrading into new oil in a refinery.

One way to finesse these intricacies might be to coin a special term for the kind of materials recovery associated with pyrolysis -- perhaps "reincarnation" or "molecular recycling" will do. However, experience and theory suggest that virtually any set of criteria for what is and is not recycling leads to troublesome counter examples and inconsistencies [see Reaven 1994].

(iii) Does Pyrolysis Undercut Conventional Recycling?

This issue also could affect public acceptance of pyrolysis. The National Recycling Coalition drafted a revised hierarchy of waste management methods in the fall of 1993:

1. source reduction
2. reuse
3. conventional recycling
4. composting of organics

5. processing for recovery of materials and fuel products
6. conversion of nonrecoverable combustible fractions for energy
7. disposal through incineration or landfilling

There is great debate within the recycling community as to what alternatives should be listed and their relative desirabilities. Moreover, there is a thoroughgoing debate as to whether it is reasonable to set up a hierarchy at all, as has New York State: many argue that it is more advisable to design a well-integrated system for each region that puts each waste management technology on an equal footing *a priori* and selects the mixture that best minimizes total system costs, risks, and environmental impacts.

Nevertheless, even under the proposed new National Recycling Coalition hierarchy, pyrolysis is preferable to incineration and landfilling. Even when pyrolysis is presented as the option to select only for waste materials not well-suited to the first four options (source reduction, reuse, conventional recycling, and composting), large quantities of pyrolyzable wastes remain available.

Conceived in this way, pyrolysis becomes the backup of choice for the first four options, for example, when markets dry up for a particular material, when material is too contaminated for recycling, when commingled plastics and/or other organics are not economically or technologically separable, and when materials end up as MRF residue or bypass. Either way, large quantities of waste are available.

Some mechanical plastic recyclers fear that pyrolytic recycling of plastics will drive feedstock towards lower-end uses by creating low-cost monomers and other liquid chemicals. This argument forgets that it is precisely the hard-to-recycle plastic materials that are targets for pyrolysis. Indeed, since mechanical recycling cannot compete with virgin plastics at their currently low prices except at the highest value-added end, such as PET soda bottles, more economical recovery of plastics by pyrolysis is needed for plastics recycling to remain viable at all. Otherwise, mechanical recycling just may drive itself out of business.

For this reason, plastics pyrolysis complements and can reinforce conventional plastics recycling. This point was illustrated in section II.5(a). By providing at least a backstop when markets are low, pyrolysis could help justify collection of mixed plastics of many resins.

(iv) Comments on Siting

Its natural advantages of a high concentration of wastes, short transportation distances, excellent, varied waste-management facilities and infrastructure, and ready access to distribution, exporting, and brokerage networks make Long Island a logical home for pyrolysis operations. However, as noted, siting any facility is problematic these days. Several factors could be emphasized to make siting of a pyrolysis facility more attractive to proponents and more palatable to opponents.

Publicizing the role of the pyrolysis system as an alternative fuel production enterprise whose products enhance regional air quality in accordance with the Clean Air Act; this may be particularly attractive for methanol, with its biomass associations.

Incorporating the facility as part of a land recycling package that uses pyrolysis to clean up the contaminated property chosen as the site, or to mine a landfill. Other recycling and waste management industries could be collocated.

Using electricity from pyrolysis to run conventional plastics lumber plants and other recycling/reclamation facilities and keep them on Long Island. Many such operations have left Long Island, or have been tempted to do so, driven by the very high energy costs. In this way, pyrolysis could be viewed as undergirding recycling programs and markets.

Examining as potential sites Brookhaven National Laboratory, the Navy-owned Grumman facility in Calverton, the Republic Airport in Farmingdale, the former lace mill in Patchogue, and similar private, state, and federal properties.

Coordinating the siting process through a regional instrumentality. As noted in section II.5(a), the five largest Suffolk County towns are beginning to explore the advantages and disadvantages of an integrated waste management system. Waste exchanges and trading of recyclables, ash, trash, access to waste facilities could be part of this picture.

Considering the possibility of an off-island siting, perhaps at a region-scale facility, with wastes shipped via the Long Island Railroad or other means.

Some town officials are skeptical of pyrolysis. They cite its previous engineering difficulties or appear unfamiliar with recent advances. Also, they are wary of potential opposition, not so much from environmentalists who have supported pyrolysis in the past, and who support pyrolysis in other states, as from neighborhood groups worried about the potential for an explosion. While standard industrial-safety technology would seem to make the chances for this very remote, and lower than they would be at many waste management and industrial facilities throughout the region, it may be advisable for NEWME to sponsor a formal risk analysis.

The economic attractiveness of pyrolysis compared to incineration, MSW composting, and off-island shipment is likely to be one of the most important factors affecting acceptance by town governments and the public. A sharp drop in landfilling costs as large landfills in the midwest seek wastes from the Eastern megalopolis has led to increased competition for garbage, and caused some Long Island towns and private (generally, commercial waste) haulers to ship more wastes off-island. There are spot markets in Connecticut that accept MSW for \$35 per ton for incineration. Such prices could, in time, undermine the high-tipping-fee financial assumptions of incineration and recycling programs in some towns.

On the other hand, as discussed in sections II.1 - II.5, regulatory and technological factors are likely to reverse this trend, as supply and demand bottlenecks are cleared, so that the rise in disposal costs resumes.

Public acceptance, finally, will be influenced strongly by the degree to which the public perceives pyrolysis as a nonpolluting alternative to burning, as a process that is and looks like it is fundamentally different from incineration, i.e., with no high chimneys.

II.6 Regional Energy Applications

The products of pyrolysis can be used as fuel for electricity generation, industrial process heating, and transportation. Commercial use, e.g., in greenhouses, of cogenerated heat and/or steam can be a spin-off benefit.

The primary fuel from pyrolysis would be electricity (Pan American Resources), syncoal (Entropic), methanol or methanol derivatives (Hynol), or an alcohol mix blended with stripped natural gas liquids to make a low-octane engine fuel (Conrad/Tuttle). Other energy products are available with different system configurations. For example, the Pan American Resources product gases can be liquefied and then either synthesized into oxygenated fuels, or refined into heating oil or other petroleum products.

A 250 ton/day Pan American Resources pyrolysis plant would generate from 2.5 to 10 megawatts of electricity, depending on feedstock. Entropic syncoal has a heating value of upwards of 9,500 BTU/lb. Since it is environmentally comparable to low-sulfur Western coal, New Jersey, Connecticut,

and upstate New York utilities are potential markets. A 3,400 ton/day Hynol MSW pyrolysis plant, co-fired with 1,061 tons/day of natural gas obtained from utilities, would produce 2,500 tons/day of methanol. The best utility market for the methanol is in oil-fired peaking-power plants.

Peter Quinn, energy chairman of the Long Island Environmental and Economic Roundtable, has stated that "...more than 110,000 jobs have been lost in the last four years, one third of which were industrial, and energy costs were the primary factor" [Bridson 1993]. The Long Island Regional Planning Board's [1993] Long Island Strategic Economic Development Plan calls for measures to encourage independent power producers to reduce rates, and for increased natural gas imports to Long Island [Newsday, December 17, 1993]. Pyrolysis may be able to supply this fuel without imports.

Two opportunities suggest themselves. First, the New York Power Authority is advocating the construction of a natural-gas fired 340 megawatt electricity generation plant at Pilgrim State Hospital on Long Island. Mayflower Energy Partners would own and built the plant. Second, a 145 MW natural-gas-fired LILCO plant is perhaps half completed in Holtsville, Long island. It may be possible to use pyrolysis products directly or with minor upgrading in these facilities, or in industrial boilers.

Other New York City, upstate New York, New Jersey, and Connecticut utility markets could be sought for pyrolysis products, as indicated in sections II.1 - II.4. An analysis of energy supply, demand, conservation, contracts, markets and prices for utilities, refiners, and other regional energy providers and users is beyond the scope of this report (although expected fuel prices are discussed in sections II.1 - II.4). Landfill gas recovery operations could be integrated with a pyrolysis plant built at or near a landfill.

As noted, methanol and reformulated, oxygenated fuels, such as MTBE, are primary markets for the Hynol, Conrad Tuttle, and possibly the Pan American Resources systems. The end-user prices per gallon quoted by these companies are competitive with regional gasoline prices. Long Island is a Clean Air Act noncompliance area in which use of oxygenated fuel is required. Tax credits being considered by Congress to encourage the development and use of such fuels may enhance the economic outlook for these pyrolysis systems.

It may be possible to arrange funds or institutional support through the Federal Fleet Conversion Task Force, created by Presidential order in April, 1993. The Government is required to buy 11,250 alternative-fuel vehicles in FY 94, 15,000 in FY 95, and 35,000 annually by FY 1997. Alternative fuels include natural gas, methanol, ethanol, propane, and electric power. The Vice-Chair is the DOE Assistant Secretary for Policy, Planning, and Program Evaluation. NYSERDA runs an Alternative Fuels for Vehicles program. DOE and U.S. EPA are developing programs in this area. Opportunities to use pyrolytic products in federal or state fleets should be discussed with these potential partners.

II.7   Applications to DOE and Other Federal Environmental Restoration and Waste Management Programs

Approximately 4,000 contaminated Department of Energy sites require remediation and/or restoration. An April 1992 study examined 91 representative sites contaminated with hazardous wastes or mixed (hazardous and radioactive) wastes at eighteen DOE facilities [USDOE 1992]. The predominant contaminants were found to be:

- fuel hydrocarbons (such as toluene, benzene, and xylene)
- chlorinated hydrocarbons (such as trichloroethylene)
- ketones (such as acetone)
- PCBs, pesticides, and organic acids

Four of these sites are at Brookhaven National Laboratory; three were contaminated by fuel hydrocarbons, all four by chlorinated hydrocarbons. PCB-contaminated oil also was found.

Similar hazardous organic chemicals are found at most of the more than 1200 Superfund sites on the National Priority List established by the Environmental Protection Agency. Many of the 4,000 DOE sites also are on the list. Four to eight hundred new sites are expected to be added to the NPL by 2000. Fuel hydrocarbons and other hazardous organics also are found at many of the 295,000 underground storage tank sites requiring remediation.

Dozens of treatment processes and regimens will be used in these cleanup programs [Watts and Lee 1993, U.S. EPA 1993(a), 1993(b), 1993(c), and 1993(d), Petrakis and Goland 1993, NYSDEC 1993(b), InnCon 1993, Dombrowski 1993(b), Grasso 1993, Johnson, W. 1993, MacAdams 1993]. The variety and complexity of the chemical soups at the sites, and of the waste streams generated by remediation technologies, is high. In some cases, neither the wastes themselves nor the intermediate wastes generated by the chosen cleanup process would be pyrolyzable. In other cases, either the wastes or intermediates may be pyrolyzable, but non-pyrolysis options would be cheaper or otherwise more efficacious.

However, in still other cases, the preferred treatment would be direct pyrolysis of liquid or solid retrieved wastes, or pyrolysis preceded by minimal separation of nonpyrolyzables. Finally, the pyrolyzable materials could result from other treatments -- chemical, thermal, or biological -- applied directly to the contaminated sites or materials, or to intermediate materials. Several primary treatment technologies would generate pyrolyzable waste streams in certain applications: in-situ stripping of solvents and fuels, bioremediation, VOC recovery with mist-scrubbers, VOC recovery with membrane vapor separation, hydrocyclone systems, ultrasonic metal separation, electrokinetic migration, soil washing, and vapor extraction [Watts and Lee 1993, U.S. EPA 1993(a), 1993(b), 1993(c), and 1993(d), Petrakis and Goland 1993, NYSDEC 1993(b), InnCon 1993, Dombrowski 1993(b), Grasso 1993, Johnson, W. 1993, MacAdams 1993].

Pyrolysis could destroy many of these remediation products and byproducts at lower costs and temperatures than incineration. Since many of the remediation technologies were developed by DOE, there are attractive in-house capabilities to develop integrated approaches using pyrolysis as the final step in destroying of hazardous organics.

While the greatest opportunities for such projects appear to be at DOE and Superfund sites elsewhere, some Long island applications could be considered. There are twenty-four Superfund sites on Long Island. Cleanup is complete at three, and full-scale cleanups are underway at two. There may be opportunities for pyrolysis at the Ruco Polymer, Liberty Industrial, Pasley Solvents, Anchor Chemicals, Kenmarks Textiles, Action Anodizing, Mattiace Petrochemicals, and other sites. Also, there are 115 state Superfund sites on Long Island.

In principle, pyrolysis could be used to treat many mixed wastes at many DOE sites. However, doing so would require dedicated pyrolysis units that would be subject to special regulation and licensing by the Nuclear Regulatory Commission and/or state agencies in agreement states. Moreover, such units would have to be disposed of as low-level radioactive waste. If this option is pursued, collocation at Savannah River or a similar site with major radioactive materials handling operations may be advisable.

Opportunities for pyrolytic treatment of contaminated soils directly are unclear. Prospects depend on the nature and concentration of the hazardous organic contaminant, the soil type, the type of pyrolysis technology, and on the engineering performance of that technology in landfill mining. Natural gas co-firing may be required to overcome the effects of inert materials on the pyrolysis reactions.

Brookhaven National Laboratory could spearhead efforts to (a) identify and rank DOE sites and materials according to the suitability of using pyrolysis in remediation and restoration, (b) quantify the waste streams treated and, in turn, generated by other site treatments, and (c) complete the engineering development of mobile units (such as the Entropic with smaller twin screws), front-end separation systems, and field sensing and monitoring systems. BNL's proposed User Facility for Environmental Pathway Modeling of DOE environmental restoration sites could be used to assess options for pyrolysis. BNL's groundwater sampling programs also could play an important role.

DOE waste minimization programs also may prove fertile ground for pyrolysis. Hazardous organic wastes and other pyrolyzable industrial wastes are generated in ongoing DOE and DOD operations. DOE policy established in May and September, 1992, and strengthened in 1993, mandates aggressive efforts in waste minimization and pollution prevention [US DOE 1993(c)]. These include Pollution Prevention Opportunity Assessments (formerly called Process Waste Audits) and Emergency Planning and Community Right-to-Know Act Toxic Release Inventory (TRI)(Form R) compliance. The declared goal is a 50% reduction in releases of TRI-priority chemicals by the end of 1995 at some DOE sites, and a 33.3% cut at others [U.S. EPA 1993(g); DOE Pollution Prevention Advisor Winter 1994, Winter 1993]. DOE also undertook to comply with the 1990 Clean Air Act Amendments, which, *inter alia*, call for pronounced efforts to reduce VOC emissions.

These policies will change DOE waste streams in many ways (by avoided generation, recycling and reuse, chemical and product substitutions) that will create many opportunities for pyrolysis of hazardous organic chemicals.

Fixed pyrolysis units for DOE remediation and/or ongoing waste management could be sited at major federal installations or former ones. Small, rail- or truck-transportable field units, such as the Entropic Technologies units, may be attractive in many other situations. A few mobile units could "circuit-ride" as required among DOE remediation (or current operations) sites. As discussed in sections II.5(c)(ii) and II.5(d), it may be possible to site a fixed or mobile facility at a contaminated, formerly used industrial site, in exchange for remediating the property.

As noted in sections I.2 and II.1 - II.4, the carbon char itself has many environmental applications as a filter [Cheremisinoff and Cheremisinoff 1993]. There are numerous suitable applications of clean, activated or semi-activated char from pyrolysis plants in DOE remediation efforts.

The pyrolysis of hazardous materials with hazardous components that are not completely destroyed by pyrolysis yields gases or char that must be managed acceptably. Flaring completely destroys hazardous organics that survive pyrolysis. Char containing heavy metals could be placed in a hazardous waste landfill (recovery may be appropriate for some metal species). Carbon filtering material saturated with VOCs and other hazardous organics could be pyrolyzed, destroying the VOCs, and reused. These points are discussed in sections I.2 and II.1 - II.4.

Pyrolysis may help reduce the runaway costs of federal operations in environmental restoration and waste management. Savings also might be realized if industrial hazardous and non-hazardous wastes and DOE cleanup and operational wastes are pyrolyzed in the same plants. Business opportunities are substantial. The hazardous waste market in the United States is expected to triple, from \$3.4 billion 1992 to \$11.2 billion in 1999 [Frost and Sullivan 1993].

II.8   National and International Commercial Opportunities for Pyrolytic Systems and Related Environmental Technologies

The regional opportunities discussed in sections II.1 - II.5 for large-scale pyrolytic processing of MSW, plastics, tires, and industrial, hospital, and old landfill wastes are available in most other densely populated parts of the United States. The economics are less promising in less populated regions because of lower tipping fees and high transportation costs (the low concentration of available wastes requires longer shipping). However, modular 50-ton/day-and-under units may be economically attractive in less populated areas if they are cheap enough.

Niche markets, such as plastics-to-plastics, old tire piles, automobile shredder fluff, hospital wastes, and industrial non-hazardous wastes are attractive wedges in commercializing pyrolysis because of better feedstock quality control, higher fees for waste acceptance (e.g., tipping), and demanding regulatory goals for these problem wastes. States that credit pyrolyzed wastes as a form of recycling or recovery may offer tax or other financial incentives. As discussed in sections II.1 - II.5, markets for electricity and for utility and transportation fuel products will reflect the predominant regional energy sources and prices, rail and truck access, distribution markets, and Clean Air Act status and tax advantages. Generally speaking, though, pyrolysis creates multiple useful products for which markets should exist if production prices are as expected. World crude oil prices appear to have bottomed out, so that pyrolysis may be expected to become increasingly competitive.

National opportunities in hazardous waste remediation at DOE and Superfund sites appear very strong and are less subject to regional circumstances. Several hundred billion dollars may be spent in these efforts. Using pyrolysis as an element in comprehensive waste-minimization and pollution-prevention programs for operating private industrial and federal laboratory facilities also appears to be a very strong national market. Here, the driving forces are regulation and the proven profits from pollution prevention -- the result of lowering the actual costs of production and waste management, and of avoiding the much higher costs that would be encountered without waste minimization. Pyrolysis is one of several emerging techniques that promise to lower the skyrocketing costs associated with managing hazardous wastes. The allied remediation and pollution prevention applications of carbon products to filter and sequester hazardous wastes also can command high prices nationally.

These are the core national commercial opportunities. If pyrolysis gains a market foothold, the considerable commercial spin-offs that follow would improve integration with emerging waste separation technologies (for instance, for VOC separation from industrial or cleanup waste streams, and for plastics separation from MSW), and with monitoring and sensing technologies. Many other opportunities are presented in this report.

Regional opportunities for national laboratory, university, and consulting industry analytical services abound; preparing detailed technology assessments, conducting before and after waste stream audits, evaluating overall systems pollution, energy, cost, and risks of pyrolysis and its alternatives, and inventing reasonable methods of ranking of remediation sites suitable for pyrolysis. Finally, universities and national laboratories could undertake the numerous scientific research and engineering development projects in support of all of these opportunities.

Most of the national opportunities also are major global opportunities -- particularly pyrolysis of hazardous wastes, plastics, and MSW, and the development of associated separation and monitoring technologies. Additionally, there would be opportunities for DOE projects with parallel governmental agencies around the world, and with international agencies. The possible use of pyrolysis in destroying the wastes from the military complexes of NATO, Russia, and Eastern Europe, including chemical

warfare agents, may be an example. The potential market for small modular or mobile units appears particularly promising.

The determined Japanese and German efforts to commercialize pyrolysis technology should underscore the need for an American entry into this arena. Long Island's superb high-technology workforce and technology infrastructure make the region a logical launching pad for such an effort. The major global opportunities for pyrolysis of hazardous and non-hazardous wastes are in Western Europe, Eastern Europe, the former Soviet nations, India, China, Taiwan, and Korea, all of which have begun to mount substantial efforts to remove old pollution and manage existing wastes properly.

A successful regional recovery services industry that is nationally and globally oriented would bring jobs and other economic benefits to Long Island in making, servicing, and selling processing, monitoring, and separation equipment, and in providing analytical, research, and engineering services. The scale of the national and global opportunities may be gauged by the fact that the worldwide green technology market in 1993 was \$250 billion, and it is projected to be \$600 billion by 2000 [Editorial, *Scienca*, December 24, 1993, p. 1963]. The flexibility of pyrolysis in turning many waste liabilities into keystone industrial and energy assets makes it attractive to countries seeking resource self-sufficiency and clean environments in the face of growing populations. Pyrolysis technology has matured in recent years, and is well-positioned to hold its own in the global green technology market.

II.9 Potential Institutional Partners or Funders

This report has presented many opportunities for projects, and for supporting scientific research, engineering development, marketing, and institution-building activities. This section is an inventory of some (a) institutions, other than BNL and SUNY/Stony Brook, that may be interested in participating in these pyrolysis-related projects and supporting activities, and (b) potential governmental and private sources of project grants or matching funds.

Environmental Protection Agency

Emerging Recycling Technology Program Goals: increased recycling of post-consumer paper, plastics, scrap tires.

Office of Pollution Prevention

Technological Innovation Office

Risk Reduction Engineering Laboratory

Clean Air Act Amendment assistance programs

In 1994, U.S. EPA will begin a 5-year, \$2 billion effort to develop environmentally friendly technologies with global market potential. \$350 million is scheduled to be provided in 1994 directly to industry and to industry alliances with universities and governments.

Department of Defense

ARPA Technology Reinvestment Project

Chemical Management Program and

Process Waste Assessment Program

Department of Energy

Environmental Restoration and Waste Management programs (in reorganization along with related national laboratory programs)

Innovative Concepts program of Office of Energy utilization Research (Industrial Solid Waste Processing; Municipal Waste Reduction and Recycling)
National Renewable Energy Laboratory
Industrial Technology Programs
Morgantown Energy Technology Center (ER/WM materials disposition technologies, technology R&D)
Regional Biomass Development Program

Department of Commerce

NIST programs (funding up sharply)
Environmental Trade Advisory Committee (with U.S. EPA)

Other federal

Proposed legislation in the House Ways and Means Committee to restore contaminated industrial sites, including former UST and spill sites, with grants, loans, sharing cleanup costs. [Daley 1993].

Possible funds from Federal Fleet Conversion Task Force, set up by Presidential order in April, 1993. The Government is required to buy 11,250 alternative-fuel vehicles in FY 94, 15,000 in FY 95, and 35,000 annually by FY 1997. Alternative fuels include natural gas, methanol, ethanol, propane, and electric power. The Vice-Chair is the DOE Assistant Secretary for Policy, Planning, and Program Evaluation.

New York State Energy Research and Development Authority

Alternative Fuels for Vehicles program
Landfill Mining Program/Demonstration Projects
Industrial Waste Minimization RD&D Program (submit ETAP-style proposal)
5-year technical assistance grants to municipalities

New York State Department of Environmental Conservation

The new Environmental Protection Fund (municipal waste reduction/recycling, non-hazardous landfill closure, secondary material regional marketing, (under NYSDER) proposed by Governor Cuomo: Environmental Assistance Fund (financed by tire charge) for municipal recycling/landfill/environmental projects

Clean Air Act Compliance Assistance for Small Businesses (under 100 employees)

Other New York State

NYS Department of Economic Development, Division for Small Business.

NYS Department of Economic Development, Office of Recycling Market Development, Waste Prevention and Recycling Program.

NYS Energy Facilities Corporation (Industrial Materials Recycling Act) (Also has a Clean Air Act Small Business Assistance Program)

Electricity generation

Mayflower Energy Partners (NAPE/Pilgrim State)
New York Power Authority
Long Island Lighting Company
Electric Power Research Institute, including its
Northeast Regional Community Energy Center
Long Island Power Authority

Petroleum/plastics organizations (materials recycling and fuels)

American Plastics Council
American Petroleum Institute
Plastic Lumber Trade Association
Association of Plastics Recyclers
National Recycling Coalition
Center for Plastics Recycling Research
Plastics Recycling Foundation
INFORM
US Postal Service/Brooklyn Union Gas
Institute of Gas Technology
Oil re-refiners
NJ/CT/NYS oil refiners
Association of NY recyclers
Scrap Tire Management Council
Area computer manufacturers
Conference of Northeastern Governors
Northeast Recycling Council
Big 3 Auto Makers

Other trade/industry sources

SUNY/LI Electronics Manufacturers consortium on CFC/VOC elimination/reduction
Northeast Industrial Waste Exchange
National Materials Exchange Network
GM Chemical Management Program (e.g.) Long Island Rail Road -- major waste transport opportunities; tie disposal; railroad hauling of wastes is major growth industry [Cohan 1993]

Miscellaneous

Marine Spill Response Corporation
Regional Plan Association
Long island Association
Long Island Forum for Technology
Long Island Development Council
Long Island Economic/Environmental Roundtable
Long Island Regional Planning Commission
New Long Island Partnership for Jobs and Growth
Northeast Recycling Council
Various opportunities in Eastern and Western
Europe, Asia, and former Soviet regions

II.10 Recommendations

(a) Recommendations for NEWME/LIRI

If NEWME decides that the pyrolysis opportunities described in this report now merit action, NEWME should adopt three main goals:

- I. TO BRING ABOUT THE CONSTRUCTION AND SUCCESSFUL OPERATION OF A COMMERCIAL-SCALE (AT LEAST 50 TONS PER DAY) PYROLYSIS FACILITY PLANT DEVOTED TO TARGETED PARTS OF THE LONG ISLAND MUNICIPAL SOLID WASTE STREAM.**
- II. IN PARALLEL, TO BRING ABOUT THE CONSTRUCTION AND OPERATION OF A SMALLER, FIXED OR MOBILE PYROLYSIS FACILITY PRIMARILY FOR DOE HAZARDOUS AND NON-HAZARDOUS SITE REMEDIATION WASTES AND DOE-GENERATED HAZARDOUS AND NON-HAZARDOUS PROCESS WASTES. THESE EFFORTS WOULD BE PART OF A BNL-DEVELOPED, DOE-WIDE ACTION PLAN LEADING TO THE USE OF FIXED OR MOBILE PYROLYSIS UNITS IN ONE OR MORE FEDERAL CLEANUP APPLICATIONS.**
- III. TO ESTABLISH LONG ISLAND AS THE HOME OF AN INTEGRATED PYROLYSIS-BASED RECOVERY SERVICES INDUSTRY THAT MARKETS PYROLYSIS APPLICATIONS, ALLIED MONITORING, SEPARATION, AND RECYCLING SYSTEMS, AND RELATED ENVIRONMENTAL CONSULTING SERVICES NATIONALLY AND GLOBALLY.**

I. All four companies have declared their strong interest in developing a facility on Long Island, and can submit proposals promptly. They have indicated a willingness to commit substantial resources of money, equipment, and technical expertise to achieve a market breakthrough in this region. Accordingly, NEWME should sponsor discussions with the four companies and appropriate local, state, and federal governments and regulatory agencies, acting as the neutral broker to facilitate the building and operation of a commercial-scale (50 to 100-tons per day or more) pyrolysis facility. Discussions also could be coordinated with Stony Brook's Waste Management Institute, especially if plans of the five largest Suffolk County towns to explore regional waste management programs bear fruit. NEWME should encourage regional approaches to waste management whenever possible.

These discussions would cover the facility's size and siting, potentially available wastes (including materials sent from MRFs or incinerators), ownership and operating responsibility, tipping fees and product revenue sharing, cost-sharing of separation equipment, and regulatory determinations. Other parties, such as carters, utilities, and petrochemical marketers, would be brought in when appropriate.

Proposals should be invited to target initially one or more specialized waste streams, such as the tire stockpile in Kings Park, automobile shredder residue, plastics not captured by recycling programs, pyrolyzable MRF rejects and residues, institutional, restaurant, and supermarket food wastes, and textiles. The processing of available raw MSW should be planned for a second stage, after processing for the initial stream(s) is in place. Also, efforts should begin to identify specific pyrolyzable wastes obtainable from specific generators (including BNL) or stockpilers, including suitable bulk industrial and commercial scrap. All of the wastes sought should fulfill the backup strategy, explained above, that complements the existing waste management infrastructure.

Potential sites for pyrolysis facilities at Brookhaven National Laboratory, idle industrial properties slated for cleanup, active industrial sites and industrial parks, and sites in New Jersey should be considered. Old landfills may be considered if the landfills are to be mined using pyrolysis.

University, national laboratory, and business partners would be engaged for supporting technical projects and regulatory assessments. Some specific project opportunities in which Brookhaven National Laboratory could play a lead role are listed in Part B of this section.

As a next step, or as a backup strategy, NEWME should facilitate the application of pyrolysis in landfill mining. Conjoined with other technologies, pyrolysis could physically eliminate Long Island landfills, including landfill areas at BNL and New York City's brontosaurus Fresh Kills landfill.

If these efforts succeed, in the longer term, NEWME/LIRI should consider ways to foster commercial opportunities to fully integrate pyrolysis as one of the anchor technologies in regional municipal and waste management.

II. NEWME should host discussions between the four companies and BNL/DOE to identify equipment, costs, and engineering development needs appropriate for pyrolysis of federal site-remediation wastes and DOE processing wastes that advance DOE's waste minimization programs. This process should lead to a contract between DOE and the company with the best plan.

Simultaneously, Brookhaven National Laboratory should develop a DOE-wide action plan for using pyrolysis in these federal applications. BNL and university partners would (a) identify and rank DOE sites and materials according to the suitability of using pyrolysis in remediation and restoration efforts, directly, or for wastes from primary treatment technologies, (b) quantify the waste streams that would be treated and generated, to assess overall waste, risk, and cost minimization, (c) complete the engineering development of mobile units (such as the Entropic with smaller twin screws), front-end separation systems, and field sensing and monitoring systems, and (d) identify opportunities to use carbon char in DOE cleanup operations, and to recycle the char afterward.

BNL's proposed User Facility for Environmental Pathway Modeling of DOE environmental restoration sites could be used to assess options for pyrolysis. BNL groundwater sampling programs also could play an important role. All of these activities would be coordinated with BNL and other DOE development of technologies for waste stabilization and bioremediation. While these technologies are, by and large, directed at different waste streams, there appear to be opportunities for synergisms in treating contaminated sites on a total systems basis.

The action plan should lead to the construction, field demonstration, and assessment of a pyrolysis unit as soon as is practicable.

NEWME/LIRI should promote collaborations with regional industries that assist in these efforts, and that develop pyrolysis applications in minimizing wastes covered by the Toxic Release Inventory (TRI), Clean Air Act Amendments provisions on VOCs and CFCs, and other hazardous waste regulations. These include chemicals, products, coatings, packaging, and other materials, as illustrated in the body of this report. The "Environmentally Benign Manufacturing Technologies" program proposed by a consortium of area defense and consumer electronic firms and SUNY/Stony Brook would be a logical place to start, if it is approved for ARPA funding.

NEWME also should help identify specific hospital wastes, industrial hazardous process wastes, industrial non-hazardous non-MSW process wastes, and potential cleanup wastes from individual Long Island institutions, industries, and contaminated properties that could be made available for pyrolysis. These materials include wastes that may be generated in BNL environmental remediation and other Long Island Superfund cleanup operations directed at trichloroethylene, fuel hydrocarbons, and other contaminants.

III. Long Island development of applications of pyrolysis should be conceived as an integrated recovery services industry, one that recovers useful energy and materials, and sequesters hazardous materials

from a broad range of industrial, municipal, and cleanup waste streams. Such an industry would spin-off related entrepreneurial activity in monitoring, separation, and processing technologies, and in environmental consulting and assessment services.

NEWME should help arrange for local, national, and global business opportunities, acting as conduit to and from countries where potential markets are large (Russia, other former Soviet nations, Eastern Europe, Turkey, China, Southeast Asia, Western Europe).

In the longer term, research, manufacturing, environmental monitoring, and consulting opportunities may arise in connection with the alternative fuel applications of the products of pyrolysis. Several federal agencies, the New York Power Authority, New York State Energy Research and Development Authority, New York State Department of Transportation, New York State Department of Environmental Conservation, Long Island Lighting Company, Long Island Railroad, heating oil companies, and various trade groups could develop environmentally beneficial uses for hydrocarbon products, including alternative-fuel transportation development, energy storage for load management, and cogeneration.

In all of its activities related to pyrolysis, NEWME should identify and leverage matching funds from industry, government, and trade organizations (listed in section II.9), promote university and national laboratory research and assessment activities (see below), and spot and promote international market opportunities for existing and forthcoming regional manufacturing, environmental service, and environmental technology firms.

(b) Project Opportunities for Brookhaven National Laboratory and University and Industry Partners

Brookhaven National Laboratory is equipped to take the lead role in (a) research, development, and demonstration projects addressing unresolved technical issues about the pyrolysis systems and ancillary technologies, such as char applications, (b) assessment and performance studies on DOE and DOD cleanup wastes and other DOE/DOD wastes, and (c) regulatory and environmental impact studies bearing on both of these areas. These opportunities would involve other DOE labs, other federal and state agencies, area universities and industries, and the manufacturers of the pyrolysis systems. Projects would be highly leveraged and would take full advantage of Cooperative Research and Development Agreements (CRADAs) and other instrumentalities, and obtain participation by private and governmental funders. As emphasized, the four companies have indicated their willingness to commit considerable technical and financial resources as partners in projects.

Which of the project areas listed deserves priority depends on initial decisions as to what kinds of wastes would be targeted first, and on which pyrolysis technology is chosen. For example, the landfill mining projects may be preferred if NEWME determines that this is an area meriting special emphasis.

Again, projects where a BNL should play the lead role are listed here. There are other areas where the lead role could be assumed by NEWME, LIRI, or the SUNY Stony Brook Waste Management Institute: identifying and helping to secure available regional waste streams; coordination with towns, the state, carters, utilities; designing integration with existing collection, recycling, and waste prevention programs for towns and commercial, industrial, and institutional waste generators (incorporating waste stream audits, industrial waste minimization, and manufacturing engineering services); technology transfer to and from regional environmental industries; helping to obtain abandoned industrial sites for pyrolysis operations in exchange for site remediation; nurturing a regional recovery services industry, and its international markets.

These are the main project areas for BNL resources:

For any of the four pyrolysis systems, conduct bench-scale batch tests to determine the physical and chemical composition of MSW and hazardous waste feedstocks of interest, including chemical munitions, mixed wastes, preserved wood containing heavy metals, plastics of interest, and mixtures of tires with other wastes. Advanced thermochemical computer-modeling capability and sophisticated instrumentation for continuous process and emissions monitoring would be developed. Bench-scale tests and tests in full-scale facilities would develop a data base on the effect of variations in feedstock composition and the retort's operating temperature on (a) the physical and chemical composition of the char (including, for example, the nature of metal bonding and the nature and percentage of halogens trapped in the char), (b) the composition of product gases and condensates, and (c) the adiabatic flame temperature and flue stack emissions of combusted product gases. Test-scale equipment is available from some of the pyrolysis companies; for example, Pan American Resources has a 4 ton/day demonstration unit. This research program would include related gas chromatography, scanning electron micrograph and other materials strength and corrosion control/prevention studies, and environmental engineering of process controls and electronics.

Engineering development and physical-chemical testing to mate recently developed methods of upgrading char (removing ash constituents, heavy metals) to pyrolysis units processing various feedstocks. Performance trials and environmental impact studies of new char product applications: in DOE ER/WM operations as an ingredient in bulk secondary materials for use in land and marine infrastructure, and as containers for and barriers to hazardous wastes at contaminated sites; and, in industrial process applications, as an adsorber for VOCs or other contaminants.

For projects in most of the areas listed, engineering and testing of new sensing and monitoring technologies can be developed by DOE, SUNY, and area industries.

Improve separation of product gas streams to maximize product uniformity and energy value, and to minimize impurities.

For the Entropic system, additional regulation-driven tests with MSW and non-MSW feedstocks containing U.S. EPA-listed chlorinated hydrocarbons, followed by laboratory tests of synthetic coal to assay the conversion of chlorinated hydrocarbons to soluble salts, and to monitor syncoal combustion and vent gases, ash content, and leaching potential. Several such tests have been conducted, but more extensive testing is needed to confirm economic and regulatory parameters, and to explore the technical limits of this method for destroying hazardous wastes.

For Entropic system, final production engineering of the Model 12 co-rotational twin-screw pyrolytic processor, to expedite delivery of three finished units on order.

For the Hynol system, engineering development to tailor the hydropyrolysis equipment (the first step of the three-step Hynol process) to specific MSW feedstocks, and to gauge the fraction of natural gas co-feedstock used in the second, steam pyrolysis step. For the Conrad/Hynol system, similar studies gauging blending ratios for SNGLs for the product liquids resulting from various feedstocks.

For the Entropic system, engineering development and demonstration of transportable field unit for site remediation: matching screw sizes and types, and off-gassing and corrosion prevention, to the materials and chemical characteristics of the waste streams being

processed. Similar waste-stream-specific process-control work for the Pan American retort and feedstock airlock system.

Performance evaluation and systems design and engineering of state-of-the-art technologies for separating MSW waste stream components and for size fractionation so as to maximize the range of feedstocks processed. Tailor to wastes of interest, such as printed circuit board wastes, CCA marine, railroad, and telephone lumber, automobile shredder fluff, tires, household non-food plastics, industrial plastic containers, strapping, fibers, and laminates, commercial textiles, and food. Emphasize dewatering of organics; separation of plastics, integration with output streams of rejects from MRFs, incinerators, and mechanical plastics reclaimers; advanced plastics sorting (including the laser/computer system developed by Sandia National Laboratory).

Improvement and demonstration of high-efficiency, heavy-duty equipment for separation, shredding and grinding, and dirt and moisture reduction suitable for landfill mining. This work also dovetails with projects processing contaminated soils at ER/WM sites.

Assisting waste exchanges in identifying and obtaining materials suitable for pyrolysis that are not otherwise recycled or reused -- especially bulk chemicals, solvents, and coating materials.

Demonstrating an integrated sealed-container system for hospital waste shredding and processing designed for pyrolysis.

Making quantitative studies of net reduction in "total system" pollution and health risk and of models for regulatory guidance and approval pertaining to Clean Air Act compliance. System studies would include the impacts of using alternative fuels for transportation or by the utilities. Special attention would be paid to applications to Federal fleet conversion.

Integrated project demonstrating use of pyrolytically produced alternative fuels in federal fleets.

Other regulatory compliance and permitting studies, as needed -- particularly for the complex regulatory issues concerning hazardous and mixed waste processing at federal sites.

Brookhaven National Laboratory could spearhead efforts to (a) identify and rank DOE sites and materials according to the suitability of using pyrolysis in remediation and restoration efforts, (b) quantify the waste streams treated and, in turn, generated by other site treatment technologies, and (c) complete the engineering development of mobile units (such as the Entropic with smaller twin screws), front-end separation systems, and field sensing and monitoring systems. BNL's User Facility for Environmental Pathway Modeling of DOE environmental restoration sites could be used to assess options for pyrolysis. BNL groundwater sampling programs also could play an important role. DOE/DOD Pollution Prevention Opportunity Assessment efforts would be dovetailed.

A similar effort could be mounted to identify promising military and industrial cleanup opportunities in Russia and Eastern Europe.

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