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SCRAP TIRES: A RESOURCE AND TECHNOLOGY EVALUATION OF TIRE PYROLYSIS AND OTHER SELECTED ALTERNATE TECHNOLOGIES

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ABSTRACT

This report presents the results of a technical and economic evaluation of scrap tire pyrolysis and discusses some other alternative uses for scrap tires. A scrap tire, by definition in this report, is one for which there is no economic end use. Information is presented on the scrap tire resource, pyrolysis processes, pyrolysis products (char, oil, and gas), markets for these products, and the economics of tire pyrolysis. A discussion is presented on alternative ideas for using scrap tires as an energy resource. The study was conducted for the U.S. Department of Energy Office of Industrial Programs by EG&G Idaho, Inc., prime contractor at the Idaho National Engineering Laboratory, in conjunction with Galaxy, Inc., and Science Applications, Inc.

SUMMARY

The tire industry produces and sells about 240 million tires annually. Of all the tires removed from vehicles about 30% are consumed in various ways, i.e., used tire market, recap market, rubber reclaim market, ground rubber, and other uses. The other 70% are dumped in landfills or junk yards and present health, safety, and environmental problems. Since single tire contains about 300,000 Btu of energy, the dumped tires represent about 5×10^{13} Btu of usable energy annually, a sizable resource.

The Department of Energy's Office of Industrial Programs authorized this study on the recovery of this energy resource. The original emphasis of the study was on the economic and technical assessment of tire pyrolysis. In conjunction with this work, an assessment of the size and locations of major scrap tire stockpiles was conducted. As the study progressed, it became evident that tire pyrolysis was a fairly well established technology. The lack of widespread use of this technology was due to some major economic problems relating to product marketability, product quality, and product prices. The economics were favorable only when disposal fees were collected and the pyrolysis products (char, oil, and gas) were used on site.

The scope of the study was later broadened to identify other uses for scrap tires. These alternative uses had two requisites: (a) to use scrap tires as an energy resource; and (b) to identify areas of potential research of interest to the Federal government.

The resource assessment portion of the study considered only stockpiles that are easily accessible and easily recoverable. Tire stockpiles are classified as either static (fixed size) or dynamic (changing size). Dynamic stockpiles are further subdivided into shrinking, growing, and steady state. Where static stockpiles are the *only* resource available, large stockpiles would be required even for small plants. For example, a stockpile of 600,000 tires would supply a small, 2-tons-per-day (TPD) plant for the average 10-year plant life. Stockpiles containing 1.5 to 3 million tires would support a 5- to 10-TPD plant for 10 years. In order to supply any large-size conversion recovery system, it would be essential to identify growing, dynamic stockpiles with active collection networks. Very large plants on the order of 100 to 300 TPD exceed the supply capabilities of any existing stockpile and/or collection network. Several existing stockpiles could support a medium sized plant (20-50 TPD).

Scrap tire generation rates were found to approximate one scrap tire per person per year. Although metropolitan and rural input rates differ somewhat, large metropolitan areas offer the best opportunities for tire conversion plants because of the higher densities of scrap tires.

The pyrolysis technology assessment identified 31 existing facilities. These facilities use a wide variety of processes, with a number of reactor types, process conditions, and heat transfer media. Only about half of the projects are still active. The others have been abandoned, typically for economic reasons.

The assessment demonstrated that tire pyrolysis is a mature, well-developed technology. Numerous technical problems have been encountered in the various type pyrolysis processes, but these problems have been and are being resolved by the developers. Tire pyrolysis is technically feasible.

The economics of tire pyrolysis, however, appears marginal at best, except in a few specific instances: (a) where high tire disposal costs,low tire acquisition costs, and significant on-site energy savings can be realized, (b) where the tax advantages of municipal development are used, or (c) where higher value products such as benzene/toluene are refined from the pyrolytic oil.

There are some areas of research which might lead to improved economics for tire pyrolysis. The areas include:

- Exploration of inexpensive techniques to upgrade pyrolysis product (oil, gas, char) quality.
- Optimization of pyrolysis process operating conditions to maximize high value product yields.
- Exploration of pyrolysis product suitability for new uses (new markets).

Several alternative uses for scrap tires were reviewed as a result of the broadened scope of this assessment. In general, the alternatives studied involved reuse of tires, use of tires with no processing (artificial reefs, crash barriers, etc.), low processing uses (tire splitting and crumbling), and processes which degrade the rubber and produce valuable products.

The last area, rubber degradation, offers the largest potential for research in the use of scrap tires. Several technologies, including chemical and thermal degradation of tire rubber, have been used for many years but still offer potential for additional research. Other technologies that have been researched little are microwave devulcanization and microbiological degradation. Of the alternative uses reviewed, the following appear most promising for further research:

- Microwave devulcanization of tires to allow reclamation of the rubber.
- Biological degradation of tires to produce reclaimed rubber or chemical by-products such as organic acids.
- To a lesser extent, exploration of more suitable agents for chemical reclamation of tires.

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CONTENTS

GLOSSARY

Aromatic	- A hydrocarbon characterized by the presence of one or more 6-carbon ring units—for example, benzene.
Asphalt	- Brown to black bituminous substance, consisting chiefly of hydrocarbons, that is found in natural beds and also occurs as a residue in petroleum refining.
Asphalt concrete	- Pavement mixture, with asphalt binder approximately 1/18 by weight and the remainder aggregate.
Asphalt rubber	- A material formed by heating a mixture of asphalt and ground rubber. The rubber can be as much as 33% of the total.
Barrel of oil equivalent	- 5.8×10^6 Btu
Batch	- A process in which the entire charge of material being processed enters the process at the beginning of the operation.
Carbon black	- Finely divided carbon produced by incomplete combustion of hydrocarbons.
Carcass	- The foundation structure of a tire. It includes sidewalls, bead, and cord body.
Char	- The solid residue remaining after pyrolysis of a tire and after removal of steel and fiberglass, if present.
Continuous process	- A process in which material enters and leaves continuously with time.
Conveyor	- A device to transport particulate material through a vessel. The device may be a traveling grate or a screw.
Copolymer	- A polymer that uses two or more different monomers.
Cracking	- A process whereby one material is reacted to produce two or more materials of smaller molecular weight.
Crumb rubber	- Particulate vulcanized rubber buffed from tire carcasses.
Ebullated bed	- A reactor in which a hot gas is bubbled upward through a liquid with suspended oil and rubber particles.
Elastomer	- A polymer that has, or can be treated to have, elasticity.
External fire	- Describes a process in which heat is transferred to the reacting substances by means of a secondary medium such as preheated gas, preheated ceramic balls, or preheated oil, or by conduction through the reactor container walls.
Fluidized bed	- A gas-solids contacting device in which the gas flows upward through a loosely-packed bed of granular solids; the entrained solids are conveyed upward and disengaged from the gas at the top of the vessel.
Internal fire	- Describing a process in which heat is transferred directly to the reacting substances by means of combustion of gas or liquid within the reactor volume, microwave heating, or plasma heating, etc.

Naphtha	- The lowest-boiling-temperature fraction of the pyrolysis oil.
Octane rating	- A quantitative measure of the resistance of a gasoline to knocking a spark-ignited internal combustion engine.
Oil carrier reactor	- A reactor in which pyrolysis oil is dissolved in hot, sprinkled oil as it forms.
Oxidative	- A process in which the chemical reaction occurs in the presence of oxygen.
Petrochemical	- A chemical material derived from petroleum.
Plasma	- A completely ionized gas composed of an equal number of positive and negative charges.
Polymerization	- The process by which low molecular weight materials combine to produce materials of high molecular weight.
Pro Forma	- A projected financial statement that shows how the actual statement will look if specified assumptions are realized.
Pyrolysis	- The process of breaking organic chemical bonds by heating—also known as destructive distillation, thermal depolymerization, thermal cracking, carbonization, and coking.
Pyrolysis gas	- That portion of the vapors leaving a pyrolysis reactor that is not removed by the condenser.
Pyrolysis oil	- That portion of the vapors leaving a pyrolysis reactor that is removed by the condenser.
Quad	- One quadrillion (10^{15}) Btu—sometimes abbreviated as Q.
Quench tower	- A vessel in which a hot material is cooled by immersion in a cool liquid.
Reclaim	- Rubber compound reclaimed from scrap tires. The rubber has been devulcanized and partially depolymerized.
Reductive	- A process in which the chemical reaction occurs with a very limited supply of oxygen.
Residence time	- The time interval during which a representative element of material actually remains in the reactor.
Residual fuel oil	- Used for fuel in large stationary boilers.
Retort	- A stationary vessel in which the material is heated to cause distillation or decomposition.
Reverberatory furnace	- A furnace in which heat is supplied by burning of fuel in a space between the charge and the low roof.
Rotary kiln	- A cylindrical vessel lined with refractory material, usually inclined at a slight angle and rotated at a slow speed.

Rubber compound	- Unvulcanized rubber blended with carbon black, extender oils, and other additives for use in tires or other products.
Rubberized asphalt	- A mixture of asphalt and a small percentage ($\leq 5\%$) of rubber particles.
SBR	- Styrene butadiene rubber.
Scrap tire	- A worn tire for which no economic end use has been found.
Semicontinuous	- An otherwise continuous process in which a portion of the materials enters intermittently during the operation.
Spouted bed	- A gas-solids contacting device in which the gas flows upward through the center of a loosely-packed bed of granular solids; the entrained solids are conveyed to the top of the bed where they then flow downward in a surrounding annulus.
Tipping fee	- Fee paid to a tire collector for disposal.
Tire buff	- Rubber buffed (abraded) from a tire carcass in preparation for retreading.
Tread	- The portion of a tire that makes contact with the road surface.
Vertical Retort	- A retort in which the axis of flow of the material is in a vertical direction.
Vulcanization	- The process whereby rubber attains elasticity through the action of sulfur in the presence of heat.
Worn tire	- A tire that is removed from a vehicle and replaced.

SCRAP TIRES: A RESOURCE AND TECHNOLOGY EVALUATION OF TIRE PYROLYSIS AND OTHER SELECTED ALTERNATE TECHNOLOGIES

INTRODUCTION

Approximately 200 million automobile tires and 40 million truck tires are discarded annually in the United States. Less than 20% of the tires removed from vehicles are recovered for recapping or resale, and 10% are reclaimed for other uses.[1] The remaining 70+% of waste tires are a disposal problem. Scrap tires used as landfill have no economic value and present health, safety, environmental, and handling problems. Tires do not biochemically degrade sufficiently when buried and may resurface in landfills, providing an excellent breeding ground for vermin and mosquitoes.

A number of alternatives to disposal of waste tires exist. Worn tires can be sold as a "used" tire or recapped for continued use as a tire. Worn tires can be used in artificial reefs, highway crash barriers, or children's swings. Splitting, grinding, and rubber reclamation are other uses for worn tires. Whole or shredded tires can be burned directly or pyrolyzed for energy recovery.

To provide a perspective on the extent of the energy lost in the form of scrap tires, an average tire mass is 20 pounds with an average fuel value of 15,000 Btu per pound. This amounts to approximately 0.05 quad per year[a] of energy, or 23,800 barrels of oil equivalent per day. In 1981, total oil consumption in the U.S. was about 15,100,000 barrels per day; thus, the gross energy that can theoretically be recovered from 240 million tires per year is about 0.16% of the annual U.S. consumption of oil. Because scrap tires represent such a large energy resource, it would benefit the national energy interests to find an efficient method to convert old tires to a usable energy form.

For purposes of this document, worn tires are defined as all the tires removed from vehicles. Scrap tires are defined as those worn tires for which there is no end use and which pose disposal, health, environmental, and handling problems. Scrap tires are the specific resource for consideration as an alternative energy source.

Definition of the Problem

The scrap tire problem has been studied considerably because each tire represents a significant quantity of energy, not only in terms of heat recoverable through direct combustion, but also in terms of the energy consumed in processing petroleum and natural gas into the principal constituents of tires—carbon black, extender oil, and elastomer. Recovery of part of this energy content in a form with the highest possible value, i.e., crude oil or chemical feedstock, would provide a valuable resource and also alleviate a growing environmental problem.

Although the current economic uses for worn tires is limited to 30% of all tires removed from vehicles, the remaining 70% of worn tires have no economic value and present serious disposal problems. Scrap tires are the focus of this study with an emphasis on research and development needs to provide insight into potentially viable means of recovering energy from this waste product.

The Purpose of the Study

The purpose of this study was originally identified as an assessment of tire pyrolysis technologies, an assessment of the scrap tire resource, and an assessment of pyrolysis economics. The ultimate goal of the study was to identify pyrolysis research and development needs where the Federal government has a role. As the study of pyrolysis progressed, it became evident that tire pyrolysis was a mature technology and that the role for the Federal government in pyrolysis research was limited. Therefore, additional means of alleviating the scrap tire problem and converting a waste product to energy

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[a] Quad = 10^{15} Btu.

were briefly investigated. The results of the study point to several areas where government supported research is appropriate.

The assessment of pyrolysis technologies included the major process types: oxidative, steam, inert, microwave, fluidized bed, rotating retort, and molten salt. The evaluation of products included the common types of products from pyrolysis (oil, gas, char) and their current markets. A market assessment was performed which identified a number of scrap tire feedstock locations. The tire feedstock resource was analyzed by size, location, collection systems, input rates, input mechanisms, and ownership (private or public). The assessment of process economics identified capital costs and operating costs for pyrolysis.

Methodology of the Study

The Office of Industrial Programs of the U.S. Department of Energy funded this study to determine research needs. The study was conducted under the supervision of the Idaho Operations Office of DOE, by EG&G Idaho, Inc., with assistance from Science Applications, Inc., and Galaxy, Inc. The study was subdivided into a resource assessment, a technical assessment and an economic assessment. The methods used to accumulate data included telephone inquiries, telephone interviews, literature reviews, and personal contacts. Pyrolysis operators in the U.S. and overseas were contacted for technology information. State and municipal officials in the U.S. were contacted to identify the location and size of tire stockpiles, the characteristics of the stockpiles, and the regulatory factors impacting collection, storage, and disposal techniques for scrap tires. Although a number of tire pyrolysis studies were conducted in the 1970s, most of the resulting commercially sized projects were abandoned. A few projects are currently in construction, startup testing, or commercial operation in the United States, Great Britain, West Germany, and Japan. An evaluation of the existing projects along with a review of the literature has provided a systematic categorization of tire pyrolysis technologies.

The presentation of the study is organized in the following manner. The first element of the study is an evaluation of all currently known uses for worn tires. Second, the resource is defined and identified, including stockpile locations and sizes, collection mechanisms, collection fees, ownership of stockpiles, and institutional factors. Third, an overview of pyrolysis is presented, with descriptions of various pyrolytic units that were in actual or potential use. Fourth, a discussion of product quality, product quantity, and marketability is presented. Fifth, the economics of specific pyrolysis sites are discussed along with an evaluation of economic viability of the industry. Finally, potential research and development needs for scrap tires are identified for potential government support.

ALTERNATIVE USES FOR WORN TIRES

Five desirable characteristics which scrap tire disposal processes[2] should have include: (a) no adverse effect on environment; (b) conserve natural resources via raw material recovery recycle; (c) minimum impact on established industries; (d) adaptable to widespread use with a commercially valued product; (e) competitive cost range. Many processes can satisfy the first four requirements, but the fifth criteria is the most difficult to achieve.

In the worn tire market, the available supply of worn tires preferentially satisfies the demand associated with the highest-value economic use. The demands for successively lower-valued uses are satisfied until either supply or economic uses are exhausted. Scrap tires represent the supply that has no demand and are the disposal problem. The following paragraphs rank and discuss existing and potential economic uses for worn tires. As used in this discussion, the term "value" refers to the difference between selling price and total processing cost.

The highest-value use for a worn tire is as a used tire,[3] since a price approximating that of a retreaded tire can be obtained, and the processing cost consists only of handling and inventory costs.

Following use as a used tire, retreadable carcasses represent the next highest value.[3] Only 30% of the energy of new tire production is needed to retread a casing; a retreaded tire gives about 80% of the wear of a new tire. This represents real value to the customer. Any industry where tires are a major expense recognize the value of retreads such as truck, bus, airline, and automobile fleets. Two estimates of the percentage of retreaded truck and bus tires are 30%[4] and 70%.[2] By contrast, only about 17 to 18% of the worn tires removed from privately owned vehicles are retreaded.[2,4] Overall, about 20% of waste tires are retreaded. Not all of the retreadable tire carcasses are retreaded, because the demand for certain sizes and types does not justify the storage and inventory costs, and because some potentially retreadable tires are discarded.[2,3]

The next highest value, after retreading, is a non-tire use for which there is little or no processing cost. Among these uses are artificial reefs, highway crash barriers, highway base materials, children's playthings, etc. Presently, these uses do not represent a large market (<0.1% of waste tires), but the potential for growth of this market is appreciable. One estimate of the number of tires that could be consumed by artificial reefs is 1.5 billion tires, about seven years' production of waste tires.[5]

The next highest value use for a worn tire is in the splitting industry.[6] Tire splitting involves removing the bead and cutting away the tread, which leaves a tough, durable, fabric-reinforced rubber sheet that can be die-cut into a number of shapes. The products include gaskets, seals, suspension straps, conveyor flights, dock bumpers, floor mats, etc. This is a high-value use because of the relatively small amount of processing necessary to upgrade a worn tire to saleable products. Splitting only consumes about 1% of the worn tires generated.[7]

The next ranking high-value use is the production of ground or crumb rubber, which comes from tread buffing for recapping or is removed from tires that are not recapped, used whole, or split.[3] Unprocessed, crumb rubber can be used as a filler in tires, in molded rubber products, in asphalt paving material, as an additive to asphalt, and in concrete. Using only rubber powder recovered from waste tires and vulcanizing agents without the virgin rubber compound, elastomeric materials with useful physical properties have been produced.[8] The range of applicability of the products is not available. The potentially increased durability of asphalt-crumb rubber mixtures could lead to large reductions in the labor and material costs of road repair.[9] Little or no modification of existing equipment is needed to handle asphalt-rubber, and if it can save one or two resurfacings compared with the use of ordinary pavement, then one pound of rubber would replace five pounds of asphalt, whose energy value is over 90,000 Btu.[10] Substitution of asphalt-rubber is generally a break-even proposition if one resurfacing is saved. If 25% of the binder used annually in asphalt were replaced by rubber from tires, then 400 million tires per year would be used. However, the use of worn tires is an asphalt-rubber additive is not generally accepted due to pavement contractors initial costs and uncertainty about durability and performance.

Rubber reclaiming is the next-highest value use for worn tires, because this option requires more processing than other uses of crumb rubber. Reclaiming refers to chemical or thermal devulcanization of the rubber (rupturing the carbon-sulfur bonds that cross-link the molecular chains). The devulcanized rubber can then be blended with virgin rubber in the production of new tires and other rubber products. This process can be quite successful with natural rubber or synthetic polyisoprene, but the results are not as good for Styrene Butadiene Rubber (SBR).[11] Since SBR is the principal component of most tires, rubber reclaiming only accounts for about 5% of the use of worn tires. Reclaim technology is an old and well-established technology, but has been declining due, partially to the inability to handle steel-belted tires.[9] The energy displaced by reclaim is about 27,000 Btu/lb of tire. Approximately 70 to 80% reclaim is used in tire carcass and sidewall compounds where tread-type performance is not required. Reclaim advocates state that up to 30% reclaim could be used in tires without compromising product quality.[9] The Japanese are actively seeking suitable agents for the chemical reclamation of waste rubber.[12,13,14,15] Another use for reclaimed rubber is in inks for electrostatic copiers.[16]

Reclamation of waste rubber by microwave treatment has been patented by Goodyear[17,18,19,20] and by the Japanese.[21] In 1971, the Goodyear plant in Lincoln, Nebraska, started laboratory tests to determine the feasibility of using microwave energy to recycle rubber hose waste. A commercial unit was in operation by 1977. The process continuously treats 6 to 10 mm feed particle size EPDM (ethylene-propylene-diene-terpolymer) at 500 to 660°F for 5 min. Tests indicate that scission of sulfur-sulfur and carbon-sulfur crosslinks occurs. The material can be recycled more than once without detriment to the physical properties. The energy expenditure is about 1200 Btu equivalent/lb at 95% feed recovery with a cost of $0.15/lb. Only fair success was obtained with waste tires as feed after the metal and tire fabric was removed. Another microwave reclaim process used naphthenic oil mixed with the rubber powder.[21]

After the demands for the above uses are met, about 70% of the scrap tires remain. Since a tire has a heating value of 15,000 Btu/lb, this represents about 0.05 quad/year of wasted heating value. Of the available processes for recovering the energy from scrap tires, combustion and pyrolysis appear to be two processes that can be employed on a large enough scale to have an important impact on the problem in the short term. The decision between pyrolysis and combustion depends on the required end use. For example, tire combustion is better suited to the production of process heat, since combustion directly releases about 75% of the combustion energy in the tire. A comparable overall combustion efficiency for pyrolysis is about 66%.

Table 1 summarizes the energy recovered, the applicability of the process plant scale, and the potential to consume all or part of the available waste tire supply for selected alternatives in the processing of waste tires.[9]

Another potential alternative for scrap tire disposal is microbiological conversion. Nickerson at the Institute of Microbiology at Rutgers University and the Firestone Tire and Rubber Company have reported the results of studies of fermentation of scrap tire vulcanizates.[22,23] Natural rubber was known to be attacked by microorganisms as early as 1914, and definite indications of synthetic rubber degradation were noted in the experiments.

A highly desirable point of attack for microorganisms would be the sulfur-carbon bonds created by vulcanization. If the chemically combined sulfur could be removed without significant depolymerization, the resulting product would be a superior grade of reclaimed rubber, a relatively high-value product. Although no reported work exists, specific species of microorganisms could be isolated that would metabolize the tire matrix and produce a valuable chemical byproduct, i.e., organic acids, fuel, or monomers.

A chemical or radiation pretreatment could accelerate the microbial digestion of tire polymeric material by random cleaving of the large highly reduced molecules. Increased kinetics of degradation would benefit the economic feasibility of any designed process.

Very little work in this area has been accomplished. However, with more emphasis being placed on biotechnology processing systems to assist in solving energy and waste problems, degradation of tires should be investigated.

In summary, asphalt substitute is considered a promising option for using waste tires with state-of-the-art technology when potential energy savings and consumption of waste tires are evaluated. However, there are three process areas that merit further study. These are microwave devulcanization, microbiological degradation, and chemical reclamation. These areas have been researched recently, but more specifically for waste rubber products than for scrap tires.

Table 1. Selected processing alternatives for scrap tires

Process	Energy Recovered (Btu/lb) Initial Saving	Energy Recovered (Btu/lb) Later Combustion	Comments	Plant[a] Scale	Potential[b]
Combustion of whole tires	15,000	—	Requires special furnace; replaces coal	L	A
Combustion of shredded tires	15,000	—	Co-fire with coal in existing stoker furnace; replaces coal	S	A
Pyrolysis (fuel products only)	11,000-14,000	—	Up to 12,000 Btu/lb petroleum replaced	L	A
Pyrolysis (recover fuel products and carbon black)	19,000-23,000	4,000	Cost $1.50; revenue $1.80/tire carbon black quality in dispute	L	A
Depolymerized scrap rubber (DSR) substitute for No. 2 fuel oil	17,000 (per lb DSR)	—	Experimental	S	A
Reclaim	27,000	15,000	Often considered an inferior product; use declining until recently	S	P
Biological degradation	30,000	15,000	Experimental	S	P
Microwave devulcanization	33,000	15,000	Still experimental for tire rubber	S	P
Asphalt substitute	90,000	—	Most promising option	S	A

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a. S = applicable on small scale; L = large scale only.

b. A = could consume all scrap tires; P = could consume only part of supply.

RESOURCE DESCRIPTION

A discussion of scrap tires becomes more meaningful when a flow chart diagram on the life cycle of tires is included. Figure 1 itemizes the life cycle of tires. Through this flow chart one can determine that the bulk of scrap tires go to landfills and junk yards.

Assessment of the magnitude and significance of the scrap tire resource requires a definition of the types of stockpiles, the locations, the sizes, and the growth dynamics of the stockpiles. Any user of scrap tires needs to be aware of all of these factors. The amount of tires required for any worn tire use should be related to stockpiles. In addition to the above, some of the legal and institutional problems associated with scrap tire collection and use will be explored.

Definitions

Scrap tire stockpiles can be defined as a concentration or accumulation of tires in one location where recovery is feasible without excessive effort

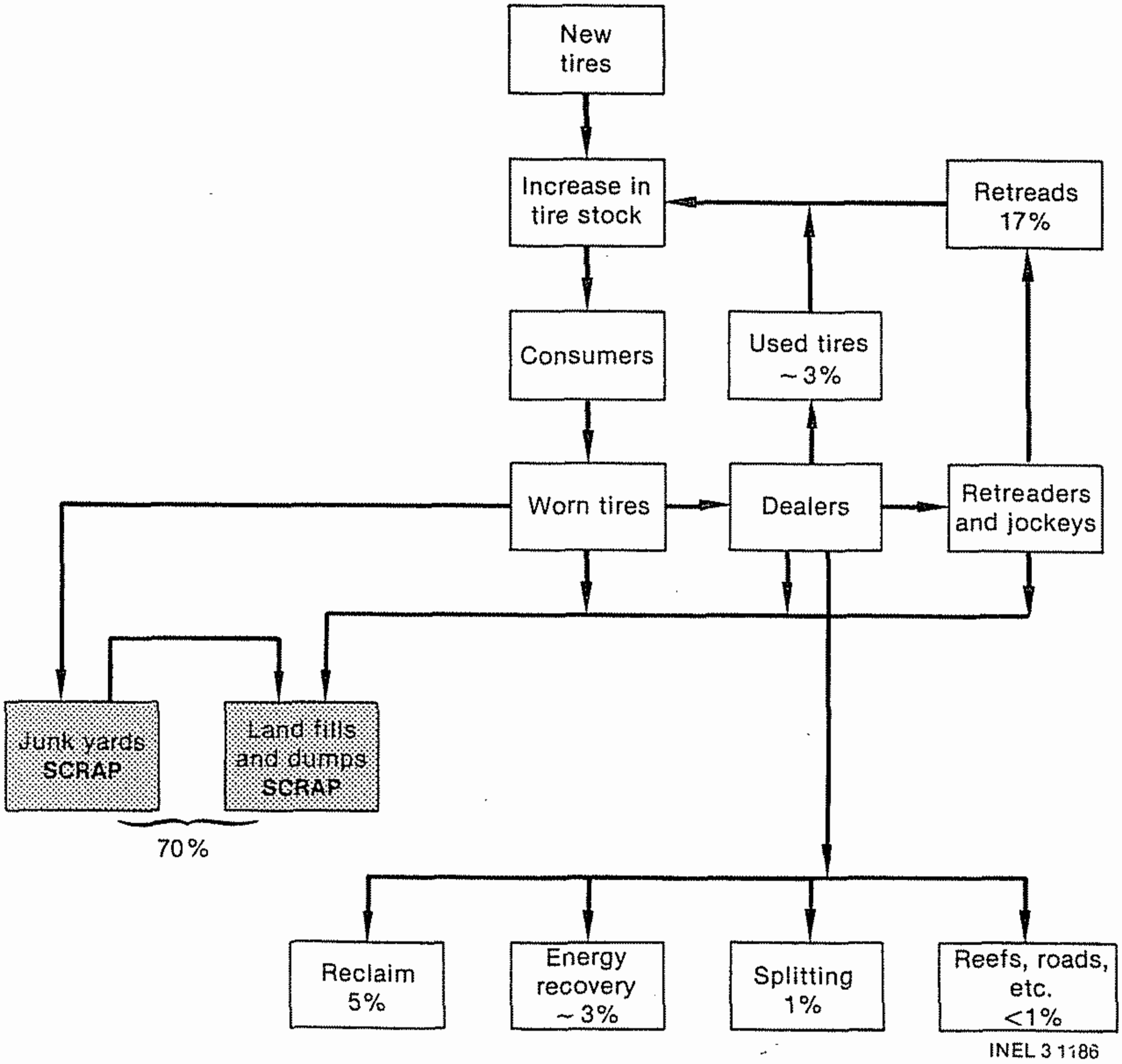

Figure 1. The flow of tires from new tires through the current uses of worn tires.

or cost. Thus, for the purposes of this study, large, easily accessible, and easily recoverable piles of tires are of prime interest. Tires that are buried in landfills or other such disposal sites are not considered because of the expense of recovery. These tires may be "mined" or recovered in the future if their value as a resource considerably exceeds their recovery cost.

Tire stockpiles fall into two main categories: static and dynamic; dynamic is further divided into steady-state, shrinking, and growing categories. Static stockpiles are accumulations of tires that are not being used and no additional tires are being dumped. Such piles could be of use as an auxiliary reserve, but basing any economical recovery operation on a static stockpile is only attractive where the stockpile is large enough to accommodate feedstock needs over the entire expected lifetime operation.

A steady state stockpile is one in which the absolute size of the pile changes little; tires are constantly being accumulated and removed for some end use at approximately equal rates. Since an operational collection system is present, such a stockpile could become more valuable to any conversion process than a static stockpile. A shrinking stockpile is one in which the end use or output rate exceeds the input rate. It would thus be expected that such a stockpile would have little value for any conversion process. A growing stockpile has a collection rate that exceeds any end-use rate. A dynamic growing stockpile offers an opportunity for conversion processes because a collection system is already in place.

Table 2 shows the relationship between potential plant capacity and tire supplies required. To supply a 20-ton-per-day (TPD) plant, a static or steady state stockpile of six million tires would be needed to provide feedstock for l0 years, assuming that the plant operates 300 days per year and a stockpile is the only source of tires. A 50-TPD plant would require a stockpile of 15 million tires for the same 10-year period. Thus, very large static or steady state stockpiles are required if they are the only source of supply for any system. Since very few stockpiles of this magnitude exist, it is important to consider both a stockpile and a collection system so that the stockpile is either drawn down slowly over the life of a project or at least offers a suitable buffer (e.g., 60 day supply). Thus, for the same 20-TPD plant, a stockpile of about 120,000 tires would offer a supply for 60 days. Growing, dynamic stockpiles offer a unique opportunity for exploring energy conversion technology. Thus, if a stockpile of 120,000 tires grows at a sufficient rate to meet plant capacity requirements, the 20-TPD plant would always have a 60-day supply of the resource as inventory.

For the purpose of this study, a minimum stockpile size of 100,000 tires was selected. All known stockpiles of 100,000 tires or more are detailed in this study. In addition, stockpiles centered within 100 to 150 miles of a major metropolitan area were considered valuable because of collection networks that would expand or evolve if tires were purchased.

Methodology of Stockpile Location

A number of sources were consulted to obtain information on tire pile locations and sizes, collection systems, transportation systems, stockpile ownership, and regulations. These sources were obtained through telephone directories and city information offices. Participation by state and municipal officials was effective, with nearly all of the contacts providing information. The state officials provided (a) lists of stockpiles, (b) lists of people involved in reclamation or recovery operations in their states, (c) names of others within their state who could provide information on stockpiles or recovery operations, and (d) copies of regulations. The state officials discussed state efforts in coping with tire disposal (past, present, and future), tire disposal legislation, incentives, and other regulations. From all these sources, more than 34 stockpiles were identified.

Location and Size

Projections of the numbers of tires scrapped have usually been based on either production or population. Early statistics were based on product sales and assumed that scrap rubber was disposed of in the same area in which the products were sold.[24] Other estimates have used a rule of thumb that one passenger car tire is disposed of each year for each individual in the population. This general rule was obtained by simply dividing the reported annual tire disposal in the U.S. by national population; it does not allow for local variations in tire wear, mileage, and vehicle-to-population ratios.

Table 2. Relationship between plant capacity and tire supplies

	Plant Capacity (TPD)								
Tire Supplies	1	2	5	10	20	50	100	200	500
No. Tires/Day (20 lb/tire)	100	200	500	1,000	2,000	30,000	10,000	20,000	50,000
30-Day Supply (no.)	3,000	6,000	1,500	30,000	60,000	150,000	300,000	600,000	1.5×10^6
60-Day Supply (no.)	6,000	12,000	30,000	60,000	120,000	300,000	600,000	1.2×10^6	3×10^6
Year Supply[a] (no.)	30,000	60,000	150,000	300,000	600,000	1.5×10^6	3×10^6	6×10^6	15×10^6
5-Year Supply[a] (no.)	150,000	300,000	750,000	1.5×10^6	3×10^6	7.5×10^6	15×10^6	30×10^6	75×10^6
10-Year Supply[a] (no.)	300,000	600,000	1.5×10^6	3×10^6	6×10^6	15×10^6	30×10^6	60×10^6	150×10^6
Year Supply[a] (tons)	300	600	1,500	3,000	6,000	15,000	30,000	60,000	150,000

a. Plant operating 300 days per year.

In order to validate the rule of thumb, a model generated by Intenco, Inc., was used because it incorporated factors not included in projections that are based solely on population or production. The model calculates the total tonnage of scrap tire generation for the United States. A detailed explanation of the model is given in Appendix A. This total is calculated using: (a) tire production rates; (b) mileage; (c) tire life expectancy; and (d) vehicle registration.

The total worn tires was calculated to be 3.4 million tons per year (TPY) of which about 1.9 million tons is from cars and 1.5 million tons is from trucks. No reduction in the numbers was used for the amount of retreads. If retreads are subtracted, the amount of scrap tires from cars is about 1.5 million tons and from trucks is 0.9 million tons, or about 2.4 million tons or 240 million tires.[1] This roughly equates to one tire per person per year.

The model calculated the scrap tire generation for each individual state. The same technique is applied to major metropolitan areas. The results are given in Appendix A. The tables include a column on pounds of scrap tires per person. By using regression analysis, a correlation coefficient of 0.94 was found between scrap tires and population, which means that there is a very strong correlation between population and scrap tire generation.

However, a regression analysis applied to tire pounds per person and population density (population per square mile) showed a very low correlation. This indicates that a higher per-capita scrap tire generation occurs in larger, less-populated states, which is probably due to life-style in larger states. The total volume of scrap tire generation will be greater in larger metropolitan areas, and it is these areas that must be considered as potential conversion process operations. This point is illustrated by comparing the metropolitan data and tire supplies needed for various plant capacities shown in Table 2. Thirty-five of the major metropolitan areas will generate the more than 15,000 TPY of scrap tires needed to supply a 50-TPD plant operating 300 days per year. Fifteen of the areas will generate the scrap tires needed to supply a 100-TPD plant, and only six can support a 200-TPD plant. Because major metropolitan areas are important to any tire conversion process the specifics of a number of large cities are given in Appendix B.

Table 3 lists the stockpiles of more than 100,000 tires, by location and approximate size. The table indicates stockpile dynamics describes current use. The table is organized by decreasing stockpile size. Stockpiles of less than 100,000 tires are listed in Appendix C.

The table indicates that few existing stockpiles would be able to support a large conversion process for its entire design lifetime. Only one stockpile exists that could almost supply a 50-TPD plant over a 10-year design life, and there are three stockpiles that could support a 20-TPD plant. In addition, one of the four largest stockpiles is owned by an entrepreneur active in shredding to produce a marketable fuel supplement, one is in litigation, one has no current market for its scrap tires and at this writing one is burning, apparently out of control. Indeed, of the 12 largest stockpiles, only three have no known current or potential use.

These results confirm that for most plants, tires would have to be collected from another source to ensure a continuous adequate supply of tires for the design life of the plant. The tires accumulated in stockpiles would not be adequate, and a plant would have to rely on tires being generated in a major population center.

Collection

Collecting tires presents a unique problem or opportunity depending on the motive of the collector. Private businesses with a profit motive probably have collection networks in place. For example, "tire jockeys" are small entrepreneurs who collect used tires from small establishments and sell the retreadable tire for profit while disposing of the scrap tires. Public facilities may require a fee for dumping tires in a landfill site, which poses a major problem for some disposers. Thus, the availability of scrap tires can be influenced by collection costs and transportation costs. These costs will limit the geographic area for effective collection efforts. Collection costs are also influenced by volume reduction before shipment.

Shipping costs for tires depend on two factors: shredded or whole tires; truck or rail transport. Shredding reduces the volume by 15 to 25% of its original volume and reduces costs of shipping by 20%.[11] Estimated costs of shredding vary depending upon the process between $0.10 per tire to $0.75 per tire.[4,11] Shipping costs vary between $0.16 to $1.00 per tire for truck transport with an average of $0.50 per tire.[11] Train transit of tires reduces costs by about 50% if the distance traveled is greater than 200 miles.[4,25,26]

Table 3. Major stockpiles

Location	Size (No. of Tires)	Expansion/Contraction	Use
1. Ed's Tire Disposal Westly, CA	14 million	Collects 3-4 million per year	Grinding and marketing product; expects to process 3 to 4 million each year
2. Colorado Disposal, Inc. Denver-Arapahoe, CO disposal site	10-11 million	60,000 in/out per year	Potential pyrolysis
3. Winchester, VA	6 million	Expanding	No known use
4. Southeastern NH	6 million	Inactive	In litigation
5. Rubber Resources, Inc. Everett, WA	4-5 million	480,000 in/out each year	Selling ground rubber for fuel
6. Somerset Auto Salvage & Repair St. Croix County, WI	4-5 million thousand per year	Growing at 150 to 200	Developing own pyrolysis
7. Cecil Heidelberger Anoka County, MN	3-5 million	Growing, unknown amount	None
8. Dresser Tire and Rubber Co. at Lynwood and Alameda, CA, and 6208 Alameda, LA	3-4 million on 35 acres, and 7 acres	Actively being disposed	None
9. Tulare County, CA Woodville Landfill 10 mi SE of Tulare	3-4 million 29 acres, 12 ft high	Growing, unknown amount	None
10. NuWay Landfill Irwindale, CA (Genstar Conservation Systems)	70-80 acres, 50 ft deep, probably several million	Growing, unknown amount	Unknown
11. Western New York (contact Miracle Sales & Service, Niagara Falls)	2 million in four year	Growing at >5 million per	None
12. Broward County Landfill, FL (Fort Lauderdale area)	2 million year	Growing at over 1 million per	RFP out to dispose of tires
13. Uneeda Tire Co. Rochester, NY	1.5 million on 5 acres[a]	Growing	None
14. Roplex in Hughesville, MD and Smithburg, WV	250,000 and 1 million	Shredding incoming tires	Shredding for fuel
15. Joy Reclamation Glen Burnie, MD	1 million	Inactive	None
16. William Beraneck Dawson, PA	1 million	Conflicting information but may be growing as much as 1 million per year (see text)	None
17. Mullins Landfill Harford County Belair, MD	800,000	Inactive	RFP out to get rid of tires
18. Pontiac City Landfill Pontiac, MI	600,000 to 700,000 on 5.5 acres	Inactive	Only small amount being used
19. U-Rent Storage & Salvage Yard, 12311 Weld Co. Rd. 41, Hudson, CO	600,000	Growing, unknown amount	Pyrolysis
20. Manaforte Bros. Plainville, CT	500,000	Inactive	None
21. Bergey's Tire Service Franconia, PA	500,000 to 1 million	Growing, unknown amount	Pyrolysis
22. Tire Pits Carrol County, MD	400,000 or more	50,000 per year	None

Table 3. (continued)

Location	Size (No. of Tires)	Expansion/Contraction	Use
23. Blackwater Storage Land fill; Wicomico County, MD	300,000 to 400,000	Growing at 35 to 40,000 per year	None
24. Houston, TX: (1) Hwy 59 & Loop 610 (2) 313 W. Canino	100,000 250,000	Actively being disposed	None
25. Leon County Landfill, L (Tallahassee area)	Well over 100,000 on 4 acres, 10 ft deep	Growing at ∼60,000 per year	None
26. Resource Recovery, Inc. Miami, FL	Well over 100,000 on 160 acres	Growing at 50,000 to 60,000 per year	None
27. East Hartford, Incin. East Hartford, CT	4 large piles >100,000	Growing at 80,000 per year	None
28. Crystal Tire Co. Crystal City, MD	>100,000	Growing at 35,000 per year	None
29. Madison, WI: (1) Green County Landfill (2) Dane County Landfill Verona, WI	110,000 tires (1,100 tons, shredded)	Green County, Inactive Dane County, Growing at 40,000 per year	None None
30. Beck's Tire Service, Inc. Kansas City, MO	Several large stockpiles, but owner will not confirm size or other details.		
31. Belair Sanitation Stillwater, MN	30 to 40 acres; owner has developed own pyrolysis process of 10 tons per hour; he is reluctant to give further details.		
32. Brazil, IN	2 to 3 million tires reported, cryogenic volume reduction facility is associated with stockpile and is scheduled for startup in January; have been unable to contact owner.		
33. Granular Systems Sacramento, CA	Buying tires and shredding and feeding to Ed's Tire Disposal in Westly (see 1. above); owner reluctant to provide further details.		
34. Massachusetts Tire Corp. Boston, MA	Buying and stockpiling tires in Boston area; has developed a pyrolysis plant that is ready for startup with expected throughput of 1,200 to 4,000 TPD; owner reluctant to give further details.		
35. Scientific Development, Inc. Eugene, OR	Stockpiling shredded tires, but owner will not provide details.		

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a. One layer of tires evenly distributed over one acre would contain about 10,000 tires.

The consensus is that about 100 miles is the maximum economic distance involved in any active collection systems. Fees charged to collect tires through collection systems ranged from 20 to 50 cents per tire. The study did not identify major differences between collection systems for car tires and those for truck tires.

A "tire jockey" would collect all tires from an establishment for a fee of 25 to 50¢ per tire. He would sell the better grade used tires to a recapper for $4.00 to $5.00 per tire and dispose of rest of the tires.

Transportation costs and reduction costs tend to make tire collection and volume reduction prohibitively expensive. The collection networks identified during the study are summarized in Table 4.

Public Collection

Because tire disposal is generally a municipal problem, it is important to understand local and state efforts. A few states and some metropolitan areas are making efforts to resolve the waste tire

Table 4. Existing collection networks

Locality	Description	End Use
New York	Existing systems that could generate large numbers of tires or serve as a collection system are the local utility, the phone company, tire dealers, and gas stations. The city itself generates several hundred tons per month (TPM) (Sanitation Department is extremely interested in cooperation).	None
D.C. - Fairfax, VA - MD	Roplex, out of Hughesville, Maryland, has a trailer at county landfills to collect tires; they also have established contracts with several Maryland county landfills to process their tires.	Combustion feed stock
Atlanta	Tire dealers are forming a co-op to supply a new landfill dedicated to tires only; they intend to store the tires for the possibility of sale later.	Storage
Denver	A pyrolysis plant operator has apparently established network with tire haulers and dealers to deliver tires to his plant in Hudson, Colorado. Local authorities express doubts that the pyrolysis plant will become operational, because funding is unavailable.	Possible pyrolysis
Akron	The city has established a network with local dealers and stockpilers to supply their recovery plant.	Combustion feed stock
Seattle	A stockpile operator in Everett, Washington, has established a collection network in the Seattle, Tacoma, and Everett areas. He is still looking for markets for tires, and this established network could probably still be exploited.	Boiler feedstock
Cleveland	The city is in the process of establishing a collection network to collect tires from commercial establishments in the city.	Landfill
Illinois	There are strong networks of recappers in the state.	Landfill
San Francisco	Ed Filbin of Westly, California, is collecting tires from all landfills and commercial outlets within a 125-mile radius.	Combustion feed stock

disposal problem. Although, many efforts are combined with solid waste disposal plans, a number of areas have specifically identified tires as a unique waste. The emphasis of the problem is quantified when one looks at the landfill fees required by specific localities (Table 5).

These fees reflect the difficulty involved in handling tires, the trouble involved in keeping them buried, and the amount of landfill space they occupy if buried whole. In some areas, notably Pittsburgh, Kansas City, St. Louis, and New Jersey, illegal dumping of tires has accompanied the high charges for legal disposal methods. In other areas, recovery efforts have increased or tires have been shipped to nearby areas where laws are less restrictive.

Some municipal areas are aggressively pursuing tire recovery and recycling efforts. Houston and

Table 5. Landfill fees

City or County	Regular Fee	Tire Fee	Truck Fee
Portland, Oregon			
Demolition landfill	—	$2/tire	$5/tire
Regular landfill		20¢/tire	$2/tire
Salt Lake City, Utah	$4.50/ton	$20/ton	—
Kansas City, Missouri	$9.50-10.50 per load	$20/ton or load	—
D.C.-Fairfax, Virginia	—	$45/ton	—
Pittsburgh (Allegheny Co.), PA	—	$5/tire	—
L.A. County	$3.75/ton	$4.75/ton	—
Seattle, Washington	Regular fee +	25¢/tire	—
King County, Washington			
Whole tires	—	$30/ton	—
Sliced tires		$18.50/ton	
Cincinnati, Ohio			
Public landfill	—	$5.70/yd	—
Private landfill		$2/tire	
San Francisco, California	—	10% extra	—
St. Louis, Missouri	—	$2/tire	—
Ohio	—	$2.50/tire	—
Phoenix, Arizona	—	$1/tire	—
Denver, Colorado			
Private landfill	—	$1/tire or	—
Public landfill		$5.50/yd	
		$4.50/yd	
New Jersey		25¢ to $3/tire	—
Tulare County, California	—	25¢/tire	$2/tire
Dallas, Texas	Regular fee +	$11/ton	—
Detroit, Michigan (charges for special collection over 4 tires)	—	—	—

Minneapolis have made attempts to get local utilities to use ground rubber as part of their boiler feed. Houston Power & Light decided against this use because they would have to alter their scrubbers. Akron, Ohio, is in the process of establishing a refuse recovery system that uses garbage as a feedstock and converts steam to heat downtown buildings, the local university, and some hospitals. Table 6 summarizes the state efforts, while Table 7 summarizes specific metropolitan efforts in tire disposal.

Several states have established grants to provide support in obtaining shredders for landfills, to reuse scrap tires, or to study the feasibility of resource recovery of any solid waste. New Jersey has established a tax on solid waste going to the landfill; the money will be used to promote recycling and energy recovery activities. Connecticut is trying to enact a similar law.

Ownership and Purpose

A review of Table 3 shows that most major stockpiles are privately owned. This reflects the natural tendency for the public sector to use scrap tires in landfills. The purpose of the ownership of these large stockpiles is to avoid disposal costs of scrap tires or hold them for future use.[27] Their potential for energy conversion is attractive.

Institutional Issues

Regulations that affect waste tire collection, processing, burning, or other disposal methods can occur at the federal, state, or local level.

Scrap tires contain 83% carbon, 7% hydrogen, 2.5% oxygen, 1.2% sulfur, 0.3% nitrogen, and 6% ash by weight.[28] The 1.2% sulfur content of tires relates to sulfur dioxide emissions from any chemical or processing plant; likewise, the ash content of about 6% relates directly to particulate emissions. The sulfur content is between the typical sulfur values of low- and high-sulfur coal.[28] The ash content consists mainly of zinc, titanium, and silicon oxides.[28] Other chemicals found in the tire include antimony, arsenic, cobalt, boron, barium, copper, cadmium, calcium, sodium, and potassium.[29]

Table 6. State efforts toward waste tire disposal

State	Effort
California	State sent a letter to all Class II and III landfill operators asking them to examine the possibility of stockpiling concrete, wood, and tires. The state Solid Waste Management Board issued an RFP on using scrap tires; three grants were awarded.
Connecticut	Officials are trying to establish a statewide disposal-energy recovery system; they have recommended to legislature that a disposal tax be placed on each tire. The bill would be similar to bottle bills; money collected would be used to finance a statewide system.
Georgia	Grants of $50,000 for shredders were given to two county landfills; state officials are involved with a local co-op to store tires at a local landfill.
New Jersey	A January 1982 law put a tax on all solid waste that goes to landfills; the money will be used to promote recycling of all materials.
Ohio	Grants are being awarded for litter control.
Wisconsin	A recent law provides grants of up to $50,000 for feasibility studies for resource recovery of any solid waste.

Any plant's emissions would have to meet all existing air, water, and land regulations. The following paragraphs discuss applicable federal, state, and local regulations.

Table 7. Local efforts to resolve waste tire disposal problems

Locality	Effort
Akron	The city is developing a demonstration project using tire chips in a recovery system.
Baldwin Park, CA (L.A.)	City officials wanted to collect tires, grind them, and ship ground rubber to Arizona for asphalt. They decided the project was not economical and have abandoned the idea.
Clearwater, FL	The city has a 2,000-TPD resource recovery unit (refuse-derived fuel) operating; the unit will process some tires.
Harrisburg	There used to be a county-wide recycling system; tires were sliced and shipped to B. F. Goodrich in Akron; the cost exceeded the return, and so the project was stopped.
Houston	Houston Power & Light was asked to use ground rubber as a part of their boiler feed; they refused because of the consequent need to alter their scrubbers.
Kansas City	The city is in the procurement stage on a refuse-derived fuel project; the unit will take some tires.
Madison, WI	Schriptek Marketing is shredding tires at many landfills; shredded tires are being stored for future recovery.
Minneapolis	Officials are urging the University of Minnesota to use scrap rubber in its heating system.
New Orleans	The city is investigating shredders so that they can take more tires and shred and store them for future use; the city also has a recovery and recycle center.
Philadelphia	The city has a contract with a private company to recycle a limited number of tires.
San Antonio	The city is in preliminary stages of building a 2,000-TPD resource recovery plant that will produce refuse-derived fuel.
San Francisco	The city is planning to use refuse-derived fuel; some tires will be included in the effort.
St. Louis	Tires used to be separated from other waste at landfills, but labor costs made this uneconomical.
Tampa	The city is retrofitting for 1,000-TPD resource recovery unit; the unit will process some tires.
Trenton, NJ	The city is investigating a recycling center and is currently choosing a site.

Federal Regulations. One federal law with several provisions encouraging tire recycling was the Resource Conservation and Recovery Act (RCRA) of 1979 Public Law, 94-580. The provisions for tire recycling were: (a) grants for 5% of shredder costs, (b) a study of the flow of discarded tires, and (c) commercialization encouragement.

Under the RCRA, standards were established for sanitary landfills specifying procedures for environmentally sound landfilling of materials.[4] Federal air quality regulations would impact any tire recycling effort since any plant would have to apply for permits and meet existing standards. The federal air quality standards are given in Appendix C. State air quality standards are at least as stringent as federal standards and may be more stringent, especially where areas of nonattainment are involved.

There are no solid waste regulations at the federal level that would specifically impact the collecting, storing, or processing of used tires. In response to the Solid Waste Planning Guidelines of RCRA, most states have developed solid waste management plans. Tires are considered solid waste, but the federal guidelines do not require the states to address tires specifically. As a part of solid waste management, all states are supposed to submit a plan for EPA approval. The status of these plans for all the states is included in Appendix C.

State and Local Regulations. Discussions with state officials confirmed that most states do not have specific regulations on tires. Appendix C contains tables showing state and local regulations. State solid waste bureaus normally require that landfills have permits. To obtain a permit, landfill operators must submit site plans that address air, water, and land-use considerations. Most states require that landfills cover waste each day, which affects any tires included in the waste. Of the states investigated, only five have specific requirements on tires and landfills. Florida, Ohio, and Virginia require burying of all tires in landfills. Pennsylvania requires all tires be split circumferentially before burying. Wisconsin allows stockpiling at landfills. Three other states make recommendations that do not have the force of the law to landfill operators. Connecticut and New Hampshire discourage stockpiling and Virginia recommends that tires be split before burial.

Almost all states or localities could act to remove problem stockpiles through existing health or nuisance laws, but several states did have laws specifically addressing stockpiling of tires. Table 8 summarizes these laws.

Many large cities regulate tire disposal or storage. Three metropolitan areas have made a comprehensive attempt to regulate tires: Portland, Houston, and Minneapolis. In Portland, a solid waste ordinance was passed that required tires to be shredded before landfilling, established fees for accepting tires at landfills, limited the number accepted at one time, and specified how tires could be stored. Through this ordinance, shredding increased and machinery was perfected so that uniform particles suitable for conveyor handling could be produced. Now the particles are being used for boiler feedstock and there is competition for tires in the Portland area.

In Houston, a city ordinance was passed to cope with large numbers of tires and illegal tire dumping because of an outbreak of encephalitis where illegally dumped tires provided a breeding ground for mosquitoes. The ordinance specifies that: (a) city trucks will take only four tires per resident per year; (b) if tires constitute more than 5% of a load of refuse, they must be quartered before landfilling; and (c) tires must be stockpiled inside or protected from the weather.

In the Minneapolis-St. Paul area, seven counties are establishing uniform ordinances on tires. The ordinance requires anyone processing or storing tires to have a permit and they must perform volume reduction before disposal. The intent of the ordinance was to establish control of mosquitoes and rats and to make tires easier to landfill.

Table 8. State regulations on stockpiling of tires

State	Stockpile
Colorado	To store, owners must have access to water and soil for fire protection.
Connecticut	A solid waste management permit is required; guidelines restrict tire piles to 100 ft on site, with a 50-ft fire lane; no height restriction; state will issue permit if the spirit of law is met.
Florida	Stockpiling is discouraged because of mosquitoes and rats, but there is no law; stockpiling may be included in a regulation revision this year.
Georgia	Permits are required to store tires; fire lanes, water, and control of mosquitoes and rats are required.
Missouri	Tires must be stored in an environmentally sound manner; no dumping of any solid waste on the ground is allowed except in permitted disposal areas or at a processing facility.
New Hampshire	Stockpiling of tires is discouraged.
New Jersey	Stockpiles must be buried or covered and treated for vector control; if the end use of the tires is reclaiming or recycling, then the stockpile is regulated by the Public Utility Commission.
Oregon	If a stockpile is declared a disposal site, a permit is needed. Plans for the permit must specify how tires will be stored, spacing, and fire protection. As a practical matter, no permit is required if tires are just stored to be processed.
Utah	Stockpiling of tires is discouraged.

PYROLYSIS PROCESS

Pyrolysis is the process of breaking organic chemical bonds by heating. Pyrolysis is also known as destructive distillation, thermal depolymerization, thermal cracking, carbonization, and coking.

Rubber Pyrolysis Overview

Tire rubber can be pyrolyzed by several processes. These involve a number of reactor types, process conditions, and heat addition methods, many of which have been reported in the literature.

Characteristics of Tire Rubber. Pneumatic tires contain the following components: vulcanized rubber, a rubberized fabric containing reinforcing textile cords, steel or fabric belts, and steel-wire-reinforced rubber beads. The tires are constructed on a mold. The first layer is rubber, followed by the two beads and a number of plies of the fabric, followed by another layer of rubber, with a thick circumferential layer of tread rubber. The assembly is cured by heat in a mold that contains the tread pattern and the information embossed on the tire's sidewalls. Most modern tires are of belted radial construction, in which the fabric cords are oriented radially and a circumferential steel, fiberglass, or fabric belt overlays the cords and underlays the tread rubber.

The most commonly used tire rubber is styrene-butadiene copolymer (SBR), containing about 25% by weight styrene. In combination with SBR, other elastomers such as natural rubber (cis-polyisoprene), synthetic cis-polyisoprene, and cis-polybutadiene are also used in tires in varying amounts. A typical recipe for tire rubber is given in Table 9.

Table 9. Rubber compounding recipe

Component	Weight Percent
SBR	62.1
Carbon black	31.0
Extender oil	1.9
Zinc oxide	1.9
Stearic acid	1.2
Sulfur	1.1
Accelerator	0.7

The carbon black acts primarily to strengthen and impart abrasion resistance to the rubber. The extender oil is usually a mixture of aromatic hydrocarbons having the primary function of softening the rubber to make it more workable. The sulfur molecules react with the double bonds in adjacent polymer chains to cause cross-linking, which hardens the rubber and prevents excessive deformation at elevated temperatures. The accelerator acts as a catalyst for the vulcanization process and is typically an organosulfur compound such as 2-mercaptobenzothiazole. The zinc oxide and stearic acid, in addition to enhancing the physical properties of the rubber, also act in harmony with the accelerator to control the vulcanization process.

Carbon black is essentially particulate amorphous carbon; it is produced primarily by partial combustion of hydrocarbon-air mixtures in the furnace. Current-day technology for carbon black production uses an intermediate-boiling-range oil fraction as a feedstock; earlier production used natural gas as a feedstock. The carbon black is separated from combustion products by electrostatic precipitation and cyclones. Although other properties of carbon black (such as surface area, particle shape, purity, etc.) influence its marketability as an ingredient for tire building, the most important characteristic for a furnace black appears to be particle size. The finer the particles, the better the rubber-reinforcing properties; the lowest grade is designated as SRF (semireinforcing furnace) and the highest grade as SAF (super abrasion furnace).

The marketability of tires depends on two dominant characteristics, tread life and traction. To some extent, these characteristics are incompatible since, all other things being equal, the softer the tread rubber, the better the traction, but the worse the tread life, and vice versa. Nevertheless, tire manufacturers can vary several parameters—such as tread depth, amount and quality of the carbon black, extent of vulcanization, amount of extender oil, relative amounts of different elastomers, and others known only to individual tire manufacturers—to achieve the best combination of tread life and traction. With so many variables, it is impossible to know the exact composition of a particular used tire, so that a complete knowledge of the mechanism of tire pyrolysis is not available. However, a complete characterization of the complex reactions of tire pyrolysis is not necessary for the purposes of this study.

The structure of the natural rubber molecule is diagrammed in Figure 2.

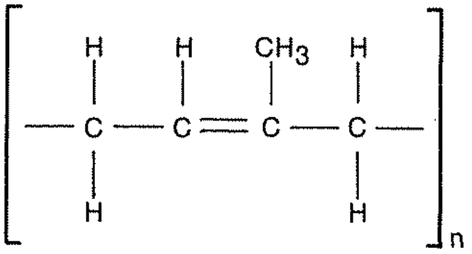

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Figure 2. Structure of natural rubber molecule.

Two characteristics that all vulcanizable elastomers have in common are: (a) the presence of double bonds in the molecular chains, and (b) a preferred location for thermal rupture of the carbon-to-carbon bonds. The double bond is the characteristic that allows vulcanization to take place, since sulfur reacts and forms a bond between double bonds of adjacent rubber molecules. It is this "cross-linking" between the molecular chains of elastomer molecules at a controlled number of locations that is responsible for the property of elastomers to regain their shape after deformation. The presence of the double bond also directs the thermal rupture to the β-location relative to the double bond. (The β-location is the second carbon-carbon bond from the double bond.) Hence, the bonds shown at either end of the repeating unit of the rubber molecule shown in Figure 2 are where chain rupture will preferentially occur. When chain rupture propagates along the chain, highly-reactive free radicals are formed. The free radicals will tend to be subchains of the original elastomer molecule, and when the process is carried to its logical conclusion, the monomer or monomers from which the elastomer was formed should be produced in significant yield. Since the predominant monomers in worn tires are styrene and butadiene, these are found in the liquid products of pyrolysis. A wide variety of olefins is also produced by thermal cracking. Formation of benzene and toluene can be expected through reactions involving the styrene monomer, along with a wide range of higher aromatics and condensed ring compounds. The temperature and residence time of pyrolysis are important in determining the extent to which high-molecular-weight compounds are cracked; hence, higher pyrolysis temperatures and longer vapor residence times promote gas production at the expense of the liquid fraction. The solid fraction, which contains zinc oxide or zinc, steel, iron oxide, potentially a number of trace metals, carbon black, and a solid hydrocarbon residue, contains relatively less hydrocarbon residue when the pyrolysis temperature or the solids residence time is increased. Hence, for highest production of liquid fraction, the temperature should be carefully controlled. Also, the residence time of the vapors released from the tires should be minimized. The processes that are presently commercial do minimize the residence time for gases by removing and condensing them as they are evolved.

Process Types. A number of criteria can be used to classify the numerous pyrolysis processes. Those used in this report include the atmosphere within the reactor, the method of heat addition, the reactor type, the process conditions, the required feed preparation, and whether the reactor is batch or continuous. The most important of these criteria is the atmosphere within the reactor, i.e., whether the atmosphere is oxidative or reductive with respect to the tire materials. The other criteria are used to partially cross-classify the processes in the detailed process descriptions, but they are not used in this section.

Oxidative Processes. The oxidative processes include those that inject air, oxygen, or steam as reactants. Air and oxygen injection result in the combustion of a portion of the tire materials to give carbon monoxide, carbon dioxide, and hydrogen, which gives rise to the term "substoichiometric combustion." The relative yield of gas is higher and the heating value of the gas is lower in oxidative processes than in reductive processes. Furthermore, the heat of pyrolysis is furnished by combustion of tire materials, so that the gas evolved need not be burned to heat the reactor. When air rather than oxygen is injected, the nitrogen in the air further degrades the heating value of the gas. No clear effect of an oxidizing atmosphere on liquid and char yields can be noted from the few data that are available.

Steam is oxidative, as far as the tire materials are concerned. The predominant reactions involve the cracking of hydrocarbons to carbon monoxide, carbon dioxide, and hydrogen so that a higher value gas product is produced than is the case for a substoichiometric combustion process using air or oxygen as the oxidizer. No effect on liquid and char yields is evident from the scanty data found in the literature. By contrast with air or oxygen injection, steam injection requires an external source of heat to furnish the heat of reaction for cracking, and this would typically be supplied by burning all or a portion of the product gas.

Reductive Processes. The majority of pyrolysis processes are reductive. Indeed, the oxidative processes are considered by some not to be pyrolysis, but rather combustion. Reductive processes include those with hydrogen injection and those that produce a reductive atmosphere by excluding air and other oxidizers. The main effect of adding hydrogen is to hydrodesulfurize the tires, thus adding hydrogen sulfide to the gas and reducing the sulfur content of the oil and char. The gas from all reductive processes has a high heating value, in some cases double that of natural gas, and the usual practice is to burn a portion of the gas to heat the reactor.

General Process Description. While minor differences among the 34 different tire pyrolysis processes exist, the similarities are more significant than are the differences. Consequently, the common features of tire pyrolysis are discussed to provide a broad understanding of the process in general. Figure 3 shows a general flow diagram for a continuous tire pyrolysis process of the reductive type. The steps indicated apply equally well to a batch operation.

As scrap tires are received from shipping or inventory, they are shredded into 2- to 6-in. pieces. The shredding process allows some steel to be magnetically separated, but few operators remove steel at this stage of the process. Any of a number of solids transport devices can be used for moving the tire pieces into feed storage, which is typically a hopper that feeds the reactor by gravity through a multiple rotary valve sealing arrangement. Some systems feed whole tires to the reactor, which eliminates the shredder.

Although not shown on the process diagram, feed pretreatment to partially depolymerize the rubber presents interesting possibilities for improving the pyrolysis process. Less-severe processing conditions could be used, and the product distribution could be altered. The chemical treatments used in rubber reclaiming or biological digestion could be used for pretreatment, since they are known to partially depolymerize the rubber.

The following types of reactor are represented among processes that are either in or nearing commercial operation:

- Fluidized bed
- Rotary kiln
- Traveling grate kiln
- Retort.

In the oxidative type of process, air, oxygen, or steam is injected into the reactor.

Other reactor types, such as molten salt, hot oil bath, plasma, and microwave, have been studied in experimental facilities, but none has been commercially operated.

The solids leaving the pyrolysis reactor are cooled in the solids recovery system. Partial size reduction to break up large agglomerates allows steel removal by magnetic separation, and fiberglass removal by gravity separation. The remaining material is char, which can receive a variety of post treatments to enhance its marketability. The facilities for char treatment are not shown, however.

The vapors released by pyrolysis are typically cooled in a quench tower, which can be operated to collect either all of the pyrolytic oil or the high-boiling pyrolytic oil fraction. Additional quench towers and/or heat exchangers may be present to collect additional pyrolytic oil fraction. If more than one liquid fraction is collected, the lowest-boiling fraction collected is rich in benzene and toluene. Though no oil processing is shown, the oil can be made more valuable by further processing.

The gas remaining after pyrolytic oil recovery is typically composed of paraffins and olefins with carbon numbers up to five. In the case of oxidative processes, the gas also contains carbon monoxide, carbon dioxide, and hydrogen. The gas also contains nitrogen if air is the oxidizing agent.

Some or all of the gas is burned as a source of heat to the reactor in the case of reductive processes and steam injection. When air or oxygen are injected, combustion inside the reactor provides the necessary heat to the reactor.

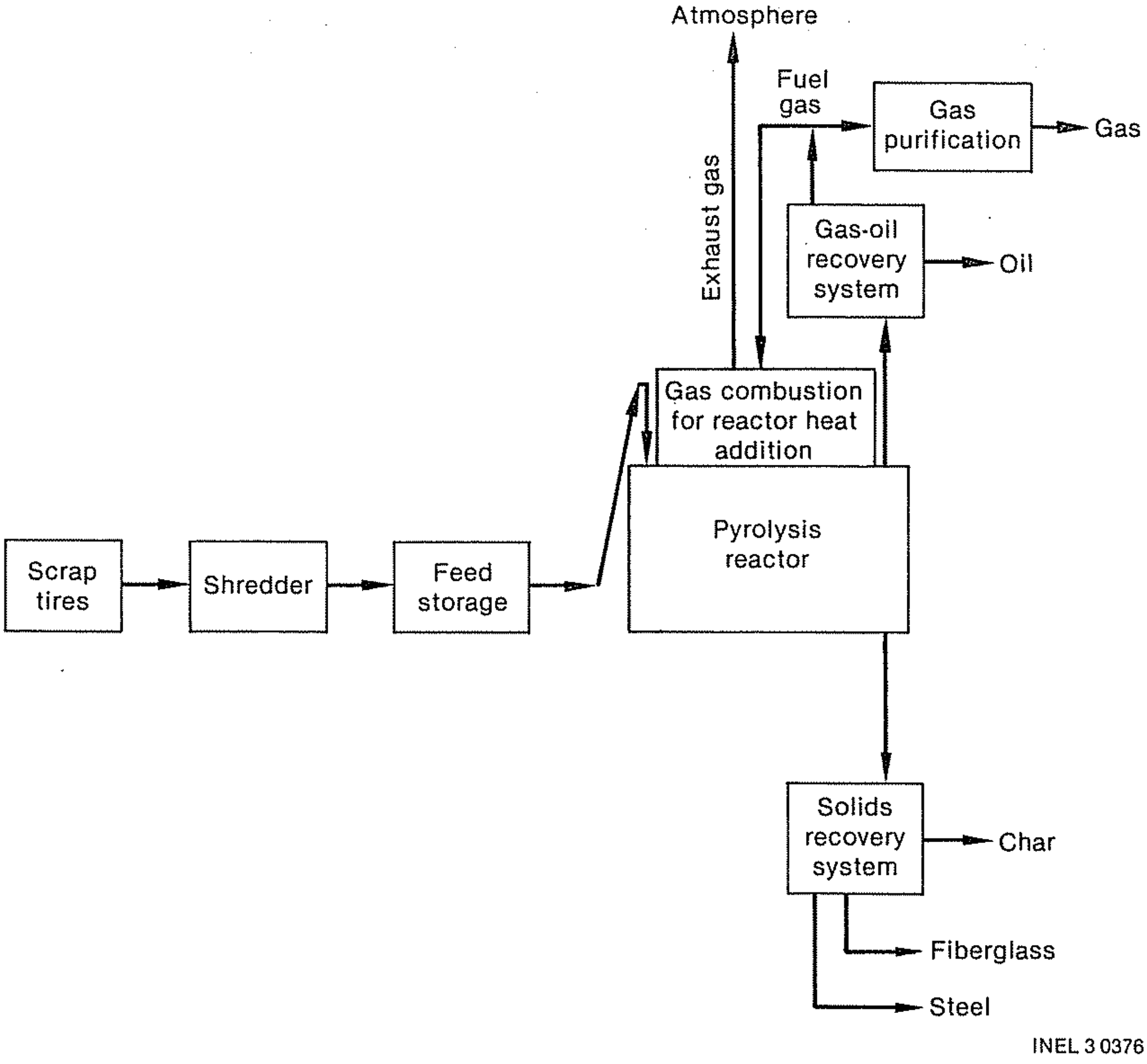

Figure 3. General flow diagram for a continuous tire pyrolysis process of the reduction type.

The remaining gas may be purified (hydrogen sulfide removal, typically), then either sold or flared. In some cases, combustion or flaring of the unpurified gas may be permissible.

Pyrolysis Reactor Design. As indicated earlier, four basic types of reactors are represented among those that are either in or nearing commercial operation. These four reactor types—fluidized bed, rotary kiln, traveling grate kiln, and retort—are discussed in the paragraphs below. These reactors provide extended solids residence times and short vapor residence times, and both reductive and oxidative processes can be carried out. Figure 4 shows a schematic diagram of a fluidized bed pyrolysis reactor. The two principal advantages of a fluidized bed are the good solids mixing and uniform solids temperature in the fluidized bed. The most important disadvantages of a fluidized bed are the need to remove entrained solids from the vapors and the need to provide fluidizing gas. The fire tubes are required only for a reductive system, and the fluidizing gas for such a system is usually the excess pyrolytic gas. An oxidative system can use air as the fluidizing medium, and no external heat source is required in such a case.

In operation, tire pieces or whole tires, if the reactor is large enough, are fed to the bed. The abrasive action of the fluidized particles abrade the rubber from whole tires as reaction takes place, eventually reducing the tire material to small pieces of char.

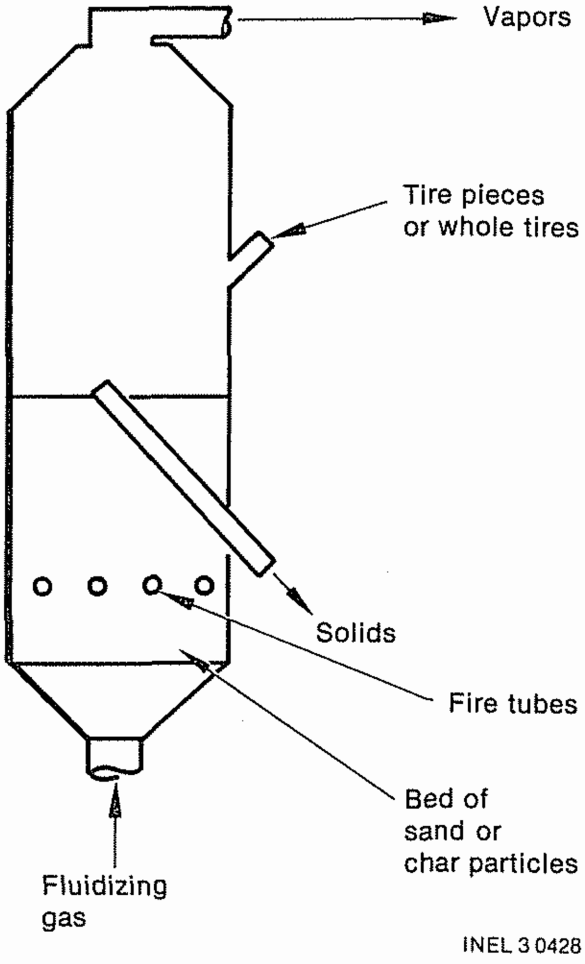

Figure 4. Fluidized bed pyrolysis reactor.

As feed is added, the bed volume increases, and char particles displaced by the feed overflow through the outlet pipe. The vapors leave the vessel with the fluidizing gas and entrained small char particles, which are usually removed in a centrifugal separator and returned to the bed.

The rotary kiln pyrolysis reactor is shown on Figure 5. Whereas the solids in a fluidized bed reactor are well-mixed, solids travel through a rotary kiln in plug flow (i.e., there is little mixing along the length of the reactor). The usual practice with a rotary kiln is to place paddles on the inside wall of the kiln to continuously lift solid material away from the bottom, then drop it so it falls through the gases in the kiln; this solid gas contacting pattern gives good temperature uniformity at any position along the length of the reactor. However, only skimpy details concerning the internals of rotary kiln pyrolysis reactors have been reported. The primary difficulty with this type of reactor is the large area that needs to be sealed, which makes excluding air difficult.

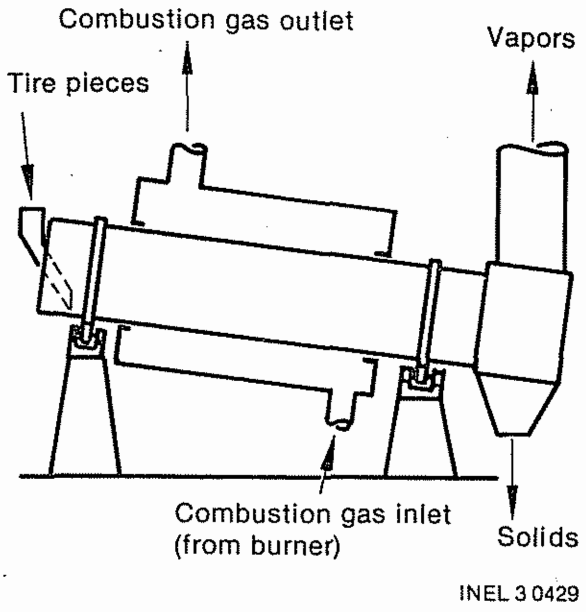

Figure 5. Rotary kiln pyrolysis reactor.

The traveling grate pyrolysis reactor is shown in Figure 6. This reactor design has in common with the rotary kiln the plug flow of solids, but differs in that the solids are quiescent as they travel through the reactor. Heat transfer is by radiation from the fire tubes, and so solids temperature uniformity at any axial position would not be as good as with the rotary kiln reactor. This reactor design is somewhat easier to seal than the rotary kiln, and it is mechanically simpler.

The retort reactor shown in Figure 7 is of the horizontal, batch class. After the reactor is cooled, tire pieces or whole tires can be loaded through the open door, the door can be closed, air can be purged from the reactor, and heat can be applied to the exterior surface. Vapors are continuously removed during the cycle. At the end of the cycle, the reactor door is opened, the solids are removed, and the reactor is loaded for a new cycle. A retort reactor can be oriented vertically or operated continuously. Simplicity and ease of sealing are the greatest advantages of a retort reactor. The disadvantages of a batch operation are relatively low productivity and high labor costs.

Product Characteristics. Pyrolysis of tires generates three products—gas, oil, and char. Table 10 presents approximate distributions of gas, oil, and char as functions of temperature for a reductive process.[30]

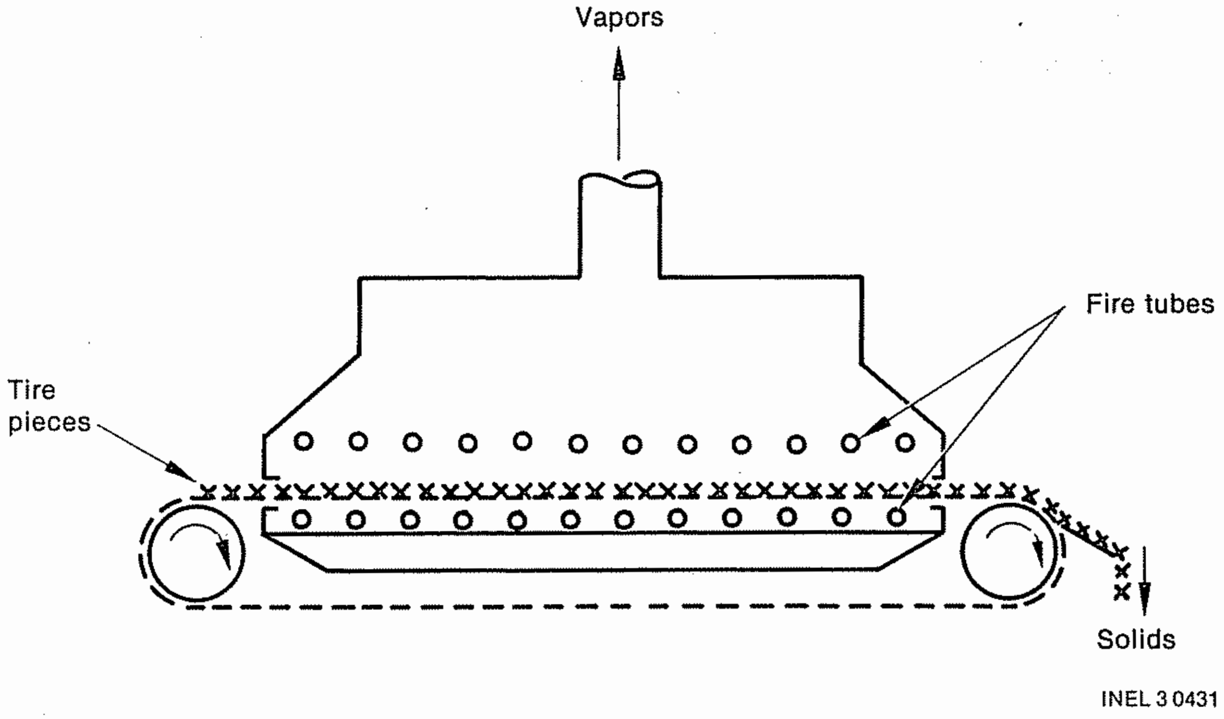

Figure 6. Travelling grate pyrolysis reactor.

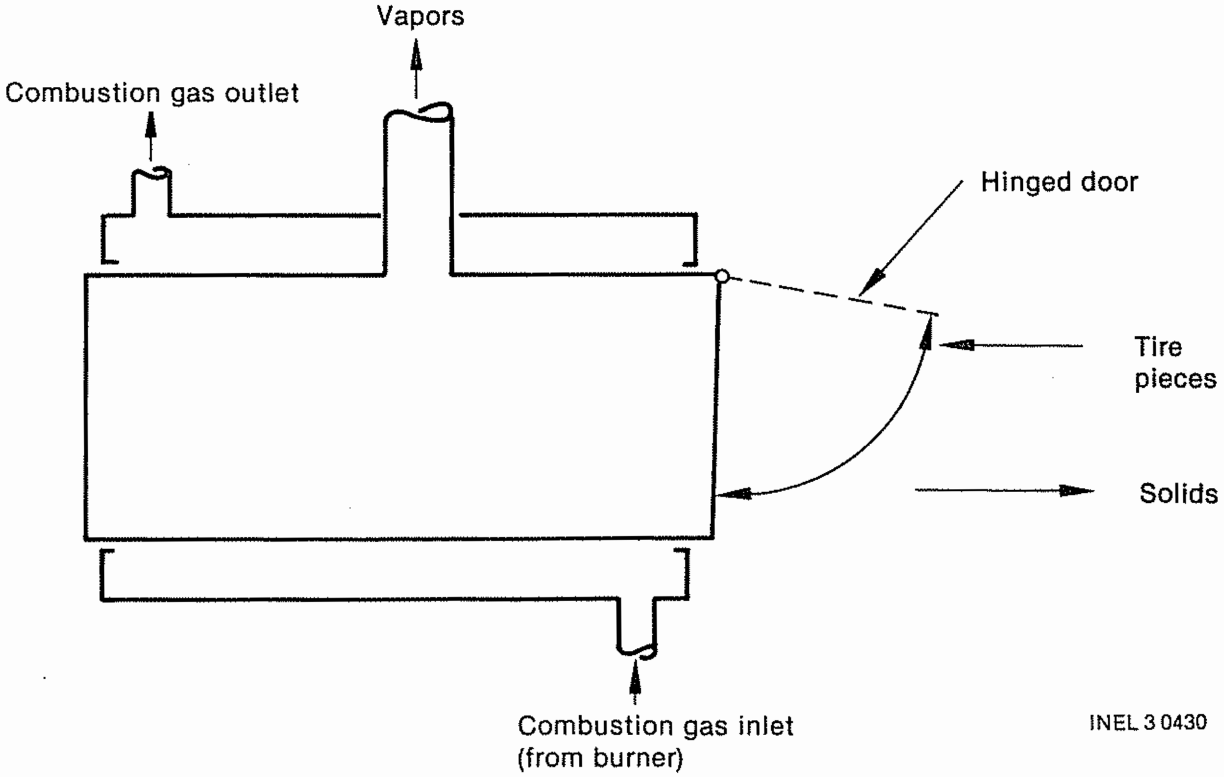

Figure 7. Retort pyrolysis reactor.

Table 10. Approximate product distribution as a function of pyrolysis temperature

Pyrolysis Temperature (°F)	Product Weight Percent Gas	Oil	Char
932	6	42	52
1,112	10	50	40
1,292	15	47	38
1,472	31	40	29

Most of the processes studied are reductive, and the relative product yields shown are typical of the majority of pyrolysis processes. Since the reductive processes use product gas to furnish heat for pyrolysis, whereas this heat is furnished by partial combustion of the tires in the oxidative processes, a process for which the objective is gas production should be oxidative and operated at high temperature (above 1500°F). Such a process would produce relatively little oil and char.

Oil yield reaches a maximum at a pyrolysis temperature between 840 and 1275°F for reductive processes.[31,32] Since the oil contains a high percentage of aromatic hydrocarbons, significant potential exists for recovering the light aromatics (benzene, toluene, and xylenes) to enhance gasoline octane rating, or for use as petrochemical intermediates. Since the highest value for the pyrolysis oil is as petrochemical intermediates, this would be the preferred market if the product quality were sufficient. The next-highest value for pyrolysis oil is as a gasoline blending stock, and the lowest value is as a boiler fuel.

Table 10 shows a trend of decreasing char yield with increasing pyrolysis temperature. Since no obvious mechanism for carbon loss with increasing pyrolysis temperature within the range studied exists, it is reasonable to infer that higher pyrolysis temperatures volatilize some of the hydrocarbon content of the char. The particle size and surface characteristics of carbon black are thought to be the most important variables in determining the mechanical characteristics of rubber. The processes for upgrading char described in the literature[33,34,35] include simple size reduction, extraction with a solvent, and leaching with an acid. However, nowhere in the literature that was examined for this study was a char black shown to be equivalent to a high-quality carbon black.

Environmental Aspects

The purpose of this section is to discuss potential environmental impacts associated with the pyrolysis of scrap rubber tires. The environmental impacts related to handling and processing are addressed.

Environmental Impacts Related to Handling. There are several potential problems associated with the handling of the scrap tires prior to pyrolysis. Most of the reports addressed the negative aesthetic quality of discarded tires and the potential health hazards due to rodents and insect pests living in tire stock piles. However, the storage requirements of the tires prior to processing were not addressed. With the daily volume of rubber required in a typical process (about 2000 tires per day), storage may be a potential problem.

It is assumed that a certain volume of the tires or scrap tire materials (shredded, chipped) will be stockpiled on-site to ensure continuous operation. Normally, a 5- to 10-day reserve feedstock supply is assembled for such purposes. This means that from 10,000 to 20,000 tires would need to be stored on-site. The aesthetic and health problems associated with the stockpiling of the tires on site need to be addressed.

Open or enclosed storage requirements need to be addressed. The discarded tires may have contaminants (i.e., mud, dirt, oil) adhering to their surface. Similarly, other contaminants may be present depending on how and where the tires were used and stored prior to reception at the site. Open storage would permit direct exposure to precipitation, which may wash these contaminants from the tires. The dirt would increase the sediment load in the storage pile runoff, and the oil plus other contaminants might be released in runoff. The same concerns would apply if shredded rather than whole tires were received on-site for the process. And the potential environmental impacts could be compounded if whole tires were received on-site, shredded or chipped, and stockpiled on-site.

Apart from the storage requirements, other handling procedures (prior to pyrolysis) may have adverse environmental impacts. Fugitive dust and process dust may be a problem. Rubber particles or materials associated with the tires (i.e., mud, dirt, fiber cords) may be distributed by the wind, thus becoming fugitive particulates. A couple of reports indicated that tires would be washed prior to combustion. Washing would generate liquid waste that would require appropriate treatment. The types of contaminants associated with this waste stream are uncertain, and therefore treatment technology cannot be appropriately prescribed. Solid waste materials generated from the handling should also be addressed. Particulates collected during preprocessing for the control of dust and sludge from the treatment of liquid waste should be monitored for contaminants and disposed of properly.

Many materials other than rubber are used when a manufacturer makes tires. Elastomers are compounded with inorganic materials, including carbon black, sulfur, zinc oxide, clay fillers, calcium and magnesium carbonates, and silicates, as well as a variety of inorganic pigment materials. Oil is used to extend the rubber in the manufacturing process and is present in the tire product. Inorganic materials are usually unchanged in the process and are concentrated in the char. Sulfur and the oils may be volatized and collected with refining products and may be emitted and released to the atmosphere. Apparently, the inorganic and volatile materials may be associated with different process products and by-products; therefore, the products and by-products lines should be closely monitored. Use and disposal of these products and by-products will potentially be affected by the presence of the inorganic and volatile components. However, existing pollution control technology and that under development for the petrochemical and synthetic fuel industries will be adequate for tire pyrolysis plants.

Process water requirements need to be addressed, since water may be needed for cooling. Steam may be required for heat tracing product lines.

Other liquid wastes may be produced from the combustion process. Solvents may be used for cleaning operations. The use of these materials should be characterized (quality/quantity) as much as possible. The handling, control, and disposal procedures should be addressed for these materials.

Solid wastes from the combustion process should be disposed of properly. Approximately 5% of the rubber tire is ash material (i.e., carbonates, silicates, and zinc oxide). Zinc is found in the char. However, it is not particularly toxic to humans. In fact, zinc is an essential and beneficial element in the human metabolism that may be consumed at 10 mg/L of drinking water with no harmful side effects. However, fresh water organisms (i.e., algae, minnows, trout) have exhibited a reduction in reproduction fecundity at zinc concentrations of 0.1 mg/L.[36] Therefore, the release of zinc to an aquatic system may result in adverse impacts to the environment.

In the pyrolysis process, the char will be contaminated with ash. Removal of ash from the char may pose additional environmental impacts.

Storage of the products from the pyrolysis process may also pose environmental impacts. Gases, oils, and other liquids could be a source of hydrocarbon vapors released to the environment. Adequate controls would need to be applied to restrict hydrocarbon release within regulatory guidelines. Char handling, processing, and storage procedures may be a potential source of fugitive dust.

Process Analysis

Technical information obtained in a global search by Galaxy, Inc., on tire pyrolysis activities has been classified according to several criteria:

- Method of heat addition
- Material handling
- Reactor type
- Feed preparation.

Further subclassification has been done. Process types include oxidative and reductive. Methods of heat addition include external fire, internal fire, indirect heating, microwave, and plasma. Feed preparation categories are whole tires and shredded tires. Material handling modes are batch, continuous, and semicontinuous. Pyrolysis reactor types are retort, rotary kiln, conveyor, fluidized bed, and oil carrier. Process conditions considered are temperature, residence time, pressure, and catalyst. Products evaluated are gas, oil, char, steel, and waste.

The individual process descriptions that appear in Appendix D are necessarily brief in many instances because of the proprietary nature of the information obtained from the respective pyrolysis project managers. With many projects, much information concerning energy and material balances and product quality cannot be made available. The projects analyzed in this report include paper studies, laboratory bench-scale studies, pilot plants, and commercial plants. The current status ranges from those abandoned for technological or economic reasons, those awaiting investment capital to begin construction, those in the construction phase, to those in commercial operation.

Pertinent information on all the projects is presented in Table 11A and 11B. The individual descriptions which appear in Appendix D are arranged in the same order as in the table.

Discussion and Evaluation

Quantitative evaluation of the available pyrolysis data is difficult in many instances because much of the information was obtained from the questionnaires that were sent to the projects by Galaxy, Inc. Many of the questionnaires were returned incomplete because the information was either unknown or considered proprietary. Much of the information that was received, particularly that from foreign sources, was not verified. Consequently, many inconsistencies occur within processes and between processes, possibly because of misinterpretation of the questionnaire, transcription errors, incomplete specification of assumptions, etc.

Table 11A lists the tire pyrolysis projects with capacities, temperatures, and product yields. Table 11B shows other process parameters. Examination of these tables leads to several general observations:

- Only about half of the projects are in the planning, construction, or commercial operation stage. The others have been abandoned, usually for economic reasons.
- All but seven processes require some form of tire feed preparation, such as shredding, grinding, etc.
- Process throughputs vary from the bench-scale experiments rated at a few pounds per hour of tire rubber to designs for commercial plants rated at 110,000 TPY.
- In most of the processes, rubber is continuously fed to the reactor.
- The division between processes using external or internal heat addition to the reactor is essentially even.
- The most common process heat source is recycled product gas, which is used to fire heating tubes or to heat secondary heat transfer media such as molten salt, ceramic balls, steam, or hydrogen.
- Reactor types include retorts, rotary kilns, fluidized beds, conveyor kilns, hot oil baths, molten salt baths, arc plasma, and microwave ranges.
- Reaction temperatures range from 460 to 1830°F.
- Product yields vary widely: oil, 0 to 73%; char, 0 to 52%; gas, 0 to 100%; and steel, 0 to 17%.
- Product oil yields generally decrease with increasing temperature, although maximum oil yields have been reported at 840°F[37] and at 1100°F.[38]
- Char yields are more dependent on process type than temperature.
- Gas yields generally increase with increasing temperature.

Although some would not consider the oxidative processes as true pyrolysis processes, they have been included for reasons of comparison with the reductive processes. Since the feed materials and the products are similar for the two groups, both types have been evaluated.

The product characteristic that varies most widely among the processes is the gas heating value, which ranges from 170 to 2375 Btu/ft^3. Natural gas heating values are about 1000 Btu/ft^3 by comparison. The lower observed values typically are the result of nitrogen, carbon dioxide, carbon monoxide, etc., being present in significant amounts in the gas as air or as gas combustion products. The

Table 11A. Tire pyrolysis projects

Name	Capacity (TPD)	Reaction Temperature (°F)	Yields of Products (wt %)				
			Oil	Char	Gas	Steel	Waste
OXIDATIVE							
1. Quinlynn	120 480[a]	1100 1500	64 27	16 3	11 61	9 9	0 0
2. Atomic International	<0.1	1690	0	0	100	0	0
3. Nippon Zeon	26.5	840 to 930	56	31	3	10	0
4. Sumitomo	5	1300	54.7	31.7	9.5	4.1	0
5. Tosco	15 300	900 to 1000	52	29	11	4	4
REDUCTIVE							
6. Kobe Steel	26.5	930	7.5 to 14.5[b] 40.5 to 43[c]	32 to 34	6 to 8	5	N/A
7. MVU	2.6	1200 to 1300	22	47	17	10	4
8. Herko/Kiener	238[a]	1020 to 1110	47	30	17	6	0
9. BKM	158[a]	N/A	N/A	N/A	N/A	N/A	N/A
10. ERRG	3 25	1600	37.5	30	27.5	3.5	1.5
11. Carbon Oil & Gas	60	1100	45	33	13	9	0
12. Intenco	100	900 to 950	52.2	35.0	7.4	3.5	1.9
13. Nippon Oils & Fats	26.5	930	49	36	10	5	0
14. Kutrieb	6[a]	800	35	38	20	5	2
15. Garb-Oil	112.5	1700 to 2000	40 to 45	30 to 38	18	6	0
16. Yokohama	2.2	930	50 to 56	30 to 35	N/A	N/A	N/A
17. Onahama	30	750	21	20	51	7	1
18. Firestone	0.2 0.2 N/A	930 1650 1650	44 to 50 20 20 to 50	40 to 44 52 30 to 40	3 to 5 21 10 to 20	N/A N/A N/A	N/A N/A N/A
19. Oil-Tec	15	N/A	51[d]	34	9	1.5	4.5
20. Bergbauforschung	1.3[a]	1470 to 1830	5	35	20	10	0
21. DRP	25	1330	27	39	22	12	0
22. Kansas State	0.3[a]	1155 to 1450	17 to 51	25 to 52	20 to 29	0	N/A
23. Occidental	300	1000 1200 1600	30 to 40 34 1	41 to 50 35 36	14 to 19 31 63	4 0 0	N/A 0 0
24. Tyrolysis	165	840 to 1110	45	39	0	16	0
25. Uniroyal	N/A	N/A	50	40	10	0	0

Table 11A. (continued)

Name	Capacity (TPD)	Reaction Temperature (°F)	Yields of Products (wt %)				
			Oil	Char	Gas	Steel	Waste
26. HRI	1000	850 (460 to 850) (500 to 2000 psig)	59.5	37	4.4	0	0
27. Institut Francais	0.75	700	59 to 73[e] 8 to 10[f]		4 to 6	15 to 25[g]	
28. University Aston	33	N/A	26 to 33	30 to 40	7 to 18	14 to 17	N/A
29. Plasma	120[a]	N/A	N/A	N/A	N/A	N/A	N/A
30. Osaka	<0.1	N/A	10 to 22	42 to 44	35 to 45	N/A	N/A
31. USSR	<0.1	N/A	N/A	N/A	N/A	N/A	N/A

a. Assumed Operation: 24-hr/day
b. Heavy
c. Light
d. 30 Tar
e. Oil + Char
f. Gasoline
g. Steel + Waste

highest heating values probably result from short residence times of the rubber in the reactor and moderate reaction temperatures that cause minimum cracking of the hydrocarbons, with the result that the major gas components are pentane, pentane, butane, butylene, propane, and propylene. Residence time information correlated with gas compositions and heating values are seldom available. The heat transfer contacting efficiency within the rubber material in the reactor also is expected to be an important factor in the product yields and compositions.

The most frequent use for the product gas is to supply process heat. The gas usually has a carbon monoxide composition that exceeds the maximum limits for transportation in natural gas pipelines, and the olefin content would result in undesirable polymers if the gas were stored. If potential nearby users are not able to consume the excess product gas, it is usually flared.

The char yields average about 37% of the products, ranging from zero for the molten salt process to a high of 52% when no steel is present in the feed rubber. Conflicting claims have been made by the various representatives of several processes with respect to the effect of temperature on the char quality and yield. For example, Occidental[39] reported that the reinforcing properties of char produced at 1400°F was measurably better than that produced at 1200°F. Kobe Steel[40] maintains that better char is obtained from their process when the reaction temperature is kept below 1100°F. Hydrocarbon Research[41] concluded that temperature, pressure, and the presence of catalysts had no significant effect on their product char quality. Sulfur, water, ash, and volatiles were lower at higher reaction temperatures in the Firestone char, and consequently, the reinforcing properties improved with increasing temperature. One possible explanation is that the temperature range of the Hydrocarbon process was 460°F to 850°F, while the range for Firestone was 930°F to 1650°F. Perhaps the lower temperature range was not high enough for the actual residence time to effectively decrease the volatiles content of the char.

Most of the projects have made some attempts to upgrade the product char to a material comparable with commercial carbon black. Steam activation, pulverizing, screening, acid leaching, benzene extraction, filtering, etc., have been considered. The best grade of carbon black obtained has been reported to be comparable with GPF if

Table 11B. Tire pyrolysis projects

Name	Status (January 1983)	Tire Preparation	Operation[a]	Heat Transfer Medium	Heat Source	Reactor Type
OXIDATIVE						
1. Quinlynn	Construction design	Shredded	C	Gas	Oxygen	Vertical retort substoichiometric
2. Atomic International	Abandoned	Shredded	C	Molten salt	Air	Marshall furnace substoichiometric
3. Nippon Zeon	Abandoned	Shredded	C	Gas	Tire fragments	Fluid bed substoichiometric
4. Sumitomo	Abandoned	Whole	B	Steam	High frequency	Retort
5. Tosco	Abandoned design	Shredded	C	Steam & ceramic balls	Recycled gas	Rotary kiln
REDUCTIVE						
6. Kobe steel	Commercial	Shredded	C	Kiln wall	Recycled gas & oil	Rotary kiln
7. MVU	Planned	Shredded	C	Kiln wall	Recycled gas	Rotary kiln
8. Herko/Kiener	Construction	Shredded	C	Kiln wall	Recycled gas	Rotary kiln
9. BKM	Construction	Shredded	C	Kiln wall	Recycled gas	Rotary kiln
10. ERRG	Pilot plant construction	Shredded	C	Kiln wall	Recycled gas	Paddle conveyor
11. Carbon oil & gas	Commercial	Shredded	C	Reactor wall	Recycled gas	Belt conveyor
12. Intenco	Planned	Shredded	C	Molten salt	Molten salt	Screw conveyor
13. Nippon Oils & Fats	Abandoned	Shredded	C	Reactor wall	Recycled gas	Screw conveyor
14. Kutrieb	Commercial	Whole	B	Reactor wall	Recycled gas	Retort
15. Garb-Oil	Planned	Shredded	SC	Fired tubes	Recycled gas	Retort
16. Yokohama	Abandoned	Shredded	B	Recycled gas	Recycled gas & oil	Retort
17. Onahama	Commercial	Shredded	C	Recycled gas	Recycled gas & char	Retort
18. Firestone	Abandoned Abandoned Abandoned	Shredded Shredded Shredded	B B C	Reactor wall Reactor wall Reactor wall	Electricity Electricity Electricity	Retort Retort Retort
19. Oil-Tec	Abandoned	Shredded	N/A	Reactor wall	Tire fragments	Retort
20. Bergbauforschung	Abandoned	Whole	B	Reactor wall	N/A	Retort
21. DRP	Construction	Whole	C	Gas	Recycled gas	Fluidized bed
22. Kansas State	N/A	Shredded	C	Gas & steam	Propane	Fluidized bed
23. Occidental	Abandoned	Shredded (24 mesh)	C	Nitrogen	Recycled gas	Entrained bed
24. Tyrolysis	Construction	Shredded	C	Gas	Recycled gas	Counterflow gas
25. Uniroyal	Abandoned	Shredded	C	Gas	Recycled gas	Crossflow gas
26. HRI	Abandoned	Shredded	C	Hydrogen	Recycled gas	Ebullated bed + hydrogenation catalyst
27. Institut Francais	Pilot plant design	Whole	B	Oil	Electricity	Hot oil depolymerization
28. University Aston	Abandoned	Whole	B	Molten salt	N/A	Molten Salt
29. Plasma	Abandoned	Whole	B	Arc plasma	Electricity	Arc plasma
30. Osaka	Abandoned	Shredded	B	Microwave	Electricity	Microwave
31. USSR	N/A	N/A	B	N/A	N/A	N/A

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[a] B = Batch; C = Continuous; SC = Semicontinuous; N/A = Not applicable.

the ash and the volatiles are substantially removed. Otherwise, the ash content is commonly reported as 10 to 15%, which adversely affects the char's reinforcing properties. The typical particle size of the char is usually too large to qualify as a high-quality carbon black.

The possibility exists that the pyrolysis oil could be used as a petro-chemical feedstock, particularly to obtain the aromatic fraction. The oil aromatic content has been reported as high as 85% at 1650°F, and it tends to increase with increasing temperature. The aromatics are benzene, toluene, xylene, styrene, naphthalene, and various other 3-, 4-, 5-, and 6-ring compounds. Most of the oil analyses report a sulfur content of about 1% and a heating value of 17000-18000 Btu/lb. Various ASTM fuel oil tests indicate that the oil is comparable with No. 2 to No. 6 fuel oil. The sulfur content often exceeds the maximum allowed, and the high aromaticity requires the addition of antioxidants to prevent gum formation during storage. Three different boiling point fractions are often distilled from the oil: naphtha, fuel oil, and extender oil. Temperature differences between the pyrolysis reactor walls and the rubber inside the reactor, accompanied by variations in residence times, conceivably could account for the different temperatures at which the maximum oil yield is obtained by Tyrolysis and Kobe Steel.

The steel yield depends on the type of rubber feed. Tread rubber would yield no steel, while a scrap tire pile that had a high percentage of steel-belted radial tires would yield more steel. Consequently, the reported steel yields vary from 0 to 17%. Most of the projects expect to sell the steel as scrap.

The net energy balances for some of the projects where the information is available suggest that the energy recovery is about 75 to 82% based on the heat of combustion of the tire rubber. The energy requirement for some of the tire shredding processes varies from 1.5 to 6% of the net energy recovered in the products.

Process Conclusions

1. Within the estimated accuracy, product yields are independent of process type and depend on processing parameters (temperature, residence time, etc.).

2. A large number of tire pyrolysis processes have been conducted in either laboratory or pilot-plant equipment. Most were found to be technically feasible, but were abandoned on the basis of economics. Except for Kobe Steel and Onahama in Japan, none of the processes currently under investigation has reached sustained commercial operation.

3. Marketability of char as carbon black requires posttreatment of the char, including acid leaching to remove the ash, solvent leaching to remove volatiles, and size reduction to increase the particle surface area. Investigators do not agree on the relative value of solvent and acid leaching, or on the carbon black grade achievable. The best grade claimed is GPF.

4. The marketability of the liquid fraction as a gasoline octane extender or as a petrochemical feedstock has received little attention from most investigators. The relatively high value of octane extenders and petro-chemical feedstocks suggests that this line of investigations would be fruitful.

PYROLYSIS PRODUCTS AND MARKETS

Quality and Quantity

As discussed in the preceding section, pyrolysis of scrap pneumatic tires produces gas, liquid, and solid products in varying proportions, depending mainly on pyrolysis temperature. Most of the processes use a portion of the gas product as a heat source for the process; the remainder of the gas has a high heating value, but it probably cannot be marketed as pipeline gas because of excessive carbon monoxide content. Typically, the gas contains low-molecular-weight paraffins and olefins, hydrogen, carbon monoxide, and hydrogen sulfide. Consequently, the gas could be a feedstock for a number of syntheses or even for carbon black production if the hydrogen sulfide were removed and if some or all of the components were separated and purified. However, the most likely end use of the surplus gas is as a fuel to produce process heat.

The division between gas and liquid products is process dependent, depending on the condensation temperature used to separate liquid from gas. A workable definition of gas product is that it contains most of the hydrocarbons having a carbon number of five and lower. Similarly, the liquid product is specified to contain most of the hydrocarbons having a carbon number six and higher.

The liquid product consists almost entirely of aromatic hydrocarbons, with about 26% by weight either benzene or toluene. The balance consists of higher molecular weight aromatics. It is conceivable that benzene and toluene could be separated from the liquid product with sufficient purity to be petrochemical feedstocks, but the most likely market for the benzene and toluene content is as a high-octane gasoline blending stock. The heavy oil fraction (the portion of the liquid product that remains after the benzene and toluene have been removed) can be considered as an extender oil for tire rubber, but this use is very small. Conceivably, the heavy oil could be catalytically cracked to yield more benzene, toluene, and xylenes for gasoline blending, but the likely end use of this fraction is as a liquid fuel comparable with No. 6 fuel oil. Most investigators anticipate use of heavy oil as a fuel oil.

The solid product is essentially carbon, ash, sulfur, and relatively nonvolatile hydrocarbons, and it is usually referred to as "char." Many investigators expect to recover the carbon black essentially in its original form. Since the carbon black market is a high-value market, this is certainly a worthwhile goal. To evaluate the possibilities for achieving this goal, it will be helpful to discuss the characteristics of carbon black.

Carbon black is essentially particulate amorphous carbon; it is produced primarily by the furnace process, wherein hydrocarbon-air mixtures are partially burned to give carbon black and combustion products. The carbon black is recovered by electrostatic precipitation and cyclones. Although other properties of carbon black (such as surface area, particle shape, purity, etc.) influence its marketability as an ingredient for tire building and other uses, the most important characteristic for a furnace black appears to be particle size. The finer the particles, the better the rubber-reinforcing properties, with the lowest grade designated as SRF (semireinforcing furnace) and the highest grade SAF (super abrasion furnace). Table 12 gives a listing of carbon black grades, with their important characteristics.

One investigator[42] claimed that finely ground char produced rubber that was only slightly inferior to rubber obtained from HAF carbon black. However, close scrutiny of the results reported by

Table 12. Carbon black characteristics

Grade	Approximate Particle Size (μm)	Comment
SAF	20	Highest grade, not used in tires
ISAF	N/A	Used in tread rubber
HAF	30	Most common carbon black in tread rubber
FEF	N/A	Carcass grade, not used in tread rubber
GPF	N/A	Carcass grade, not used in tread rubber
SRF	90	Carcass grade, not used in tread rubber

this investigator revealed that only in terms of tensile strength was the claim true, and that there was much scatter in the tensile strength data. In all other characteristics, the rubber produced from char was at best roughly comparable with rubber obtained from SRF carbon black. In the other work examined for this study,[43,44,45] char black has consistently been inferior to HAF carbon black and marginally comparable with SRF carbon black.

The inferior properties of char black appear to be associated with at least three characteristics:

- Ash content (up to 15% by weight)
- Solid hydrocarbons
- Particle size.

Since the ash is predominantly zinc sulfide, zinc oxide, and/or metallic zinc, with some silica, iron, and titanium dioxide,[46] an acid leach could be expected to reduce the ash content and thus upgrade the char. One investigator reported significant improvement in char black properties using a 2-hour wash with moderately concentrated hydrochloric acid, but the treated char black was inferior to an HAF carbon black.[45]

A reasonable expectation is that removing the solid hydrocarbons would improve the properties of char black. One method of doing this would be to pyrolyze at a higher temperature, since the higher temperature will volatilize some of the solid hydrocarbon in the char.[47] Another method is extraction with a solvent. A toluene extraction produced a marked improvement in char black properties, but the treated char black was inferior to an HAF carbon black.[45]

Apparently not yet investigated is the combined effects of acid leaching, toluene extraction, and high-temperature pyrolysis. It is an open question, also, whether a better solvent such as supercritical carbon dioxide or propane gas would produce a char black substantially better than that obtained by toluene extraction.

In tests of char black for several unnamed organizations or individuals, Ashland Oil Company reported that char blacks are generally inferior to SRF carbon black, at least partially due to the particle size being too large.[48] However, one investigator reported that mean particle sizes in the 1 to 2 μm range could be obtained, and that reducing the particle size improves the quality of char black. Since HAF carbon black has a mean particle size of approximately 30 μm, and since the much smaller char black particles gave inferior rubbers, it is clear that fine particle size alone does not ensure a high-quality carbon black. The surface reactivity of carbon black is reported to be lost when it has been used in rubber, and char black lacks the surface reactivity of new carbon black.[49] It is therefore possible, though not probable, that a more thorough examination of char black treatments might reveal a particular combination of treatments or a new treatment that would further improve char black properties. However, a point that should be emphasized is that, since HAF carbon black is only used in tread rubber, and since most of the tread has been worn away in a scrap tire, the quest to recover char black higher than carcass grade, no matter what sort of posttreatment is used, may not be a fruitful one.

Other potential high-value uses of char black are relatively low in volume. In the case of printing ink, char black did not do well,[24] and so the pigment market appears to be closed to char black. In the case of activated carbon, steam treatment produced a good grade of activated carbon, but the volume of the market is not as large as that for tires. The carbon black market is very large—more than 2 billion pounds per year—but it is a shrinking market, considering the well-established trend to smaller cars and longer tire life. One observer described the carbon black market as "depressed," with too many producers at present.[27] Sellers of char black can be expected to encounter considerable difficulty in penetrating such a market, even with a high-quality product.

Of the potential areas for increasing product value, the most promising appears to be the liquid fraction, which can yield significant quantities of benzene, toluene, and xylenes for gasoline blending.

Price

The price that the products will sell for is surrounded with uncertainty. The pyrolytic oil probably equates with No. 6 fuel oil which currently sells for $.64 per gallon or $26.88 per barrel. The gas product is not suitable as pipeline grade gas and cannot be marketed per se. One idea, distilling the pyrolytic oil to further stages to release benzene and toluene, merits further study. It would be possible to sell some of the gas if a neighboring industrial facility wished to purchase it at a price lower than utility gas. This type of special arrangement can be referred to as "across the fence" sales. Although the price spectrum on the char of the pyrolysis operators served ranges from 2¢ to 22¢ per pound, a real price on the char is uncertain due to the quality of the material. One firm claims to have a contract with a major distributor of carbon black selling all the char at 20¢ per pound. The steel sifted from the char can be sold as scrap steel at the market price which currently is valued about $20 per ton.

PYROLYSIS ECONOMICS

Overview

Assessment of the tire pyrolysis economics is difficult because of the specific situational variables that occur. While a project in Germany may be considered economically feasible, it may not be economically viable by U.S. standards unless it is subsidized by the government. Germany directly subsidizes the infant pyrolysis industry. In Japan, the form of government subsidy is a low-interest loan (4.8%) for 100% of the capital costs. In England, the pyrolysis plant is funded partially by a government grant as well as by grants and loans from the European Economic Community.

In the United States, tire pyrolysis could be considered economically viable only in certain facilities where the tire collection network is in place and tires are at zero cost or a fee is paid to the operator. On the other hand, a large plant may not be considered feasible even though it may provide the required return on investment. The tire feedstock may become the limiting factor. In other words, a 300-TPD plant may provide a 30% return on equity invested, but it may be unable to obtain an annual supply of 9 million scrap tires for full capacity operation. Because the investment required for a large scale plant would be between $10 to $12 million, the feedstock supply needs to be constant; 9 million scrap tires must be supplied per year for 10 years. This type of constraint restricts the construction of a large plant in any U.S. area.

Although the following analysis of the economic viability of tire pyrolysis plants is based on reported data, these data have been collected under a variety of conditions and cannot be compared on a one-to-one basis. For example, one pyrolysis process may involve very high capital costs due to its complexity while another process may be inexpensive to purchase but costly to operate. One process may have identified total installation costs while another only mentioned the equipment purchase price. One firm may have given costs in 1982 dollars and another in 1979 yen. It is only with caution that the reader infers comparability.

The analysis is based on reported data, simple pretax paybacks, calculated revenue required for a 20% return on equity, and a sensitivity analysis relative to the price of oil, price of carbon black, and the cost of tires. Another by-product, gas, will not be valued because it is not utility grade and can only be used internally on the site. Site specific considerations are discussed along with potential municipal development. Competitive processes, such as combustion, are also discussed. Finally, product market and prices are identified.

Plant Data

Economic data on plants were gathered from pyrolysis plant operators, literature, and symposia papers. For ease of understanding, foreign currency values were converted to U.S. dollar values by using the foreign exchange rates quoted in *The Wall Street Journal* early in 1983. Similarly, all units of measurement are specifically identified as U.S. units. All values are stated in 1982 dollars. Before any analysis of the data is presented, a one-paragraph overview of the specific projects is presented which gives the factual data acquired from specific projects. These paragraphs present the data as they were gathered without commenting on their reliability. Table 13 was compiled to demonstrate the variations in product prices, product yields, tire acquisition costs, operating days per year, capacity, and the year of dollar valuation.

Carbon Oil & Gas, Inc., of Struthers, Ohio, has built a medium-sized plant, but would release no information about throughput, capital costs, operating costs, or revenues. The pyrolytic oil is being marketed according to a news item released in *Resource Recovery Report*, March 1983.

Energy Recovery Research Group, Inc. (ERRG), has run a pilot plant operation with a throughput of 3 TPD. The firm estimates capital costs at $4.5 million for a 25-TPD facility. Estimation of revenues for the 25-TPD plant are $1,650,000 while the estimation of operating costs is $1,327,000, which results in a simple pretax payback of 13.9 years. This firm has an agreement to sell the char to a company producing ink for copy machines.

Foster-Wheeler Power Products, Ltd., of England is a partial equity owner of Tyrolysis, Ltd. Tyrolysis, Ltd., plans to build a 55,100-TPY facility using the Foster-Wheeler process. The facility will

Table 13. Comparison of factual data presented by pyrolysis operators

	Carbon Oil and Gas	ERRG	Foster-Wheeler (Tyrolysis)	Francais	Garb Oil	DRP	Hydrocarbon	Intenco	Kobe	Kutrieb	Oil-Tech	Port	Quinlynn	Rotter	Tosco
Yield/ton															
Oil (gal)	112	84	109	161	100	82	110	105	105	93	131	109	N/G	N/G	171
Gas (all gas is presumably burned within the unit)															
Char (lb)	667	600	700		720	800	740	760	640	570	875	600	N/G	N/G	500
Steel (lb)	N/G	80	280	75	120	200	380	140	180	100	38	280	N/G	N/G	50
Capacity/day (TPD)	69	6	165	N/G	90	N/G	1,000	100	N/G	6	25	165	5	N/G	300
Capacity/year (TPY)	—	1,980	55,100	4,400	28,080	7,716	N/G	N/G	7,716	1,500	4,000	55,000	N/G	N/G	110,000
Revenue/year															
Oil ($/gal)	—	0.71	0.85	0.52	0.95	0.49	0.07 - 0.10	N/G	0.72	0.75	0.36	0.85	0.76	0.45	N/G
Char ($/lb)	—	0.02	0.02	—	0.10	0.45	0.04 - 0.08	N/G	0.20	0.10	0.10	0.02	N/G	0.045	N/G
Gas															
Steel (lb/ton)	—	$40	$40	$27	$40	$19	N/G	N/G	$80	$100	$50	$40	$20	$20	N/G
Tire acquisition ($/tire)	—	-0-	-0-	0.15	0.20	0.09	0.10	0.20	-0-	0.25	0.25	0.20	0.20	N/G	0.09
Operating days per year	—	330	333	N/G	312	N/G	N/G	N/G	266	250	200	333	N/G	N/G	365
Simple payback (years)	—	14	3.5	2.5	1.5	N/G	<5	N/G	**	<1	N/A	13	N/A	0.5	9.3
Year of $ value	—	1982	1982	1982	N/G	1979	1972	1982	1979	1982	N/G	1982	N/G	N/G	1972

N/G = Not Given
N/A = Not applicable because data was incomplete.
**Very large payback period.

N/G = Not Given
N/A = Not applicable because data was incomplete.
**Very large payback period.

cost $10.8 million. Operating costs are estimated at $3.5 million and revenues at $6.6 million, which means the simple pretax payback period is estimated at 3.5 years. The firm claims that the "products meet standard specifications for established markets."

The Institute Francais Du Petrole has developed a pilot plant process for mixing waste tires with waste oil. The capital cost estimate is $772,000 for a 4,400-TPY facility, with annual operating costs at $2.2 million and annual revenues estimated at $2.5 million. This equals a simple pretax payback of 2.5 yr. Acquisition costs for tires are estimated at 15¢/tire. Product markets are identified as the traditional oil markets.

Garb Oil developed a small pilot plant. Future plans indicate a 90-TPD plant that would have an estimated capital cost of $4.5 million. Revenues are estimated at $6.1 million while expenses are estimated at $3.1 million, which results in a projected simple pretax payback of 1.5 yr. Tire acquisition costs are valued at 20¢/tire. It should be noted that revenues for oil are calculated on the high side at 95¢/gal coupled with yields measured for tires weighing 25 lb each instead of 20 lb each. Char sales valued at 10¢/lb roughly amount to 41% of the revenue stream. Revenues and yields are overstated. Using the lower yields for tires results in a projected simple pretax payback of 2.5 yr.

The Deutsche Reifen und Kuiststoff-Pyrolyse GmbH (DRP) is the first plant of a commercial size to be developed in Germany. It will become operational sometime in 1983. The throughput is 7,716 tons of tires per year. The plant will have an estimated capital cost between $6.5 to $8.5 million. Revenues were estimated at 49¢/gal for oil, 4.5¢ for the char (this represents the weighted average revenue for the three grades of char, i.e., soot, coarse carbon black, and fine carbon black), and $19.32/ton of scrap steel. No data were given for operating costs. Tire acquisition costs were given at 9¢/tire. No market is identified for the char. The oil market is characterized as "suitable for fuel, feedstock to refinery equipment of chemical process."

Hydrocarbon Research, Inc., estimated capital costs for a 1,000-TPD plant at $9.5 million early in 1972. The process is unique to pyrolysis because it involves hydrogenation of waste rubber products. No data were given for operating costs, but revenues were estimated on the very low side at 7¢ to 10¢/gal for oil. However, the carbon black revenues were estimated between 4¢ to 8¢/lb. The company states that the process is economically viable with a 5-yr payback when rubber collection and grinding costs are no more than $20 to $25/ton with carbon black selling at 5¢/lb and oil revenues at $3 to $4/barrel.[50]

Intenco, Inc., built a 50-TPD pyrolysis unit that was operating close to capacity and yielding products according to design specifications. However, progress was interrupted by a failure of a seal packing in the pyrolysis reactor which developed into an internal hydrocarbon and carbon fire that caused substantial damage to the reactors. All of the material Intenco submitted is considered proprietary. The only data available for publication is that the process yields 105 gal of oil per ton of tires, 760 lb of char (Pyroblack) per ton of tires, and 140 lb of scrap steel per ton of tires.

In 1979, Kobe Steel, Ltd., in conjunction with Sumitomo Cement works constructed a 7,716-TPY facility at an estimated cost of $6.5 million. The government subsidizes the project in the form of a low-interest loan (4.8%) for 100% of the capital costs. The estimated revenues are $1.62 million while estimated costs are $1.61 million, which results in a very long simple pretax payback period. However, the oil and gas products are used as stock fuels for the cement kilns while the char is considered sludge and is fed into the cement kilns. The officials at Kobe admit that the project is considered marginally economic.

The Kutrieb Corporation has developed a pyrolysis unit that has been marketed successfully to at least one firm in Franconia, Pennsylvania. The capital costs are estimated at $225,000 for a 1,500-TPY plant. Revenues are roughly estimated at $384,000 while expenses are estimated at $98,000, which results in a projected simple pretax payback of less than one year. Burgie Tire is the owner of the plant in Pennsylvania. Savings accrue to the operation in the form of fuel savings and disposal costs amounting to $87,000/yr. The fuel is used to run a retread operation. This is an excellent example of specific situational variables that allow pyrolysis to show economic viability.

Sigma Research Associates and Al-jon have developed a subsidiary called Oil-Tech Developments which produces a pyrolysis unit. The Oil-Tech unit is designed as a lease unit, and thus the only cost is leasing fees paid out of operational expenses; therefore, no payback period can be calculated. The estimated revenues are $590,000 while estimated expenses are $308,000, leaving a pretax profit of $282,000.

William Port & Sons of Geneva, New York, are working in conjunction with Foster Wheeler to establish a pyrolysis plant in the New York area. The estimated capital cost is $14 million. Revenues are estimated at $6 million and operating expenses are estimated at $4.9 million which result in a projected simple pretax payback of 12.7 yr.

Quinlynn Oil & Gas Company has a 5-TPH pyrolysis plant under construction in Oregon with capital costs estimated at $400,000. No details were obtained for operational costs or expected revenues. Quinlynn developed a scaled-up version of the pilot plant using the Rotter Gasification Process, with estimated capital costs of $4.5 million. Estimated revenues are $12.7 million and estimated operating costs are $4.9 million, which results in a simple pretax payback of six months.

The Tosco Corporation studied tire pyrolysis in the early 1970s, concluding that the only viable plant size was a 300-TPD facility. Most of the information about the Tosco process is considered proprietary, but the company estimated a 9.3 yr payback period.

Table 14, which shows the number of tires required per year of operation, provides perspective on the scrap tire supplies necessary to sustain operation of these plants.

Economic Assessment of Plants

Some of the variables in the economic analysis performed for this study are:

- Cost of scrap tires
- Plant size
- Capital cost of the plant
- Days of operation per year
- Hours of operation per day
- Oil yield per ton of tires
- Labor cost per person
- Number of laborers
- Tire preparation costs
- Energy requirements per plant process
- Char yield per ton of tires
- Steel yield per ton of tires
- Interest rate
- Value of products
- Debt/equity ratio.

All of these variables affect the process economics. Before any comparison can be made of one process with another, some uniformity in handling these variables will need to be implemented.

To illustrate the complexity of the variable problem, the raw data for each plant shows that oil yields range from 82 gal/ton of tires to 171 gal/ton of tires. The range of prices for these oil products is 36¢ to 95¢/gal. Table 15 summarizes the range for the product yields, product prices, tire acquisition costs, capacities, and operating days per year.

Thus, to provide continuity in assessing the economic viability of tire pyrolysis, it was necessary to develop a consistent set of assumptions to apply to all projects. The major assumptions include:

- The capital structure (debt to equity ratio), costs of capital, interest rates, and discount rates associated with the projects

Table 14. Tires required per year of operation

	Tons/Year	Tires/Year[a]
DRP	5,600	560,000
Francais	4,400	440,000
Kobe	7,710	771,000
Tyrolysis	55,100	5,511,000
ERRG	8,250	825,000
Garb Oil	35,100	3,510,000
Intenco	30,600	3,060,000
Kutrieb	1,500	150,000
Tosco	99,000	9,900,000

a. Assumes 300 operating days per year.

- Escalation rate of 10%
- Specific operating costs that should be included in each pyrolysis project
- Federal income tax of 46% and state income tax of 5%
- Specific used tire weight of 20 pounds of rubber/tire was assumed for this analysis (input from pyrolysis operators varied from 20 to 25 lb)
- Project life, startup costs, and the amounts of oil, char, and steel that would be saleable
- Value of oil, char, steel
- Identification of distribution channels to obtain tires and to market the products.

Table 15. Range of some product variables

Product yields (per ton of tires)			
Oil (gal)	82	to	171
Char (lb)	500	to	800
Steel (lb)	38	to	380
Gas		—[a]	
Product prices			
Oil ($/gal)	$ 0.36	to	$ 0.95
Char ($/lb)	$ 0.02	to	$ 0.22
Steel ($/ton)	$20.00	to	$100.00
Tire acquisition cost (per tire)	$ 0.00	to	$ 0.25
Capacity (tons/year)	1,500	to	110,000
Operating days per year	200	to	365

[a] All gas assumed to be burned in process.

In each of the pyrolysis projects where enough data were available for further study, a debt-equity structure of 80-20 was used. It is apparent that because of the risk involved, an 80% debt structure may be optimistic. A 15% interest rate was used for the 80% debt because corporations with good credit ratings could obtain financing at this rate. It was also determined that the Small Business Administration uses a flexible interest rate based on the prime interest rate plus two percentage points. Since the prime rate was 12% in early 1983, a 15% rate seemed fair to both the large corporation and the small entrepreneur.

Although the discount rate would normally be based on weighted cost of capital, an arbitrary discount rate was set at 20%. A 20% discount factor allows for an equitable return on equity invested. This discount rate may be lower than industry requires because of the risk involved; for this analysis, however, it provides a reference point and continuity.

An escalation rate of 10% was assumed due to the historic trend of actual inflation of fuel prices that traditionally led the Implicit Price Deflator by several percentage points. The GNP deflater is quoted in Table 16:

The average percentage change in the Implicit Price Deflator for the years listed above is 7.75%. The price of No. 6 fuel oil has moved from $11.96/barrel in 1977 to $25.35 in 1982 for an average annual compounded percentage increase of 16.2%. The *1981 Annual Report to Congress*, which contains the Energy Information Administration forecasts, projects a nominal oil price increase of 7.6% annually and a nominal GNP increase of 2.7% annually. A 10% escalation rate appears reasonable for a fuel-related industry.

Specific operating costs that need to be included for a pyrolysis plant should include labor, utilities, maintenance, property taxes and insurance, and general administrative costs. Tire acquisition costs will be included. Tire acquisition costs include the cost of collecting the tires. Preparation costs are shredding, chopping, and cleaning the tires and are part of the process. In many cases, these tire acquisition and preparation costs were not given. In a few cases, the costs were considerably higher than seemed prudent. Thus, a zero cost for tire acquisition will be used in the initial analysis, with

Table 16. Implicit price deflator

Year	1972 = 100	Annual % Change
1973	105.8	5.80
1974	116.0	9.64
1975	127.2	9.66
1976	133.8	5.19
1977	141.6	5.83
1978	152.05	7.38
1979	165.46	8.82
1980	178.64	7.97
1981	195.51	9.44

incremental tire acquisition costs used in the sensitivity analysis. The reasoning behind this decision is that most profitable operations have a collection network where they receive the used tires at zero cost or are paid to take the used tires.

Labor rates vary according to the plant location as well as the size of the plant. For example, one very large plant may require 44 laborers whereas a much smaller plant can operate with only three laborers. Thus, labor rates will be valued at the amount given with adjustments made to bring all years of valuation up to 1982.

Utilities will also vary according to location. Therefore, the only adjustment for utilities is to adjust the dollar values to 1982 dollars. It should be noted that many cases did not include any price for utilities because it was considered that the gas from the pyrolysis unit supplies the only fuel necessary to run the unit. Some electricity will be required to operate shredders and other electrical equipment, but except for shredders, the costs are usually negligible.

Maintenance was generally not given; a value of 4% of capital cost was used for those facilities where maintenance costs were not provided. Taxes and insurance were also generally not given; a value of 3% of capital cost was used for taxes and insurance. In some cases, general administrative expenses were not included. A rate of 2% of capital cost was used in those cases.

In most cases, project life was given at 10 yr. Therefore, this will be the assumption used in this analysis. Because startup costs have not been included in any of the facilities, they will be valued at zero. It is worth noting, however, that any manufacturing plant of this type will have problems with startup, and these should be included in the financial accounting preparation.

Because each process is different, the values for oil yields will vary according to the specific process. However, the char represents a more serious problem. The char is composed of carbon black, ash, and other materials. Additional processing is necessary to produce quality carbon black, which might be saleable. Because pyrolysis plants have such large yields of char, the economics can be quite favorable if all the char is sold at 20¢/lb; however, this seems highly optimistic. For the purposes of this economic analysis, it will be assumed that half the total yield of char is saleable at 2¢/lb.[a] The scrap steel will be valued at $20/ton or 1¢/lb. These values are specifically set at conservative levels so that the economic viability of the pyrolysis unit does not ultimately depend on the sale of the by-products.

It is important to note that marketing channels are extremely important in the success or failure of a pyrolysis unit. The gas is incompatible with utility-grade gas, and since upgrading would be costly, it must be burned by the manufacturer, sold nearby, or vented into the atmosphere. The oil has some unusual characteristics which allow it to be sold as a fuel oil or sold to a refinery for further refinements. The carbon black sifted from the char has some use, but it has not been accepted by the tire industry as a viable substitute for carbon black in tires. It has a potential use as activated charcoal and may possibly be burned as a coal replacement. Tire acquisition could be a problem if collection channels are not already in place for ease of collection. Purchasing tires impinges upon the economic viability of the pyrolysis unit. Thus, established marketing channels are necessary for collection of tires and for sale of the products.

Computer Model. A computer program was developed which generated a cash flow pro forma, return on equity, and the total revenues required for a 20% return on equity. The software package was written in APPLESOFT BASIC programming language and can be used on APPLE II PLUS hardware. The software package allows iterations of the basic scenario for sensitivity analyses. The basic assumptions of the computer model are presented below.

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[a] Two cents per pound for char ~$40/ton for coal.[51]

Model Assumptions

1. Working capital is based on accounts payable, accounts receivable, and inventory. It is assumed that inventory will be held for 30 days, accounts receivable will be received in 12 days, and accounts payable paid in 26 days. Interest on working capital is 15% for half the working capital; the rest of the working capital is an equity contribution or generated from net cash flow.

2. Depreciation is figured on 80% of the capital cost with a 10-yr, straight-line method of calculation. Investment tax credits are figured at 10% of the depreciable cost. No energy tax credits were used due to the December 1982 deadline for construction startup to qualify for the energy tax credit.

3. The net equity investment through Year 0 is equal to the total capital cost minus the investment tax credits and the loan.

4. All projects were considered as fully operational companies so that all tax credits and tax losses could be applied to other income.

5. Federal income tax rates are valued at 46% and state income tax rates at 5%. This means that the company would be in the maximum federal tax bracket for corporations.

Economic Results. An analysis of each project using the preceding economic parameters and computer program was performed. The results showed negative cash flows for each project. Using the accelerated capital recovery system (ACRS) still showed negative cash flows for each project. The reason for these negative cash flows is that tire pyrolysis is only economic with unique situational variables. There are a number of questions about product quality, product price, and feedstock cost which tend to lend a vagueness to the economic analysis. For example, the yields per ton of tires vary from 82 to 171 gal. The product price at 64¢/gal of oil means that the revenue stream could fluctuate between $56.48 and $138.88/ton of tires. Capacity is also a factor that multiplies this variance in revenue. Char prices were fixed at 2¢/lb, but char yields range from 500 lb to 875 lb. This results in a range of revenue from the char of $10 to $17.50/ton of tires. Capacity factors multiply this variance also.

The computer program was used to evaluate the extent of the negative cash flows. The negative first year net profit was divided by the number of tires processed each year to show how much additional revenue was necessary in the form of tipping fees for tire collection. The results are tabulated in Table 17.

The computer model was also used to generate a necessary first-year revenue that would substantiate a 20% return on equity invested. These revenue streams were recalculated using the following algorithm which is based on a weighted average of expected revenues from the majority of plants investigated: oil revenues constitute 74% of the revenue stream, char revenues 24%, and steel revenues 2%.

The results show that oil must be sold in the range of 60¢ to 99¢/gal, while char must be sold in the range of 6¢ to 8¢/lb. A comparison of projects is listed in Table 18.

The table has been subdivided into two sets of projects. The first part of Table 18 shows a reasonable value for prices that could be expected to return 20% on equity. The second part Table 18 shows very high prices required to return 20% on equity. The reason for these higher prices is very high capital costs compared to the throughout of the plant. It is important to realize that the price of char necessary to break even is relatively high.

Although it helps the economics of the Kobe Steel plant that the government supports the process with 100% financing at an average annual interest rate of 4.8%, low interest rates alone do not sufficiently offset the bleak economic picture. The primary reason Japanese firms are encouraged to develop pyrolysis in conjunction with cement kilns is that Japan imports 92% of its total energy requirements (99% in oil, 75% in coal, 83% in gas). The cement industry, in particular, is quite energy intensive. In cement kilns, waste tires are burned as an auxiliary fuel. The sulfur from the tires is adsorbed by calcined lime, forming calcium sulphate (gypsum). The waste sludge is used in the cement makeup. The tires are used primarily as a fuel in conjunction with coal. The economics are based solely on fuel savings. By a combination of direct incineration and pyrolysis, the present energy requirements for the cement kilns is being met by 10% oil, 50% coal, and 40% waste tires.[51]

Table 17. Required tipping fees per tire to alleviate negative cash flows

ERRG	Foster-Wheeler	Garb Oil	Kobe	Kutrieb
75¢	4¢	16¢	$1.03	11¢

Table 18. Break-even prices required for a 20% roe

	Foster-Wheeler	Francais	Garb Oil	Kutrieb
Oil price per gallon	$ 0.60	$ 0.99	$ 0.77	$ 0.77
Char price per pound	0.06	—	0.07	0.06
Steel price per ton	12.58	—[a]	34.83	38.59

	ERRG	Kobe
Oil price per gallon	$ 2.13	$ 2.15
Char price per pound	0.19	0.33
Steel price per ton	120.97	67.73

[a] Excessively high due to very low volume.

There are obvious reasons why tire pyrolysis shows such economic unattractiveness. One reason is that converting the waste tires into a more usable form of energy requires energy. In some cases, the energy required can be produced in the pyrolysis unit. In other cases, additional energy must be supplied, but waste heat is vented into the atmosphere. In special cases, the waste heat can be put to economic use by replacing purchased heat or steam with the waste heat. Capital intensive equipment requires a large revenue stream to support the decision to construct the plant. Unstable tire supplies tend to discourage a long-range commitment to venture into such a highly capital intensive industry. Collecting and shredding tires is relatively expensive, involving transportation and freight costs in the collecting of tires from an area and large power requirements for shredders. Product prices and product markets are not clearly defined or forecast for the immediate future. For example, one estimate of carbon black demand in the U.S. is 2.25 billion lb/yr. About 2 billion lb of this amount is supplied by the oil industry.[4] The industry currently suffers from oversupply because prices for high quality carbon black list for 36¢/lb, but are selling for 28.5¢/lb. An increase in supply from pyrolysis operators would further depress prices. Purity levels and product quality standards are an additional problem to be solved before pyrolysis operators can expect to become part of the carbon black market.[25]

Sensitivity Analysis. To find the single most sensitive item in the tire pyrolysis plant studies, two separate cases were prepared. The first case is a relatively large plant (Plant A) with throughput of 100 tons of tires per day. The second plant is a relatively small plant (Plant B) with throughput of 6 TPD. Table 19 shows the base case values. The method used was to hold all variables constant and increase or decrease one variable by 10% and 20% and solve for the total break-even revenue that would yield a 20% return on equity. Labor and capital costs were two variables that influenced the results. Utility costs are also a determining factor in assessing economic viability. If all gas generated from the unit is used to decrease the utility cost to zero, then the projects become a little more attractive, but not significantly. However, holding all operating costs constant and evaluating only tire costs and revenues yields the following result: tire acquisition costs/revenues present the single most

Table 19. Base case assumptions

	Plant A (large)	Plant B (small)
Plant Capacity (tons of tires/yr)	30,600	1,500
Capital Cost	10,500,000	225,000
1st Year Revenues		
Oil ($.64/gal)	2,467,584	89,344
Char	581,400 (5¢/lb)	11,400 (2¢/lb)
Steel ($20/ton)	42,840	1,500
TOTAL 1ST YEAR	3,091,824	102,180
Tire Acquisition Costs[a]	(306,000)	-0-
Tire Preparation Costs	306,000	-0-
Operating Labor	947,000	39,600
Maintenance	420,000	9,000
Utilities	-0-	-0-
Management Fees	102,000	-0-
General Administrative	155,000	4,500
Property Taxes & Insurance	55,000	6,700
TOTAL	1,679,000	59,800
Debt/Equity Ratio	80/20	80/20
Interest on Debt	15%	15%
Plant Life	10 years	10 years
Inventory Turn Rate	30	30
Accounts Receivable Turn Rate	12	12
Accounts Payable Turn Rate	26	26
Escalation Rate	10%	10%
State Income Tax Rate	5%	5%
Federal Income Tax Rate	46%	46%
Investment Tax Credit	10%	10%

a. Fee paid to dealer to dispose of tires.

sensitive item for tire pyrolysis. Using the base case scenario, it is clear that oil prices must be closer to $31/barrel for No. 6 fuel oil before the economic picture of pyrolysis looks profitable. Additionally, the char price and quality needs to be quantified before pyrolysis as an industry can be considered viable. Figures 8 and 9 show the results of the sensitivity analysis for labor, capital costs, and tire acquisition costs.

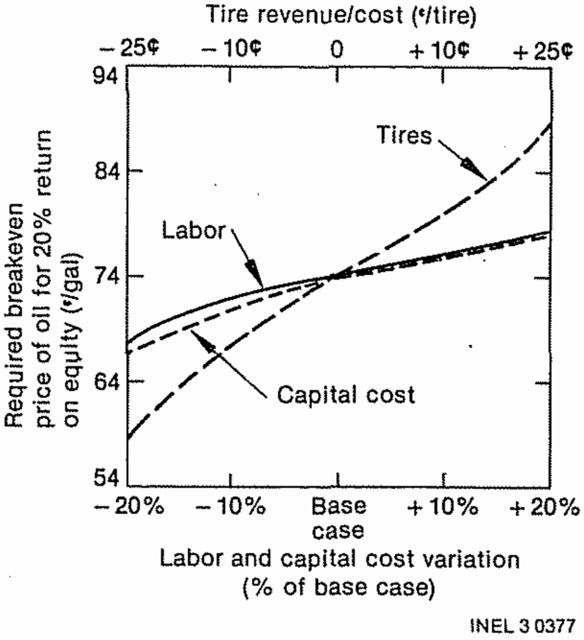


Figure 8. Results of sensitivity analysis for large plant (Plant A-100 TPD).

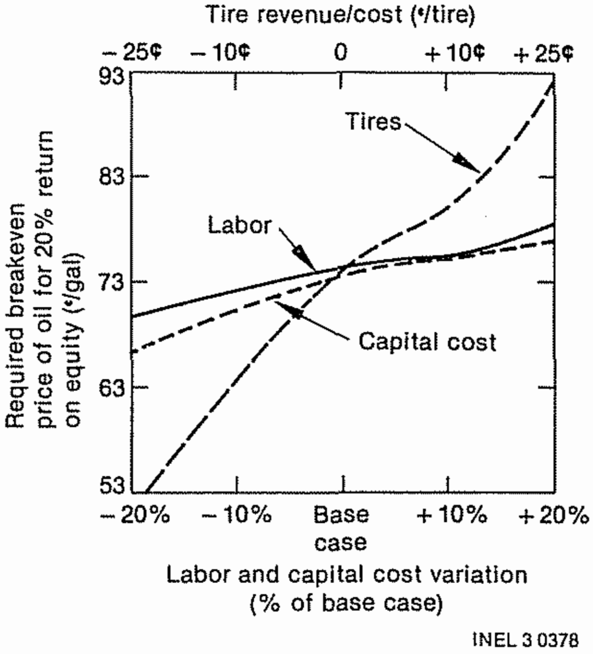
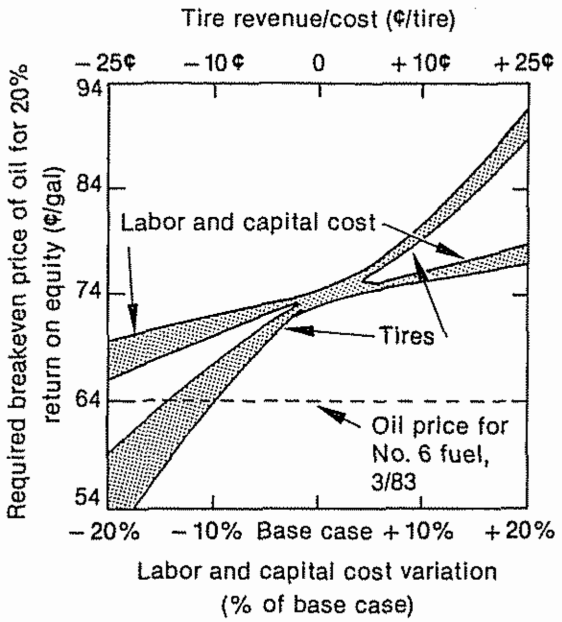


Figure 9. Results of sensitivity analysis for small plant (Plant B-6 TPD).

Figure 10 was prepared to show the overall spread between the large plant and the small plant. Tire acquisition costs or revenues still represent the single most sensitive item, but due to the smaller capital investment, a wider margin of profitability is realized as tire acquisition revenues are increased. In fact, tire acquisition costs and revenues may fluctuate as widely as ±10¢ to ±$1/tire. Truck tires often require a charge of $1 for disposal, while



Base Case

Equity—20%
Interest—15%
Escalation—10%/yr
Operating days/yr—30
(other parameters defined in text)

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Figure 10. Sensitivity analysis results, showing overall spread between large plant and small plant.

passenger tires may be disposed of for as little as a zero cost and as high as 50¢/tire, with an average price of 20¢/tire. The weighted average (based on tire weight) of these two disposal costs is 37¢ without allowance for transportation costs. The band of ±10¢ to ±25¢ appears reasonable for most areas in the U.S.

It clearly appears that corporate development of tire pyrolysis faces a serious problem for profit-motivated companies. However, there are special cases where pyrolysis presents a unique opportunity for reducing fuel bills and reducing waste tire disposition fees. For example, if tires are not purchased, but collected from dealers via a retread network where a fee is paid to the collector of between 35¢ and $1/tire, then the whole economic scenario changes. Add to this extra revenue dimension a complete reduction in fuel costs—i.e., all fuel generated in the pyrolysis unit is used for the equipment, with excess energy being used to replace purchased fuels—then the project returns a favorable profit. If tires are collected for a 10¢ fee and no utilities are paid, the return becomes 62%. If at the same time, no disposal fees are paid to landfill sites, the savings further increase the return. This type of uniqueness of operation is termed "site-specific." With site specific considerations in mind, it is impossible to predict any kind of economic pattern for tire pyrolysis.

It is interesting to consider municipal development of a pyrolysis facility. A municipality has a considerable advantage in developing tire combustion or tire pyrolysis as a means for disposing of waste tires. Municipalities pay no property, state, or federal taxes; municipalities may have a collection system in place; and municipalities may be able to offer 100% funding through tax-free municipal revenue bonds (MRBs) at a lower interest rate. Using Plant A and Plant B with municipality considerations, cash flows and break-even revenues were computed in a manner similar to that for the corporate cash flows, using 64¢/gal for oil, 2¢/lb for char (50% being marketable), and $20/ton for scrap steel. An assumption of 12% interest was used for the tax-free MRBs. It was also assumed that a tipping fee of 10¢/tire could be collected.

If a municipality operates the tire pyrolysis unit, a 53.8% return on equity can be expected with the small plant while a negative return can be generated from a large facility. The larger facility only returns 18.29% when char is valued at 5¢/lb. The conditions necessary for this positive economic scenario include charging a fee of 10¢/tire, using all the gas generated for running the pyrolator, paying no federal or state taxes, financing with MRBs at a 12% interest rate, and financing 90% of the capital costs. Although this gives the appearance of an inverse economy of scale, this inference should not be made because only two plant sizes were evaluated. The most economic plant size cannot be determined from the data presented. It is apparent that the particular tax advantages a municipality provides coupled with desirable financing and a need to resolve the waste tire problem provides an economic advantage not matched by corporate investment decisions. Cash flows are attached in Tables 20 and 21. A much lower price per gallon is required to achieve a break-even point. The break-even price of oil for the large plant is 69¢, while the break-even price of oil for the small plant is 49¢. Char still presents a minor problem in that the price required at the break-even point is 7¢ and 4¢/lb for the large plant and small plant, respectively. Because of size constraints due to tire stockpile locations and the dynamics of collection

Table 20. Cash flow for Plant A—large plant (100 TPD)

```
==================================================================================
      ENGINEERING ECONOMICS CASHFLOW MODEL : PRO FORMA INCOME STATEMENT
==================================================================================
                                 PLANT A
                                 2/15/83

YEAR    REVENUE  EXPENSES   DEPRECIATION   INTEREST       TAX        PROFIT     CASHFLOW
----------------------------------------------------------------------------------

  1     3091824  1679000       840000      1154650                   -581826     -417990
  2     3401006  1846900       840000      1092095                   -377988     -154875
  3     3741107  2031590       840000      1021992                   -152474       -3112
  4     4115218  2234749       840000       943431                     97038      163826
  5     4526740  2458224       840000       855393                    373123      347459
  6     4979413  2704046       840000       756735                    678632      549455
  7     5477355  2974451       840000       646178                   1016726      771651
  8     6025090  3271896       840000       522288                   1390906     1016066
  9     6627599  3599086       840000       383458                   1805056     1284922
 10     7290359  3958994       840000       227887                   2263478     1580665
----------------------------------------------------------------------------------


NET EQUITY INVESTMENT    = $1050000
(THRU YEAR 0)

RETURN ON EQUITY =          18.29%

NET PRESENT VALUE (20%) = $-149054

PAYBACK =                   6.7 YEARS

DISCOUNTED PAYBACK =      > 10.0 YEARS

OIL REVENUE PER BARREL = $.64
```

Table 21. Cash flow for Plant B—small plant (6 TPD)

```
==============================================================================================
       ENGINEERING ECONOMICS CASHFLOW MODEL : PRO FORMA INCOME STATEMENT
==============================================================================================
                                  PLANT B
                                 2/15/83

YEAR    REVENUE  EXPENSES    DEPRECIATION   INTEREST        TAX          PROFIT     CASHFLOW
----------------------------------------------------------------------------------------------

 1       102180     57800        18000        24989                       -609         1256
 2       112398     65780        18000        23674                       4944         9561
 3       123638     72358        18000        22198                      11081        14101
 4       136002     79594        18000        20545                      17863        19095
 5       149602     87553        18000        18691                      25357        24588
 6       164562     96308        18000        16613                      33640        30631
 7       181018    105939        18000        14284                      42795        37278
 8       199120    116533        18000        11673                      52914        44590
 9       219032    128187        18000         8746                      64099        52633
10       240935    141005        18000         5465                      76465        61480
----------------------------------------------------------------------------------------------


NET EQUITY INVESTMENT   = $22500
( THRU YEAR 0 )

RETURN ON EQUITY =         53.8%

NET PRESENT VALUE ( 20% ) = $63599

PAYBACK =                  2.8 YEARS

DISCOUNTED PAYBACK =       3.7 YEARS

OIL REVENUE PER GALLONS = $.64
```

procedures, the large plant becomes uneconomical from several directions, i.e., feedstock supply, capital cost, and expected revenue.

In fact, Baltimore tried to resolve part of its waste problem with an EPA demonstration grant for a 1,000-TPD solid waste system. The plant was designed to handle mixed solid waste, including tires. About 7.1 gal of No. 2 fuel oil per ton were combusted to provide heat for the pyrolysis reaction. Some of the gas was burned. The rest of the gas plus the oil was used to generate steam at the rate of 200,000 lb/hr, which was sold to the Baltimore Gas & Electric Company. The steam was used for heating and cooling in the downtown area. The economics are relatively unsatisfactory, with a capital investment of $20 million and a 2¢ loss per ton of operation. Discussions with EPA reveal that this system was never successful in the operational phase; this system is no longer in operation. The reasons for the failure are technical scale-up difficulties, municipal reticence, engineering problems, and material handling problems.[52] The idea of pyrolysis of municipal solid waste for heat recovery appears technically sound, but unusual problems are being encountered as pilot plants are scaled up to commercial-size plants.[53]

Another type of pyrolysis unit has been considered economically viable in Germany. The primary reason this process is considered viable is that the product revenue stream is composed of benzene, oil, gas, carbon black, and scrap steel. The process has a comparatively low capital cost of $639,000, with a throughput of 4,410 tons/yr.[54] Benzene, ungraded and unpurified, adds to the revenue stream. The sale price of benzene varies widely according to grade, but for this analysis a price of $1.55/gal was used. This results in a return on equity of 107%. The cash flow is attached in Table 22.

Although this is a relatively high return, costs may be slightly understated according to U.S. standards. Even with caution used in evaluating the estimated costs, this added revenue stream enhances the economics considerably.

Economic Conclusions

Site specific variables dominate the economic picture for tire pyrolysis. While the data collected from various pyrolysis operators looks very favorable from a simple payback criterion standpoint, a closer examination of revenues and costs shows that, with reasonable analysis assumptions, no single operation is economically profitable. A number of variables directly affect the economic viability of a project, and in many cases these variables have multiple effects. For example, a high-revenue stream (95¢/gal for oil) multiplied by an overstatement of the amount of further multiplied by optimistically stating the number of days or hours per year of operation. An understatement of costs can further complicate the economics and result in making a marginal project look very profitable.

A standardized set of economic parameters shows that none of the projects is profitable. It is necessary for tipping fees to be included as a part of the revenue stream before profitability occurs. These tipping fees need to be in the range of 4¢ to 75¢/tire. The break-even analysis shows that oil prices have to be between 60¢ and 99¢/gal, while char prices have to be between 6¢ and 8¢/lb before economic viability is attained. Current market prices are 64¢/gal for No. 6 oil and 2¢/lb for char.

Reasons for the lack of economic viability can be inferred. The major reason is product quality and product price. Because of the uncertainties involved in a commercial pyrolysis operation, product quality and price are only vaguely known. If the product oil is No. 6 fuel grade, a price can be forecast. If the pyrolytic oil contains other recoverable chemicals with a higher value, then the market value increases along with increased processing costs. This adds a degree of uncertainty for predictive capability. The price and quality of the product char are also uncertain.

The second major reason for lack of economic viability can be directly attributed to capital cost. With interest rates of 12 to 15%, a large capital expenditure requires a large debt service. All capital intensive industries suffer during periods of high interest rates. However, a return with positive cash flows merits further investigation while a negative cash flow will not be considered. Coupling the capital intensive nature of pyrolysis with an uncertain revenue stream results in a tenuous investment.

The third major reason for the lack of economic viability is the feedstock, i.e., tires. Tire collection costs could be prohibitively expensive or could

Table 22. Cash flow for benzene distillation

```
==============================================================================
     ENGINEERING ECONOMICS CASHFLOW MODEL : PRO FORMA INCOME STATEMENT
==============================================================================
                                  GERMANY
                                  2/15/83

YEAR    REVENUE  EXPENSES   DEPRECIATION  INTEREST      TAX      PROFIT    CASHFLOW
------------------------------------------------------------------------------

 1       459390   221640       51108        79162      52343     55137       64407
 2       505329   243804       51108        75636      65638     69142       89636
 3       555862   268184       51108        71569      80355     84645      100630
 4       611448   295003       51108        66878      96649    101809      112618
 5       672592   324503       51108        61468     114695    120818      125682
 6       739852   356953       51108        55231     134685    141875      139914
 7       813837   392649       51108        48039     156834    165207      155407
 8       895221   431914       51108        39748     181384    191067      172265
 9       984743   475105       51108        30192     208601    219737      190597
10      1083217   522616       51108        19177     238784    251532      210516
------------------------------------------------------------------------------


NET EQUITY INVESTMENT   = $76662
(THRU YEAR 0)

RETURN ON EQUITY =          106.79%

NET PRESENT VALUE (20%) = $403542

PAYBACK =                   1.1 YEARS

DISCOUNTED PAYBACK =        1.4 YEARS

OIL REVENUE PER GALLONS = $.64
```

provide a revenue stream. Competitive market theory indicates that if tires become a valued resource as an input for other energy forms, the scrap tires would increase in price as the supply decreased. A tire collector could conceivably pay 26¢ to 50¢/tire instead of being paid a disposal fee of 25¢ to 50¢/tire. Coupling the idea of revenue or cost for the tire feedstock with preparation costs, i.e., shredding, chopping, cleaning, etc., results in a swing factor that complicates the tire reprocessing industry economics.

A municipality offers an attractive alternative to corporate investment in the tire pyrolysis industry. A municipality offers the unique advantage of a predetermined collection network, lower financing mechanisms, and a desire to dispose of waste tires for aesthetic and health reasons as well as the fact that tires present a nuisance in landfill sites. In addition, tax advantages and revenue bond financing further increase the attractiveness.

Another economically viable treatment of tire pyrolysis is accomplished when the oil is distilled in further stages, allowing benzene to be recovered. It must be understood that any process that incurs additional capital costs for additional distillation equipment requires that the revenues obtained be substantial. The one German process evaluated showed a very low capital cost compared with similar size processes in other areas.

It is curious to note that the majority of all operators contacted are "in the process of securing financing for the commercial plant" and that this stage has been in effect for several years for some developers. One plant was developed which had a fire and is currently inoperative. One other operator has been successful in producing oil and char and in selling these products with bona fide contracts. The overall picture presented by some of the more publicized developers in the U.S. lends an aura of uncertainty to the tire pyrolysis industry.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The study concludes that tire pyrolysis is a technologically effective method of reclaiming some energy, some petrochemical products, and other products from the large numbers of tires stockpiled or discarded in landfills. Alternate methods of rubber reclaim include microwave devulcanization or microbiological degradation. Alternate uses for worn tires include asphalt, reefs, highway barriers, and fabricating split tires into a variety of higher-value products.

Scrap tire stockpiles can be defined as a concentration or accumulation of tires in one location where recovery is feasible without excessive effort or cost. Tire stockpiles fall into two major categories: static and dynamic. A static stockpile is inactive, i.e., no additions or subtractions. A dynamic stockpile can be further defined as steady state, shrinking, or growing. Steady-state stockpiles are ones where removal rates and accumulation rates are about equal, a shrinking stockpile is one where the output rate exceeds the input rate, and a growing stockpile is one where the input rate exceeds the output rate. Where stockpiles are the *only* source of feedstock for pyrolysis plants, even very small plants require very large stockpiles. A 5-TPD plant requires 1.5 million tires to supply its needs during an expected 10-year life. A large, 100-TPD plant requires 30 million tires during the same period.

Table 3 in the Resource Description section summarizes the study's findings on stockpiles. Four locations were found with more than 6 million tires stockpiled. Eight sites were identified containing 2 to 6 million tires. Sixteen locations were identified that contained between 100,000 tires and 1.5 million tires.

On the basis of car and truck tire replacement rates, the weight of waste tires, and the number of cars and trucks in the U.S., the study estimates that a total of 3.4 million TPY of worn tires are generated. Of this amount, 1.9 million are from cars and 1.5 million are from trucks. Subtracting the average percentage for used tires and retreading leaves about 2.4 million tons, or 240 million tires. This is roughly equivalent to one scrap tire per person per year, which can be taken as a rule of thumb for scrap tire generation rates. Rural and urban generation input rates vary, with the least urbanized states showing the most pounds per person. This inverse relationship can be attributed to differences in life style. However, the factor of overriding importance is that metropolitan areas, because of their population density, will provide the largest constant supply of scrap tires.

Collecting tires presents a problem or an opportunity, depending on the motive of the collector. A private enterprise may have a collection network in place that operates at a marginal cost. Public facilities usually require fees for dumping tires at landfill sites. Without a collection network in place, collection costs and transportation costs significantly influence the economics of using scrap tires as a resource. Transportation costs have been estimated to range between 16¢ and $1 per tire, depending on the distance, with an average of 50¢ per tire. If tires are collected with disposal fees, an added revenue is generated; if tires are collected using average collection and transportation costs, an added cost is generated. Thus, whether tires are collected as revenues or costs is a significant factor in the economics of a collection system.

Federal, state, and local regulations will affect scrap tire collection, processing, burning, or other disposal methods. The Federal EPA requires that all pyrolysis plants meet federal air quality standards. State regulations vary, but most states will allow landfilling of tires, although some states require shredding or splitting before disposal. Landfill fees vary from 25¢ to $5 per tire. Higher landfill fees usually result in illegal dumping of tires.

Since 1968, a large number of tire pyrolysis projects incorporating a broad range of process technologies have been carried out with laboratory, pilot-plant, and small commercial-size equipment. Most investigators found rubber pyrolysis to be technically feasible, and several commercial projects in the United States, Japan, Great Britain, and West Germany are under construction, in startup, or in operation.

Pyrolysis processes are either oxidative or reductive depending on the atmosphere within the reactor. Process data vary considerably. Reactor temperatures range from 460 to 1830°F. Reactor types vary from retorts, rotary kilns, fluidized beds, conveyor kilns, hot oil baths, molten salt baths, arc plasma, to microwave ranges. Product yields vary widely: oil, 0 to 73%; char, 0 to 52%; gas, 0 to 100%; and steel, 0 to 17%. A zero product yield implies incomplete data, since some of each product should be produced. Pyrolytic oil yields generally decrease with increasing temperature, but maximum oil yields were reported at 840 and 1100°F. Char yields are more dependent on process type than temperature. Gas yields generally increase with increasing temperature. The heating values of pyrolytic gases vary widely ranging from 156 to 2375 Btu/scf. Gases from oxidative processes generally have lower heating values than those from reductive processes.

Product quality and value are uncertain. The pyrolytic oil, if unseparated, is approximately equal in value to No. 6 fuel oil. If fractional condensation is used to produce more than one cut, values can be significantly improved. The gas is not pipeline-grade gas and cannot be commercially marketed. The char contains carbon, ash, sulfur, and nonvolatile hydrocarbons. However, the carbon must be refined further to obtain carbon black of saleable quality. Most of the data suggest that the carbon black is only an SRF grade and not suitable for reuse in tread rubber. The steel is considered scrap.

Site-specific variables dominate the economic picture for tire pyrolysis. Free tires or collection or tipping fees in the range of 4 to 67¢ per tire are a requisite before pyrolysis becomes profitable. A break-even analysis shows that oil values must be between 60¢ and 99¢ per gallon, while char values need to be between 6¢ and 8¢ per pound. The capital intensiveness of tire pyrolysis coupled with uncertain revenue streams is one reason private industry is not building many plants. Collection costs for tires also represent an added expense that further detracts from the economic picture. Before private enterprise would consider tire pyrolysis as viable, collection networks need to be existing, disposal costs for scrap tires must be avoided, and the products must be used in current operations.

Development of a tire pyrolysis project by a municipality may be a more economically attractive alternative because of predetermined collection networks, lower cost financing mechanisms, and a desire to dispose of waste tires for aesthetic, health, and environmental reasons. As another such alternative, private enterprise may be attracted by tire pyrolysis projects in which the pyrolytic oil is fractionated to yield benzene, toluene, and other higher value fractions that will provide a higher revenue.

Recommendations

Because the original intent of the study was to identify research needs in the field of tire pyrolysis and because the conclusion of the original study demonstrated limited research needs, alternate areas of using scrap tires were briefly studied. The recommendations for research tire pyrolysis are

- Exploration of product suitability and marketability for other uses
- Exploration of inexpensive techniques to upgrade product quality
- Exploration of novel process operating conditions to maximize the yield of high-value products.

New and unusual markets for pyrolysis products would enhance the economics. Product quality and marketability is an area where further research is indicated. Because pyrolytic gas contains carbon monoxide and other chemicals it cannot be sold as pipeline quality. The pyrolytic oil is considered a substitute for No. 6 fuel oil. However, the pyrolytic oil could be upgraded to produce high-octane gasoline blending stock or petrochemicals through additional processing. Char is the most prevalent solid product and the common market for char is viewed as a carbon black substitute. However, no investigator has yet been able to produce a carbon black that is comparable with a high-grade (HAF) carbon black, even with extensive posttreatment. Char black represents an area for further market development. Char black can be upgraded by pyrolysis at a high temperature and by other methods, including roasting the char at a high temperature, leaching the char with acid or solvent, and reducing the size of the char particles. These treatments do not produce a high-quality carbon black, because char black does not possess the surface reactivity of a virgin carbon black. Research directed toward increasing the surface reactivity of char black or finding alternate economic markets for char is worthwhile.

Research sponsored by the Federal government would benefit the national energy program in alternative methods for recovering energy from tires. Some alternate research areas include:

- Exploration of the use of microwave devulcanization to allow reclamation of rubber.
- Exploration of microbiological degradation of tires to produce reclaimed rubber or chemical such as organic acids, monomers, or fuels.
- Exploration of more suitable agents for chemical reclamation of tires.

Rubber reclaiming, in which tire rubber is devulcanized and blended with virgin rubber hydrocarbon, uses only about 5% of the scrap tires produced. This is due primarily to the fact that the chemical agents used to devulcanize the rubber also depolymerize rubber and degrade its properties. If a chemical, microwave, or biological methods could be developed that would specifically attack carbon-sulfur bonds but not carbon-carbon bonds, the ratio of reclaimed rubber to virgin rubber hydrocarbon could be increased without degrading the resulting product. The energy conservation potential is substantial, since rubber hydrocarbon has a high energy density.

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APPENDIX A
SCRAP TIRE GENERATION MODEL

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SCRAP TIRE GENERATION MODEL

Introduction

Intenco has previously made estimates of scrap tire generation and possible tire plant locations in the U.S. These were based on the assumptions of equal tire wear, mileage and car density across the country, such that with a knowledge of the total U.S. scrap tires generated and the population in a certain area, the tonnage of tires generated in the area was calculated in proportion to the population.

The present analysis utilizes a different approach by taking into account:

a. Revised data for total U.S. scrap tire generation (1979)

b. Considers local vehicle population (statewide)

c. Considers local mileage (statewide)

d. Considers local tread lifetime (statewide).

The car density varies significantly across the country, being low in areas with adequate public transportation. Factor "c" is important as variations in annual mileage ranges from -21% (Colorado) to +34% (Wyoming) from the national average.

Tread lifetime expectancy deviates across the country from -8% (New York) to +11% (New Mexico) of the national average.

The amount of tires generated in each state is calculated, and subsequently the amounts generated in 37 major metropolitan areas with population above one million.

Total Tonnage of Scrap Tires. The following information has been gathered through contacts with Firestone and Goodyear, and from Reference 1.

Weight of Tires. It appears that following average weight data is applicable:

	New	Worn
Car (passenger)	26 lbs	22 lbs
Trucks	85 lbs	72 lbs

Tire Production. The following number of tire units were produced (mill units):

	1978	1979	1980	1981	1982
Cars:					
Replacement	147.0	137.5	122.4	123.0	130.0
O.E.	56.5	51.1	36.8	37.0	33.0
Total	203.5	188.6	159.2	160.0	163.0
Trucks:					
Replacement	32.0	31.5	27.6	28.5	27.0
O.E.	12.0	10.8	5.8	5.5	4.5
Total	44.0	42.3	33.4	34.0	31.5

Waste Tire Generation. On the average, the lifetime of a tire is around three years, thus for our estimates of waste tire tonnage it appears appropriate to consider production and car population figures for 1979. That year had 125 million passenger cars (81%) and 29.4 million trucks (19%). The replacement factors thus becomes:

$$r^c = \frac{188.6}{125} = 1.50, \quad r^t = \frac{42.3}{29.4} = 1.44$$

The statewide car statistics available do not distinguish between passenger car and trucks, so we calculate:

Average scrap tire tonnage per vehicle and year:

$$\bar{s} = (2000)^{-1}\,(0.81 \times 22 \times 1.5 + 0.19 \times 72 \times 1.44)$$

$$= (2000)^{-1}\,(24.5 + 19.7)$$

$$= 2.21 \times 10^{-2} \text{ ton/car year}$$

This corresponds to a total U.S. scrap tire generation of:

$$S_{tot} = 154.4 \times 10^{6} \times 2.21 \times 10^{-2}$$

$= 3.412$ mill tons/year[a]

Statewide Tire Generation. The scrap tire generation for each individual state is calculated as follows:

$$S_i = S_{tot} \times \frac{C_i}{C_{tot}} \times m_i \times l_i^{-1}$$

where C_i and C_{tot} are state and total U.S. vehicle population respectively, m_i is a correction factor for local state average mileage, and l_i is a correction factor for local treadwear (or tire life).

Actual vehicle registrations for each state were used to determine C_i/C_{tot}. The relative local mileage was determined from gasoline tax records from which factor m_i is calculated:

$$m_i = \frac{f_i}{c_i}\left(\frac{f_{tot}}{c_{tot}}\right)^{-1}$$

where f_i and f_{tot} are annual highway fuel consumption for each state and total U.S. respectively.

The distribution of tread life expectancy across the country was determined according to *Tire Science and Technology* data. The computation of the relative tread life correction factor for each state is:

$$l_i = \frac{L_i}{\bar{L}} .$$

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[a] This number includes an arithmetical error; this does not, however, invalidate the conclusions of the model.

Table A-1. Estimated scrap tire generation in the U.S.

State (by region)	Scrap Tires (TPY)	1977 State Population (1000)	lb/Person
New England			
Maine	17,963	1,085	33
New Hampshire	13,168	849	31
Vermont	8,507	485	35
Massachusetts	90,264	5,782	31
Rhode Island	10,557	935	23
Connecticut	38,739	3,108	25
Middle Atlantic			
New York	188,547	17,924	21
New Jersey	101,153	7,329	28
Pennsylvania	158,605	11,785	27
East North Central			
Ohio	165,377	10,701	31
Indiana	93,823	5,330	35
Illinois	176.186	11,245	31
Michigan	143,385	9,129	31
Wisconsin	68,398	4,651	29
West North Central			
Minnesota	67,626	3,975	34
Iowa	55,285	2,879	38
Missouri	93,105	4,801	39
North Dakota	12,530	653	38
South Dakota	14,138	689	41
Nebraska	27,981	1,561	36
Kansas	42,831	2,326	37
South Atlantic			
Delaware	8,497	582	29
Maryland	55,594	4,139	27
District of Columbia	6,093	690	18
Virginia	77,704	5,135	30
West Virginia	25,660	1,859	28
North Carolina	92,465	5,525	33
South Carolina	50,490	2,876	35
Georgia	94,845	5,048	38
Florida	147,211	8,452	35
East South Central			
Kentucky	57,924	3,458	34
Tennessee	78,903	4,299	37
Alabama	67,934	3,690	37
Mississippi	41,788	2,389	35

Table A-1. (continued)

State (by region)	Scrap Tires (TPY)	1977 State Population (1000)	lb/Person
West South Central			
Arkansas	42,628	2,144	40
Louisiana	66,660	3,921	34
Oklahoma	57,814	2,811	41
Texas	249,801	12,830	39
Mountain			
Montana	16,058	761	42
Idaho	16,874	857	39
Wyoming	11,632	406	57
Colorado	45,665	2,619	35
New Mexico	23,161	1,190	39
Arizona	38,189	2,296	33
Utah	21,758	1,268	34
Nevada	15,354	633	49
Pacific			
Washington	56,774	3,658	31
Oregon	45,505	2,376	38
California	345,821	21,896	32
Alaska	6,337	407	31
Hawaii	9,083	895	20

Table A-2. Estimated scrap tire generation in major metropolitan areas

Metropolitan Area (SMSA)[a]	1976 Population (1000)	Scrap Tires (TPY)	lb/Person
New York, NY - NJ	9,509	115,500	24
Los Angeles/Long Beach, CA	6,997	110,500	32
Chicago, IL	6,993	109,575	31
Philadelphia, PA - NJ	4,803	65,300	27
Detroit, MI	4,406	69,200	31
Boston/Lowell/etc., MA - NH	3,896	60,800	31
San Francisco/Oakland, CA	3,158	49,875	32
Washington, DC - MD - VA	3,037	45,950	30
Nassau/Suffolk, NY	2,677	28,160	21
Dallas/Ft. Worth, TX	2,611	50,650	39

Table A-2. (continued)

Metropolitan Area (SMSA)[a]	1976 Population (1000)	Scrap Tires (TPY)	lb/Person
Houston, TX	2,423	47,175	39
St. Louis, MO - IL	2,384	41,700	35
Pittsburgh, PA	2,303	31,000	27
Baltimore, MD	2,144	28,800	27
Minneapolis/St. Paul, MN - WI	2,048	32,450	32
Newark, NJ	1,993	27,500	28
Cleveland, OH	1,967	30,525	31
Atlanta, GA	1,805	33,900	38
Anaheim/Santa Ana, CA	1,756	27,750	32
San Diego, CA	1,624	25,650	32
Miami, FL	1,450	25,350	35
Denver/Boulder, CO	1,438	25,050	35
Seattle/Everett, WA	1,419	22,000	31
Milwaukee, WI	1,415	20,800	29
Tampa/St. Petersburg, FL	1,367	23,800	35
Cincinnati, OH - KY - IN	1,364	21,800	32
Buffalo, NY	1,328	14,000	21
Kansas City, MO - KS	1,281	24,200	38
Riverside/San Bernadino/Ontario, CA	1,265	20,000	32
Phoenix, AZ	1,224	20,300	33
San Jose, CA	1,205	19,000	32
Indianapolis, IN	1,141	20,000	35
New Orleans, LA	1,137	19,000	33
Portland, OR - WA	1,096	21,000	38
Columbus, OH	1,072	16,600	31
Hartford/Bristol, CT	1,056	13,200	25
San Antonio, TX	996	19,400	39
	89,788	1,377,460	
	= 41.5% of U.S. population	= 40% of U.S. total	

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a. Standard Metropolitan Statistical Area.

APPENDIX B
METROPOLITAN AREAS

APPENDIX B
METROPOLITAN AREAS

The evaluation of the Metropolitan areas indicated that scrap tire generation rates combined with existing stockpiles would possibly support a pyrolysis plant. The scrap tire generation rates are based on the Intenco model with no correction for retreads. Each of the areas identified had a stockpile of at least 100,000 tires that was located within 100 miles of a major metropolitan area with a population of at least 1,000,000. For each of the larger metropolitan areas where stockpiles were found, a discussion follows which elaborates on the current disposal methods of the tires and which notes specific collectors, fees, problems, and areas of collection. This information, which is tabulated in Table 5, is presented alphabetically by state.

Phoenix, Arizona

An estimated 20,300 TPY of scrap tires are located in this area. Most of the metropolitan tires are going to Genstar Conservation Systems in Chandler. The company grinds the tires and sells to Saguard Petroleum and Asphalt Company, which makes an asphalt rubber. The asphalt is sold to the Arizona Department of Transportation. No major stockpiles have been identified in this area.

Los Angeles, California

An estimated 110,500 TPY of scrap tires are available in this area. Five large stockpiles were identified: two are located in Los Angeles proper, one in Irwindale, and two north of Los Angeles in Tulare County. The locations in the City of Los Angeles contain about 4 million tires (40,000 tons). The owner, however, is actively disposing of the tires in landfills. The sites in Tulare County cover 20 acres about 12 feet high, and probably contain 3 to 4 million tires. The sites are still accepting tires and have no current or projected use.

The site in Irwindale is a Class III landfill that accepts only tires. It apparently is a large quarry estimated to be about 70 to 80 acres and represents several million tires. The operator is collecting from at least a 30- to 40-mile radius. The landfill is operated by Genstar Conservation Systems which grinds the tires. The end use of the ground rubber has not been identified.

San Francisco, California

This area has about 50,000 TPY of scrap tires available. There is a large organized effort to collect tires. One operator located in Westly, California (south and east of San Francisco and Oakland), has collected about 14 million tires. The operator has established a large collection network, which generates 10,000 tires per day from a 125-mile radius in the area. A grinding plant is operational which processes 5,000 tires (50 TPD) with capability to process 10,000 (100 TPD) tires. The operator and Granular Systems are working together to shred the tires.

Denver, Colorado

The Denver area has an estimated 25,000 TPY of scrap tires. A very large stockpile is located at the Denver-Arapahoe Disposal Site which contains approximately 10 to 11 million tires. The stock-pile is owned jointly by the City and County of Denver and Colorado Disposal. Presently, no use is being made of the tires. An estimated 600,000 tires are stockpiled in Hudson, Colorado, about 50 miles from Denver. The operator has established a network of contacts with major tire dealers and haulers in the Denver area.

Hartford, Connecticut

The Hartford-Bristol area generates about 13,200 TPY of scrap tires. The largest stockpiles identified are in East Hartford and Plainville. Four large piles belong to the City of East Hartford. A major tire casing business in East Hartford disposes of its tires at the city site and is the source of an estimated 2,500 tires per week. The Plainville site containing about 500,000 tires is no longer accepting tires.

Miami, Florida

The Miami area generates about 25,300 TPY of scrap tires. In Florida, most tires are going to sanctioned landfills. Two large stockpiles were identified in the Miami area. The Dade County Resource

Recovery, Inc., has about 160 acres available and is accumulating 50,000 to 60,000 TPY. The Broward County Landfill 20 miles north of Miami in the Fort Lauderdale area is storing tires in cells separately from other waste. The county estimated it has about 2 million tires and accepts about 3,000 TPD. The county issued an RFP to get rid of the tires and has a bid from Gulf Industries, who is proposing to set up a shredder and pyrolysis plant. Plans are to be operational in December 1982. Broward County is guaranteed $1.50 per ton plus removal from the site. Schriptek has also expressed interest if Gulf does not become operational.

Tallahassee, Florida

The area would generate about 1,000 TPY of scrap tires. A large stockpile was identified in Leon County Landfill in the Tallahassee area. The landfill is separating tires in cells so they can be recovered. The current area of tires covers 4 acres, about 10 feet deep. They receive about 50 tons per month (5,000) in tires. A paper plant in Perry, Florida, 50 miles from Tallahassee, has for several years been considering using shredded tires as part of their feedstock. The project status is not known.

Tampa-St. Petersburg, Florida

This area generates about 24,000 TPY of scrap tires. Local officials estimate that over 6,000 tires per week are dumped into landfills. There is no fee for dumping tires. The tires are buried with the other refuse. The Tampa area is in the planning stage of developing a resource recovery unit to make refuse-derived fuel. The Clearwater area, about 40 miles from Tampa, already has an operational 2,000-TPD, refuse-derived fuel facility. Both these would include tires as a part of refuse fed into these units.

Atlanta, Georgia

The Atlanta area is estimated to produce about 34,000 TPY of scrap tires. State requirements include permits for disposal sites and does not allow open dumps. Two large abandoned tire dumps exist within 75 miles of Atlanta. The National Tire Dealers of Atlanta have established a co-op to find a landfill for tire dumping. Tires will be stored for later use.

Chicago, Illinois

The Chicago area produces about 100,000 TPY of scrap tires. About 80% of the tires are dumped into landfills and not stockpiled. The City of Chicago only takes tires from households, incinerates the waste, and then discards the residue in a landfill. There are networks of recappers within the state, e.g., Goodyear, Firestone, and Bandag. The ground rubber left from recapping is being disposed of in landfills at a cost to the recapper.

Indianapolis, Indiana

The Indianapolis area has about 20,000 TPY of scrap tires available. Most tires are going into landfills and being buried. There is a large stockpile of 2 to 3 million tires located in Brazil, Indiana, about 50 miles south and west of Indianapolis. A recovery plant is planned that will make use of these tires. The plant will use a cryogenics process to produce rubber chips for overseas export markets.

Baltimore, Maryland

The Baltimore area generates about 29,000 TPY of scrap tires. Three large stockpiles were identified in the Baltimore area; they are located in Carroll County, Harford County, and the City of Glen Burnie. The Carroll County tire pits has 8 acres of water-filled quarry with 15 years' accumulation of tires. It is estimated that about 1,000 tires go into the quarry each week. The Harford County stockpile has accumulated about 800,000 tires on about 4 to 5 acres. County officials are talking with a shredder operator from Baltimore. Each county would accumulate a batch of 10,000 tires for shredding and disposal in a landfill. The shredder operator would charge 35¢ per tire for processing. Other shredding methods would cost about 50¢ to 75¢ per tire. The Glen Burnie stockpile contains about one million unburied tires, which were collected between 1950 and 1975. Since 1975, all tires collected have been buried to comply with EPA regulations.

Wicomico County, Maryland

Another large stockpile of tires is located in Wicomico County in southern Maryland more than 100 miles from the Baltimore area. This stockpile has about 500,000 tires and is collecting at about 35,000 to 40,000 TPY. The operator has no use for the tires, but is considering disposing of them in a water-filled trench to increase available space for later recovery, and eliminate the fire hazard. A large fire about five years ago burned over 400,000 tires.

Boston, Massachusetts

The Boston area generates about 61,000 TPY of scrap tires. All landfills and stockpiles are regulated by localities in Massachusetts. Boston refuse is being shipped to West Roxbury, because they closed their public landfill areas. There is an organized effort to recycle large numbers of the tires in this area. Eastern Products, to the north in Andover, Massachusetts, has a contract with DOE to determine the feasibility of using tire-derived fuel as boiler feedstock for a paper company in New Hampshire. The company has an established network of retreaders, tire dealers, scrap collectors, etc., who accumulate tires in trailers waiting to be collected and taken to the plant.

In Boston, the Massachusetts Tire Corporation has purchased and stockpiled tires. It has built a pyrolysis plant and is ready to begin processing at a rate of 1,200 to 1,400 TPY.

In the New Bedford area, F&B Enterprises collects large tires from the entire New England area. The company is primarily interested in bias truck tires to sell to recap plants.

Detroit, Michigan

The Detroit area generates about 69,000 TPY of scrap tires. Detroit charges special collection fees for more than four tires at a time. The city has difficulty with midnight marauders that dump 500 and 600 tires at a time in urban development areas. The largest stockpile in the state is located at the Pontiac City Landfill, which contains about 700,000 tires. Small amounts of stockpile are presently being used by two pyrolysis systems in the area. Because of Detroit's status as a nonattainment air quality area, any industrial venture will be difficult.

Minneapolis/St. Paul, Minnesota

Approximately 32,500 TPY of scrap tires are available. The seven counties around Minneapolis/St. Paul have adopted uniform ordinances on disposal and stockpiling of tires, which were intended to encourage energy recovery. Many scrap tires are being transported to Wisconsin instead, which is about 30 miles away. There is one large stockpile in Anoka County north of the city which contains between 3 and 5 million tires. It is operated by a private individual. Two other stockpiles were identified. One in Stillwater, Minnesota, about 25 miles from Minneapolis/St. Paul, has about 30 to 40 acres and the operator has developed his own pyrolysis plant that processes about 10 TPH. The second is located in St. Croix County, Wisconsin, about 40 miles from the Minneapolis/St. Paul area, and contains between 4 and 5 million tires. The operator receives between 3,000 and 4,000 tires per week, many of them from the Minneapolis-St. Paul area. He is charging 10¢ per tire to accept tires and claims to be developing his own pyrolysis unit.

Kansas City, Missouri

The Kansas City area has about 24,000 TPY of scrap tires available. The city has a large problem with illegal dumping, which is associated with the relatively high cost of legal disposal at $20/ton.

St. Louis, Missouri

The St. Louis area has approximately 42,000 TPY of scrap tires available. Most landfills charge a high disposal fee (up to $2 per tire). Consequently, illegal dumping of tires presents a problem. State and local officials indicate that Jefferson County, just south of St. Louis, has become a dumping ground for tires. Two stockpiles identified are owned by tire companies. The first stockpile has only 10,000 tires but receives 600 tires per day. This operation is for retreading purposes only. The second stockpile has an unknown quantity but receives 700 tires per week.

New Hampshire

New Hampshire officials have identified a stockpile of several million tires located in southeastern New Hampshire. Because litigation proceedings are under consideration, the officials will not provide any detailed information.

Newark, New Jersey

The Newark area generates about 27,500 TPY of scrap tires. State officials estimate that most tires are being dumped in landfills. Most landfills charge a fee of 25¢ to $3 per tire; consequently, illegal dumping presents a problem. New Jersey has a state network of solid waste or recycling coordinators which are encouraging recycling. In 1982 New Jersey passed a law to tax solid waste being dumped in landfills. The money will be used to promote the recycling. New Jersey officials estimate that of the 2 million tires discarded each year, and 99.9% of them are dumped in landfills.

Auburn, New York

Energy Recovery, Inc., located in Auburn is planning to establish a recovery center to collect from a 150-mile radius at a charge of 2¢ per pound (40¢ per tire) for delivered tires. The shredded product would be sold to various vendors. One tire company in the area stated the fee is too high for tire disposal.

Buffalo, New York

The Buffalo area generates about 14,000 TPY of scrap tires. In this area, four stockpiles, owned by one person, contain about 2 million tires, with additions of about 15,000 tires per day. Currently, these tires have no end use.

New York City, New York

The New York area is the largest generator of scrap tires in the United States, producing about 115,500 TPY of scrap tires. The City of New York has a problem with illegal dumping of tires. There is no extra fee for tires, but it is estimated that only about 1 to 2% of the tires are dumped in landfills. A more stringent law recently passed allows city officials to confiscate trucks used to dump tires. City officials are interested in pursuing recovery options. They say established networks could be used for tire collection; e.g., the local utility, phone company, tire dealers, and gas stations. The city generates several hundred tons of tires per month from its vehicles.

Rochester, New York

A tire company in Rochester, New York, has 1.5 million tires on 5 acres. The stockpile is growing; the operator charges 25¢ per tire. Currently, these tires have no end use.

Akron/Youngstown, Ohio

There is an active movement to recover energy in tires in the Akron-Youngstown area near Cleveland. Akron is currently trying to demonstrate the feasibility of using tires as feedstock along with other refuse in a resource recovery unit. The unit would provide steam to heat downtown buildings in Akron. Any excess steam would be sold to B. F. Goodrich. The city is trying to get a grant from the state to help with costs of the demonstration. Carbon Oil & Gas, Inc., began operation of a pyrolysis plant in the Youngstown area at the end of November. The site was chosen because of substantial stockpiles and end product market availability.

Cleveland, Ohio

The Cleveland area is estimated to generate about 30,500 TPY of scrap tires. Cleveland shreds the tires they pick up from residents before shipping to a private landfill that requires the volume reduction. Legislation has been passed that allows the city to accept tires from commercial establishments at a fee of 50¢ per tire. Officials are currently establishing the collection network.

Portland, Oregon

Projections based on population indicate that about 21,000 TPY of scrap tires are available in this area. The Portland area is one of the few areas where there is competition for tires. A local ordinance was passed which required that tires be shredded before landfilling. Equipment was developed to generate uniform particles. These particles are being used as boiler feed in forest product industries (10%). Stockpiles no longer exist in the area. Large stockpiles in the Vancouver, Washington, area have been transported to Portland.

Harrisburg, Pennsylvania

The Harrisburg Steam Generating Facility has a stockpile of about 50,000 tires. Burning of the tires in the facility fouled up the incinerators and precipitators. The operator refuses to accept any more tires and is charging $250 per ton. Harrisburg has issued an RFP for disposal of the stockpile.

Philadelphia, Pennsylvania

The Philadelphia area produces about 65,000 TPY of scrap tires. Philadelphia has no public landfills and is currently exporting most of its tires to New Jersey landfills. Philadelphia Sanitation does not accept loads of tires; these are hauled by private drivers to New Jersey. One large stockpile of between 500,000 and 1 million tires is located in Franconia, Pennsylvania.

Pittsburgh, Pennsylvania

Pittsburgh generates about 31,000 TPY of scrap tires. Allegheny County accepts tires at its demolition landfill for a fee of $5 per tire. The high fees result in illegal dumping. Two major stockpiles were identified in Fayette County just south of Pittsburgh. One stockpile contains about 1 million tires and is growing at a rate of 1 million tires per year. The second stockpile is located on several acres and has a zoning permit to store tires.

Dallas-Ft. Worth, Texas

The Dallas-Ft. Worth area generates about 51,000 TPY of scrap tires. The City of Ft. Worth has an ordinance prohibiting the acceptance of tires at their public landfills. Tires are ending up being dumped or in private landfills. The City of Dallas accepts tires in their landfills and charges the regular fee plus $11 per ton for tires. Neither city is concerned about tires and no large stockpiles were identified.

Houston, Texas

In response to illegal dumping and potential health hazards, i.e., mosquito transmitted encephalitis, the Houston area generates about 47,000 TPY of scrap tires. Houston has established a law forbidding the open storage of tires. Houston also requires transportation permits for tire collectors, disposers, and reprocessors. The city will only accept four tires per resident per year. If tires constitute more than 5% of any load, they must be quartered before landfilling. Two stockpiles are located in Houston, one of 100,000 tires and one of 250,000, but these stockpiles are in litigation.

San Antonio, Texas

The San Antonio area generates about 19,400 TPY of scrap tires. The local landfill has a small stockpile but buries about 500,000 tires annually. Tires are not separated from other refuse. Officials in San Antonio know of about 200 mini-dumps where tires are dumped illegally. The city is investigating building a resource recovery unit for refuse-derived fuel that will process about 2,000 tons of refuse per day. This will include some tires.

Seattle, Washington

Estimates of scrap tires available are 22,000 TPY for the Seattle area. Many tires are going to county landfills where they are buried. A major stockpile exists in Everett, Washington. Between 4 and 5 million tires are stockpiled on city property. The operator leases from the city; he is grinding tires and selling them as boiler feedstock for the pump industry. About 40,000 tires (∼ 400 tons) come into the stockpile each month, and about 40,000 are processed and sold. The operator is collecting from Seattle, Tacoma, Everett, and Bellingham, which is about a 100-mile radius. He charges between 19¢ and 35¢ per tire as a collection fee. The operator of the Everett stockpile mentioned that his customers have had problems with zinc particulates and their scrubbers; they have also had to install precipitators to remove zinc from the water they discharge.

Washington, D.C.

The area around Washington, D.C., generates about 46,000 TPY of scrap tires. The tires are collected and taken to Fairfax County, Virginia, where they are dumped in a trailer and then hauled away by Roplex (a company). The county pays Roplex $175 per truckload for tire disposal. The tires are shredded and sold as rubber chips for fuel stock. Fairfax County, Virginia, uses the health code to control open stockpiles. Authorities have the power to remove stockpiles, charging the landowner with the disposal fee plus labor costs.

Milwaukee, Wisconsin

The Milwaukee area is estimated to have about 21,000 TPY of scrap tires available. An organized effort is taking place in Wisconsin to shred tires before disposal at landfills. Two stockpiles of shredded tires have been identified in the counties west of Milwaukee. In the Madison area, over 400 tons of shredded tires are dumped in the Dane County landfill. Tires are being continually collected. In Green County (just south of Madison), more than 720 tons of shredded tires are stored. This landfill is no longer accepting tires.

APPENDIX C
REGULATIONS AFFECTING TIRE CONVERSION FACILITIES

APPENDIX C
REGULATIONS AFFECTING TIRE CONVERSION FACILITIES

Table C-1. Sites with less than 100,000 tires

Location	Size (tires)
Bristol, Connecticut; Black Avenue	60,000
Yreka Landfill; 1-1/2 mi SE of Yreka, California	60,000
Bay County, Michigan; Health Department responsible	50,000
Harrisburg Steam Generating Facility; Harrisburg, Pennsylvania	50,000
Klamath Falls County; Klamath Falls, Oregon	50,000
City of Olmito, Texas	50,000
Westfield, Massachusetts; Mainline Drive tire outlet	35,000
Handy Township; Livingston County, Michigan	30,000
Near city of Littlefield, Texas	25,000
Gravel pit 2 mi South of Tracy, California	20,000
Schriptek Marketing, Inc.; Lathan, New York	20,000
City of Lubbock, Texas landfill	10 to 20,000
Beam Tire Company; Charlotte, North Carolina	10 to 15,000
Phillips County, landfill; Holyoak, Colorado	10,000
Southern Tire Company; High Ridge, Missouri	10,000
White Rock Road, 4 mi E of Sunrise Boulevard, and E of Sacramento, California	10,000
El Paso, Texas	10,000
Near city of Cretedmoor, Texas; on State Hwy 183	10,000
Richfield Disposal; Flint, Michigan	<10,000
Washington County; Tilquist, Minnesota	3,000
Near city of Garfield, Texas; on State Hwy 71	2,000
Houston, Texas; Night Road off Holmes Road	2,000
Caro, Michigan; city stockpile	≤100,000

Table C-2. State solid waste management plans

1. States with EPA-Approved Plans (20)

Alabama
Arizona
Arkansas
California
Connecticut
Florida
Georgia
Illinois
Indiana
Iowa
Kentucky
Louisiana
Massachusetts
Michigan
Minnesota
Mississippi
North Carolina
Oklahoma
Pennsylvania
Tennessee

2. States with EPA-Partially Approved Plans (2)

Oregon
Wisconsin

3. States with Plans Adopted and Submitted to EPA for Review (15)

Colorado
Idaho
Kansas
Maine
Missouri
Montana
Nebraska
New Hampshire
North Dakota
Ohio
Rhode Island
South Dakota
Texas
Vermont
Washington

4. States with Draft Plans Under Review by State or EPA (11)

Delaware
Hawaii
Maryland
Nevada
New Jersey
New York
South Carolina
Utah
Virginia
West Virginia
Wyoming

5. States that have not Submitted a Plan (3)

Alaska
District of Columbia (no Subtitle D Program)
New Mexico (no Subtitle D Program)

Source: James Michael, EPA, Washington, D.C.

Table C-3. State regulations affecting tire conversion process plants

State	Summary
Arizona	None.
Colorado	None; a pyrolysis plant to be located in Colorado only had to obtain an air quality permit.
Connecticut	The state can cut red tape; if the facility is a demonstration plant and if projected plant life is less than 2 years, state officials can move very fast. Variances are built into the solid waste management act. The entire state is a nonattainment air quality area.
Indiana	Plant would require a limited permit from solid waste management (not the full-blown permit required for landfill and disposal sites).
Maryland	Maryland Waste Management Administration would want to review plans submitted for air quality; waste disposal permits would probably be required, but a public hearing would not be required.
Michigan	The state solid waste management act purposely exempts plants of this type from permitting procedures.
Missouri	Under the state solid waste ordinance, the plant would need an operating permit as a processing facility, but no storage permit would be needed. Solid waste disposal permits are obtained from Missouri Department of Natural Resources.
New Hampshire	A permit for storage would be needed from the State Solid Waste Management.
New Jersey	Passed a law to tax solid waste being dumped in landfills.
Ohio	None.
Oregon	A permit from the State Department of Environmental Quality would be required.
Pennsylvania	A permit from Department of Environmental Resources would be required; state and local health departments would give recommendations.
Virginia	State officials are unsure if a permit would be required from Solid Waste Management. Resource recovery operations that involve burning require permits; recycle operations (e.g., aluminum) do not.
Wisconsin	The plant would need site approval as a processing plant from the State Bureau of Waste Management.
Washington	The plant would need a permit from the State Solid Waste Bureau.

Table C-4. Municipal regulations

Municipality	Regulation
Akron	If the city's recovery system is implemented, tires will no longer be accepted at landfills.
Cincinnati	The city has an ordinance on illegal dumping.
Fairfax, VA	The city uses the health code to prevent illegal dumping or storage; they can charge for cleanup in addition to disposal fee and have the power to put a lien on property.
Ft. Worth	Tires are not accepted in public landfills.
Houston	It is illegal to stockpile in the open; all haulers are required to have a permit; any tires in loads of trash containing more than 5% tires must be quartered before landfilling.
Kansas City	The city has an illegal dumping ordinance.
Minneapolis	A permit is required to store or dispose of tires; volume (7 counties) reduction is required before disposal.
New Orleans	The city is in the preliminary stages of attempting to establish regulations on tires.
New York City	The city can confiscate the trucks of those caught illegally dumping tires.
Phoenix	Volume reduction is required before landfilling tires.
Portland	Tires must be shredded before landfilling.
Salt Lake City	Stockpiles of whole tires are required to have a permit as a processing and storing facility; dumping is prohibited; violators are taken to court.
Seattle	Tires in landfills must be covered each day; tires must be spread throughout the landfill; landfills require a permit from the county Solid Waste Division; stockpiles must be fenced; the City Building Department oversees stockpiles.
Trenton, NJ	The city will collect a maximum of two tires per resident and three tires per gas station in each collection period.

Table C-5. Applicable federal ambient air quality standards

Pollutant	Federal[a] Ambient Air-Quality Standard (µg/m) Primary	Secondary
Sulfur dioxide		
Annual	80	NS[b]
24-hour[a]	365	NS
3-hour	NS	1,300
Particulates		
Annual	75	60
24-hour[a]	260	150
Carbon monoxide		
8-hour	10,000	10,000
1-hour	40,000	40,000
Sulfuric acid		
24-hour	NS	NS
1-hour	NS	NS
Hydrocarbons		
3-hour[a]	160	160
Nitrogen oxides		
Annual	100	100

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a. Source: 40 CFR 50 (1977).

b. NS = No Standard.

APPENDIX D
INDIVIDUAL PROCESS DESCRIPTIONS

APPENDIX D
INDIVIDUAL PROCESS DESCRIPTIONS

Technical information obtained in a global search by Galaxy, Inc., and by additional literature search on tire pyrolysis activities, past and present, is presented for oxidative processes and for reductive processes. The sequence of individual process descriptions is the same as that which appears in Table 11. Proprietary information and the brevity of certain published data in the literature in many instances have meant that most of the technical descriptions are necessarily brief.

Discussion and evaluation of the information obtained for the various processes and the conclusions derived from the evaluations are presented in the Discussion and Evaluation and in the Conclusion subsections of the Process Section.

Oxidative Processes

1. **Quinlynn Oil & Gas Company.** Quinlynn Oil & Gas Company, Madisonville, Kentucky, has a 5-TPH (36,000-TPY) tire pyrolysis plant under construction in Portland, Oregon.[1] A 1-TPH experimental plant operated from 1979 to 1982 and is now disassembled. They are studying a scale-up to 20-TPH to use whole tires.

The current process is a substoichiometric combustion (using 23% of the air required for complete combustion) that operates at high temperatures (up to 1500°F) to gasify shredded tires in a vertical retort under controlled conditions. The process is based on the Rotter gasification process, patented by Franz Rotter, who began his career in gasification in Germany during World War II. The Rotter gasifier is designed to be operated in either a downdraft or an updraft mode. The downdraft gasifier can produce a relatively clean tar-free gas suitable for use in internal combustion engines. Updraft gasifiers are usually larger, but they produce gas far less satisfactory for internal combustion. The feed auger delivers shredded rubber to the top of the gasifier through a rotary air lock. The rubber is fed vertically through the gasifier by gravity and by a vertical screw which recirculates material from the bottom to the heated zone. As the char is formed, it falls down the gasifier to a well containing a removal auger. The char, steel, and fiberglass are removed intermittently. Air for the combustion is supplied by fans from outside sources. The oil and gas are removed in a series of separators and scrubbers.

The product yield information apparently is based on the net salable products, excluding recycled gas burned as fuel, waste, etc. At 1100°F, the products are expressed as a percent of tire input: 7% gas, about 92% propane, with carbon dioxide, oxygen, and butane, and a heating value of 2375 Btu/ft^3; 41% oil, highly aromatic with 0.8% sulfur, 0.4% chlorides, and a boiling range 180 to 643°F; 10% char, market as fuel, 15 to 20% ash; and 6% steel, scrap. The gas yield would be 43% if it were assumed that no waste occurs. The corresponding yields at 1500°F are: 14% gas, 2.1% oil, 0.6% char, and 6% steel. The gas yield would be 91% if it is assumed that no waste occurs. The calculated net product yields as percents of products for 1100°F and 1500°F, respectively, are: gas, 10.8 and 61.8; oil, 64.0 and 26.8; char, 15.7 and 2.7; and steel, 9.4 and 9.2. Quinlynn has found several companies interested in purchasing the product oil and the char. However, the excess nitrogen, organic chlorides, and sulfur would have to be removed. A market for the zinc oxide is being explored.

Some technical advantages of the Rotter process are: no water is required; the process is not sensitive to disturbances and fluctuations; electricity is the only required outside energy input; the reactor refractory material can be renewed; the process can be fully automated; the process can be operated either as a gasifier or as a pyrolysis unit which produces more oil; the process can handle combustible solid waste material other than rubber.

The energy balance for the 5-TPH plant indicates that of the 150 million Btu/hr available in the tires (assuming 15,000 Btu/lb), 100 million Btu/hr are recovered in the gas and the oil products. The waste heat recovery through the coil in the reactor is claimed to be 3 million Btu/hr. The largest energy cost in the process operation is the shredder, which required a 400-horsepower motor for the 1-TPH plant. For the 5-TPH plant, a shredder powered by a diesel engine will be used. The fuel consumption of the shredder is estimated at 2 million Btu/hr, which amounts to 2% of the net energy.

Quinlynn plans to build two plants in the Baltimore-Philadelphia area soon. They are looking at areas with dynamic tire piles.

2. **Atomics International.** Atomics International Division, Canoga Park, California, in 1975 conducted a series of bench-scale gasification tests using molten salts.[2] The technology that was developed, i.e., the molten salt gasification process, is a two-step process.

In the first step, shredded combustible waste or shredded tires and air are continuously introduced beneath the surface of a sodium-sulfide, sodium-carbonate melt at about 1700°F. Any hydrogen sulfide formed is converted to sodium sulfide by the alkaline sodium carbonate. The salt melt retains the ash and completely oxidizes any char. No significant amounts of NO_x are formed from the nitrogen in the air because the temperature is too low. Substoichiometric quantities of air, less than 50% of the theoretical amount required for combustion, are used to permit partial oxidation and complete gasification of the waste material. A sidestream of sodium carbonate melt is withdrawn from the reactor, quenched, regenerated in an aqueous system to remove the ash, and then returned to the reactor. The buildup of ash and inorganic combustion products decreases the fluidity of the melt and its ability to remove H_2S. The second step, not treated in this analysis, consists of the complete combustion of the product gas in a conventional gas-fired boiler.

Tire tread particles, as well as other wastes such as x-ray film, pine sawdust, nitropropane, and sucrose were gasified in the apparatus. The solids were pulverized to <1 mm particle size and fed to the reactor by a screw feeder. The liquid wastes were sprayed into the reactor feed tube. Sodium sulfide was added to the sodium carbonate melt at the start of a rubber gasification of the char, since previous experiments had established that sodium sulfide acts as a catalyst to gasify the char. Thirty-three percent of the theoretical air was used to gasify the rubber to produce a gas with a heating value of 156 Btu/scf. No H_2S was detected (<30 ppm) in the product gas. The heating value of the gas can be increased by decreasing the percent of theoretical air, but there is a practical upper limit on the gas heating value because the point is reached when there is not enough heat released to the melt to sustain the operating temperature.

The maximum waste throughput is governed by the maximum superficial velocity of the gas through the melt. Beyond the maximum, entrainment of the melt becomes excessive. However, by operating at elevated pressures, the waste throughput can be increased proportionally to the pressure at a given gas superficial velocity.

An engineering evaluation leading to the economics of the molten salt gasification process had not been made at the time of the publication of the information.

3. **Nippon Zeon Company, Ltd.** The Nippon Zeon Company, Ltd., Japan, in 1974 constructed a continuous fluidized bed tire pyrolysis plant with a capacity of 7,700 TPY of shredded tires, and in 1978 abandoned the project because of the prohibitive tire collection cost.[3] In their project, steel was separated from crushed tires with magnets. Two to three percent of the tire fragments were consumed as the heat source to obtain the pyrolysis temperature of 840 to 930°F in a substoichiometric combustion process.

The product yields were: 56% oil, with up to 1.4% sulfur; 31% char, with a particle size distribution of 40 to 500 μm and a heating value of 13,500 Btu/lb; 3% gas, with a heating value of 170 Btu/ft^3; and 10% steel. The gas was burned to yield steam or hot water. The char was successfully tested as a material for waste water and gas deodorization treatment. The char was used as the fluidizing material in the reactor. Upgrading of the char to activated carbon was possible through steam activation in a fluidized bed at 1475 to 1650°F, with a yield of 30 to 35%.

During the 3-year plant operation, a high-efficiency, compact, fluidized-bed reactor was designed that required a few tens of seconds of residence time. The agitator that was part of the reactor to stabilize the fluidization process was very sensitive to the chipped steel wire. The reactor was equipped with a sulfur compound scrubber.

4. **Sumitomo Rubber Industries, Ltd.** Sumitomo Rubber Industries, Ltd., Akasaka, Minato-ku, Tokyo, Japan, about 10 years ago developed a batch-type laboratory-scale pyrolysis project using superheated steam at 1300°F in direct contact with 65 to 110 lb of whole tires. About 100 lb/hr of saturated steam from a steam boiler

was superheated with a high-frequency source before entering the reactor. The pyrolysis vapors were cooled by an air-heat exchanger, separated from particulates by a cyclone, and partially condensed into oil and gas. The oil (yield, 54.7%) was separated from water and then recycled to the steam boiler for use as fuel. The oil had a heating value of 18,000 Btu/lb and a sulfur content of 1.3%. The gas (yield, 9.5%) was burned as a fuel gas. The char (yield, 31.7%) had an ash content of 11% and about 2.3% volatiles content. The steel (yield, 4.1%) was to be sold as scrap.

A feasibility study for a 1,500-TPY plant was abandoned because of difficulty in collecting waste tires and in obtaining a suitable surplus steam source. Also, the high-frequency heating concept was not very efficient. Apparently, the steam heating did produce better char than could be obtained with external heating. The char was intended to be used in rubber tire production.

5. **Tosco.** The Oil Shale Corporation (Tosco), Golden, Colorado, began studies on the application of their TOSCO II oil shale pyrolysis to tire pyrolysis in 1971.[4,5,6,7] In 1975, Goodyear Tire & Rubber Company and Tosco entered into a joint venture to construct a pilot plant designed to handle 15 TPD of shredded scrap tires. The pilot plant completed operation in 1980. The process involves shredding the tires into 2-inch-square fragments, drying the fragments, and then feeding them continuously via a surge hopper into a 3-foot-diameter x 10-foot-long rotating retort having a steam blanketed, oxidative atmosphere. In the retort, the tire pieces are mixed with 3/4-inch-diameter ceramic balls which have been heated to 1200°F by recycled, uncondensed pyrolysis gas in a separate heater. The rubber and the balls move concurrently through the reactor. During a residence time of about one minute, the rubber is raised to the reaction temperature of 900 to 1000°F. The vapor and gas pass from the top of an accumulator vessel into a fractionator, where the oil is separated into various fractions. The gas is recycled to the ball heater. The mixture of balls and solid residue is separated with a rotating drum screen called a trommel. The warm balls are collected and returned to the ball heater. The char is separated from the steel, fiberglass, and waste and then pelletized for sale.

The oil (yield, 52%) has about 1% sulfur, a heating value of 18,030 Btu/lb, an ash content of 10%, a 95% aromatic content, a 4% olefinic content, and metals contents of (ppm): arsenic, 1.1; copper, 0.2; iron, 133; nickel, 0.3; sodium, 27.5; and vanadium, 0.8.

The gas (yield, 11%) is primarily butylene, carbon dioxide, methane, ethane, ethylene, propylene, propane, and carbon monoxide. The heating value is about 1000 Btu/ft^3, so that the gas just about offsets the process' energy requirements.

Tosco claims that the recovered char is equivalent to general purpose furnace (GPF) black and that the reinforcing properties are the same as those used in compounding rubber used in tire sidewalls. However, the ash content is about 15%, the sulfur content is 2.5%, and the chlorine content is 0.25%. The particle size and surface area of the char are not available.

Tosco and Goodyear once were considering a 300-TPD plant, but those plans were dropped because the expected revenues were insufficient to offset the apparent risks of the project. Tosco has promoted the idea of a smaller facility for a municipality as an approach to environmental management. The thought is that oil could be used as fuel oil for heating and that the carbon could be upgraded and used to filter waste water, while solid waste and landfill accumulation would be reduced.

Reductive Processes

6. **Kobe Steel Works, Ltd.** Kobe Steel Works, Ltd., Ako City, Japan, currently has a pyrolysis plant operated by Kansai Environmental Development Company.[8,9] This 7,700-TPY plant has been operating successfully (and now smoothly) since October 1979. Crushed tires are pyrolyzed continuously in an externally fired rotary kiln in a reductive atmosphere at 932°F. The kiln has paddles that scrape char from the sides. The process yields gas, oil, char, and steel. The heavy oil (40 to 43% yield) is used as stock fuel for cement kilns. The light oil (7.5 to 14.5% yield) and gas (6 to 8% yield) are recycled to produce the pyrolysis heat source, with some surplus. The oil contains carbon particles that must be removed before it is suitable for sale as a fuel oil or refinery feedstock. The cost of refining and the small output volume are considered as barriers to chemical refining. The oil has a heating value of 17,460 Btu/lb and a sulfur content of 2% or less. The char (32 to 34% yield) is pulverized with an air-jet type comminuter, after

which a small amount of special Teflon is added. According to Kobe Steel, the pyrolysis temperature must be kept below 1100°F to obtain a good grade of char. The char typically obtainable from this process does not have the same characteristics as a high-grade commercial carbon black, but it has been usable in a number of applications such as automobile mud flaps, bicycle tires, safety shoes, conveyor belts, fenders, etc. Fiberglass, waste, unpulverized char, etc., are fed to the cement kilns as sludge. The secondary waste from the plant is a small amount of waste water isolated from the light oil. Flue gases are scrubbed before release to the atmosphere. Metals obtained through magnetic separation are sold as scrap. The plant requires a 500 kW power source.

7. **MVU.** Mannesmann-VEBA-Umwelttechnik (MVU) GmbH, Eisen und Metall AG, and Rutgerswerke AG, West Germany, began pilot-plant studies of tire and plastic waste pyrolysis in 1974.[10,11,12] An industrial plant with a tire throughput of 11,000 to 16,500 TPY is tentatively planned for construction near Frankfurt in 1983 or 1984. The 220 lb/hr pilot-plant studies were concluded in 1980 because the interest in tire pyrolysis in West Germany had become oriented primarily toward the fluidized bed technology developed by Kaminsky and Associates at Hamburg University.

In the MVU process, shredded tires and/or plastic waste are fed continuously into an external-fired, air-tight, rotary kiln reactor at 1200 to 1300°F. The solid residue is discharged via a water-seal at the end of the reactor. The vapors and gases are first quenched by an extraction oil, then cooled to condense the oil and water in a heat-exchanger. The gas is scrubbed with water and caustic soda to remove hydrogen chloride, hydrogen sulfide, and hydrogen cyanide and then recycled as fuel gas (yield 17%, with a heating value of 1,075 Btu/ft^3) to heat the reactor. The gas is primarily methane. Water is decanted from the oil. In a third column, aromatics are separated by oil extraction. The hydrocarbons from the quenching, decanting, and extraction steps are distilled together so that the light fraction [benzene-toluene-xylene (BTX), yield 70% of the total oil, 22% of the total products] and the heavy fraction (yield 20%) are the product oil, considered as chemical refinery feedstock. The medium fraction (yield 10%) is used as the extraction oil. The char was not separated from the metals (total yield 57%).

Environmental controls for this process include the gas scrubber, the cleaning of the waste water from the solids recovery, the decanted water, and the caustic soda wash water.

8. **Herko/Kiener.** Kiener Pyrolyse, West Germany, originally constructed a 220 lb/hr test unit to pyrolyze tires, but they soon changed to household garbage.[13] A second test unit of 1,100 lb/hr capacity used only garbage. A 3 x 3.3 TPH plant in Goldshofe/Aalen started test runs in August 1982; results will be available at the end of 1983. The primary objective is to use the pyrolysis gas in a turbine to generate electricity. Tests made in 1978 with shredded tires at 1020 to 1110°F produced the following yields: 47% oil; 30% char; 17% gas, with a heating value of 930 Btu/scf; and 6% steel. The product gas contained 16% nitrogen, which was assumed to enter the system through air leaks.

9. BKM. Babcock-Krauss-Maffei (BKM), Munich, West Germany, has a pyrolysis plant with a 2 x 3.3 TPH throughput under construction. The design is based on that of a 0.55-TPH test unit. The plant was planned to begin operation in Gunzburg/Donau, West Germany, by the beginning of 1983. The reactors are two parallel rotary kilns fired by recycled pyrolysis gas. The excess gas is to be used in a steam turbine to generate electricity. The process apparently is planned to pyrolyze municipal waste at first, although it might be able to pyrolyze tires or plastic wastes.

10. **ERRG.** Energy Recovery Research Group, Inc. (ERRG), Portland, Oregon, constructed a 3-TPD tire pyrolysis pilot plant in 1977. In 1978 ERRG was assigned rights to a patent of Franz Rotter on the process and apparatus, and they designed a 25-TPD, modular, commercial plant. The pilot plant demonstrated the feasibility of the process by operating continuously for as long as 120 days, and ERRG is now seeking financing to construct the commercial plant.

The ERRG process involves a 24 hr/day, continuous process with a capacity of 8,250 tons of shredded tires per year.[14,15,16,17] The tires are washed, shredded, and then fed into the reactor through a screw conveyor and bucket elevator. The feed rate is regulated by air seal valves with variable speed motor drives. The reactor consists of one or more large retort tubes mounted inside an insulated combustion chamber. The tire feed drops by gravity into the retort and is continuously propelled to the discharge end by a paddle auger conveyor. Multiple burners in the combustion chamber with individual burner settings are intended to assure uniform heating and minimize hot spots. Waste heat is recovered from the combustion flue gases. The offgas and vapors are separated from the particulates that are carried overhead. The oil is separated from the gas in a quench tower designed to produce one or more boiling fractions. The oil is then cooled, filtered, and sent to storage. Typically 50 to 80% of the noncondensable gas is recycled for process fuel. Excess gas could be used in a turbine or used elsewhere as fuel gas. The solid residue is discharged by gravity from the reactor, cooled, conveyed to a grinding mill to be reduced to fine particles, separated from the metal magnetically, separated from the fiberglass by screening, and then bagged as char black.

The product yields and properties are: 37.5% oil, containing 1% sulfur, 25% naphtha fraction (below 400°F) with a heating value of 19,500 Btu/lb, 33% diesel fraction (400° to 650°F) at 18,230 Btu/lb, and 42% fuel oil fraction (above 650°F) at 16,700 Btu/lb; 30% char, with 12% ash, 3% zinc oxide, 2% silica, 1.8% sulfur, 325 mesh size, and 13,400 Btu/lb; 27.5% gas, 1,000 Btu/ft^3; 3.5% steel, scrap; and 1.5% inorganic wastes. The oil is claimed to be a high-quality No. 4 heating oil with a potential also for refinery feedstock blend. The char black is claimed to be essentially a GPF-grade black usable as a reinforcing filler, but the ash should be removed.

The net energy value of the products is about 22.75 million Btu/ton of tires input (char, 8.04 million Btu; excess gas, 2.2 million Btu; oil, 12.5 million Btu). At 15,000 Btu/lb of tire, the energy value of the one ton of tires is 30 million Btu, so that about a quarter of the tires' fuel value is lost in the pyrolysis process. The tire shredder energy requirements are not available. Obviously, the economics of the process will be favored by the extent to which char black is usable as a carbon black and to which the oil can be used as chemical feedstock.

Process advantages are:

- Mechanically simpler than the rotary kiln approach
- Modular concept, 25-TPD reactor units
- Compact plant design
- Environmental cleanliness, i.e., little water pollution since tire washing and equipment cooling are the only uses of service water (the Portland plant was cleared without special environmental controls)
- Low operating costs.

11. **Carbon Oil & Gas, Inc.** Carbon Oil & Gas, Inc., Struthers, Ohio, has had a 7,000-TPY tire pyrolysis plant in operation since January 1983.[18] Shredded and classified tire fragments are fed continuously by conveyor through an access port into the top of the externally fired reactor. The access/dump ports are purged with CO_2 to remove the air. The rubber is conveyed through the reactor and pyrolyzed at 1100°F for a residence time of 30 minutes. The overhead vapors from the reactor are continuously removed and flashed in three stages to produce three oil fractions (naphtha, No. 6 fuel oil, and a benzene-toluene rich phase) along with a noncondensable gas. The gas is cooled to separate the water and then scrubbed to remove the hydrogen sulfide. The gas is either flared (1/3) or recycled for process heating (2/3). The solid residue leaves the reactor through a dump port and is quenched, the steel is magnetically separated, and the remaining residue is pulverized.

The product yields are: oil, 45% yield, 0.9% sulfur, aromatic and olefinic; gas, 13% yield, contains CO, 1100 Btu/scf, 18000 scf/hr or 6000 scf/ton; char, 33% yield, filler grade; and steel, 9% yield. The oil can be used as fuel oil or as refinery feedstock. The char could be used as a fuel or as a low-grade filler black.

12. **Intenco, Inc.** Intenco, Inc., of Houston, Texas, built and operated a 50-TPD tire pyrolysis demonstration plant during 1979 and 1980.[19,20,21] The plant was apparently producing yields as designed in April 1980 when the failure of a seal packing in a pyrolysis reactor caused air to be pulled past the seal, resulting in an internal hydrocarbon fire and considerable reactor damage. Since then, seal design modifications and various safety systems have been designed to eliminate the possibility of fire. Some process enhancements also have been designed to improve product quality. The plant has not yet resumed operation. Designs for a 100-TPD plant have been formulated.

The Intenco process is based on the continuous pyrolysis of shredded tires in a screw-conveyor-fed reactor at ∿850 to 1050°F in a reductive hydrocarbon-vapor atmosphere indirectly heated by a high-temperature molten salt system. The tires are reduced to fragments of approximately one to two square inches by a tire shredder. The tire fragments pass through a magnetic steel separation step and are introduced by a screw conveyor through a rotary air lock into the reactor which operates at a vacuum of a few inches of water. The reactor has an internal rotating hollow shaft with appendages and is heated indirectly by the introduction of molten salt into the shaft. The residence time of the rubber fragments in the reactor is typically 30 minutes.

The vapors pass through a two-stage scrubbing and condensing train in which the oil is condensed into two fractions (heavy fuel oil and light naphtha), and the small amounts of char, fiberglass, and water are separated. The clean oil is stored. The oil yield is about three barrels per ton of rubber processed, or about 52% of the total products. The aromatic content is high; and consequently, antioxidants must be added to the oil to inhibit polymer formation. Alkyl benzenes, 3-, 4-, 5-, and 6-ring aromatics, naphthalenes, and styrenes are the predominant oil components. Water and sulfur contents are less than 1 wt%; total chlorides are less than 0.1 wt%. The heating value is almost 19,000 Btu/lb. The oil can be separated into several boiling range fractions, from naphtha (<400°F), similar to gasoline with a high unleaded octane number, through the middle range (to 600°F), suitable for sale as No. 2 or No. 4 fuel oil, to the heavy range (600+°F), similar to the original extender oil in the new tire.

The uncondensed gas (7% yield) is used as fuel for heating the salt. The hydrogen sulfide content is about 150 ppm. The hydrocarbon content consists primarily of butenes, propylene, ethylene, propane, ethane, and methane. Some carbon monoxide, carbon dioxide, and nitrogen are also present in amounts exceeding 3 wt%.

The solid phase consists of char, steel wire, fiberglass, and ash. The char is cooled, steel is removed magnetically, and fiberglass is removed by screening. The char is then pulverized, further purified, mixed with hot softened water, pelletized, dried, screened, and bagged as carbon black, with a yield of 35%. The black typically has about 14% ash and 2% sulfur contents. Otherwise, it is comparable in characteristics with a semireinforcing furnace (SRF) black. Intenco claims that a significant market exists for their black at 10¢/lb below the virgin carbon black price. The steel could be sold as scrap.

The utilities required for a 100-TPD standardized plant are estimated at 400 to 500 kW electricity (96 to 120 kWh/ton), 14,400-gpd makeup water (144 gal/ton), and diesel or natural gas for startup.

The tire cord and fiberglass would have to be disposed of in a suitable landfill if no market is established. The quantity of particulates in the form of carbon black dust to be disposed of is estimated to be less than 300lb/yr.

Fiat, Torino, Italy, recently contacted Intenco, Inc., in Houston, Texas, about licensing the Intenco pyrolysis process in order to build and operate a plant in Italy.[19] But the results of a market and design study of pyrolysis technologies influenced Fiat to abandon any plans to venture into tire pyrolysis.

13. **Nippon Oils and Fats Company, Ltd.** Nippon Oils and Fats Company, Ltd., Tokyo, Japan, conducted limited experiments on tire pyrolysis based on a low-temperature cracking process developed for tar sand, oil shale, and coal. Final designs were completed for a 26.5-TPD plant, but construction apparently was not begun. Shredded tires were to be conveyed by screw through a retort at 932°F heated externally by tubes fired with recycled product gas. The residence time of the tire fragments was to be 30 minutes to produce oil (yield, 49%), gas (yield, 10%), char (yield, 36%), and steel (yield, 5%). The oil had an unspecified sulfur content; otherwise, it was considered marketable as a fuel oil. Further distillation of the oil was expected to yield 10% naphtha. The unprocessed char was considered for addition to the heavy oil as a colloidal fuel. The char also could have been further pulverized, screened, and steamed to produce a rubber filler black. The steel wire was to be sold as scrap. Some research was conducted to optimize the screw design and speed to minimize the tire shredding requirements. However, the project was abandoned, apparently in part because others were selling general pyrolysis plants with comparable technology.

14. **Kutrieb Corporation.** Kutrieb Corporation, Chetek, Wisconsin, has sold a tire pyrolysis plant to Bergey's, Inc., Franconia, Pennsylvania.[22,23,24,25] The plant, which has a design capacity of 500 lb of

tires per hour (or 1,500 TPY), is presently in the startup mode. The process can accept whole tires in a batch mode with a targeted cycle time of 3 hr. To satisfy the Pennsylvania state regulations for scrap tire storage, the tires are cut in half circumferentially. The tires are loaded into the reactor chamber, the loading door is closed airtight, the reactor is purged with uncondensed gas from the condenser, and the reactor is heated to about 800°F by externally fired, multifuel burners. Recycled oil and gas from the pyrolysis process are burned simultaneously. The reactor operates with a slight vacuum of about 1 inch of water. The only oxygen present in the reactor is that which occupied the air space at the time of loading. Consequently, the pyrolysis reactions occur under reductive conditions.

The pyrolysis vapors are condensed in an air-cooled condenser for storage as fuel oil (yield, 35%), while the gas is compressed and then stored as fuel gas (yield, 20%). The oil has a sulfur content of about 1%, a water content of about 1.1%, an ash content of 0.01%, and a heating value of 17,000 to 18,000 Btu/lb. The gas has an estimated heating value of 0.127 gallon of oil equivalent per pound of gas, or about 1,033 Btu/scf.

After a cycle is complete, the solid residue is cooled down to 200°F and then pushed from the reactor by a ram. A pair of compression rollers breaks the char into smaller particles. Some bead steel (yield, 5%) and fabric are separated by a vibrating grate; smaller steel pieces then are separated magnetically and are available for sale as scrap. Much of the cord is not pyrolyzed and remains in the char. The results of independent testing of the char (yield, 38%) as a rubber filler indicate that the char particle size is larger than for commercial carbon black, giving a poor dispersion rating, and that the tensile strength and initial modulus are significantly reduced. The ash content is about 15%, the sulfur content is about 3.5%, and the heating value is 12,480 Btu/lb. The operator is presently pursuing methods of upgrading the char to improve its marketability.

The utility requirements are less than 4 kW of electricity, no cooling water, and 15% of the product oil and gas as process fuel. The net energy recovery for the process is estimated by the process developer to be about 80% assuming 500 lb of tires processed per hour, a char heat value of 14,309 Btu/lb, a stack heat recovery of 6.9 gal of oil equivalent, a gas heat value of 1,033 Btu/scf, an oil density of 7.5 lb/gal, and process yields of 35% oil, 20% gas, and 38% char. The actual analyses of the char produced by Bergey's, Inc., suggest that char heat value is only 12,500 Btu/lb, or about 13% lower than that assumed.

Kutrieb assumes that the oil and gas produced by their process as well as waste oil would be used as fuel in their multifuel burners to produce process heat, steam, or electricity. If all the oil and gas produced from 500 lb of tires per hour is used for steam and electrical generation, 125 kW could be generated. They claim that as many as six pyrolysis units could be ganged together and operated from two control centers. Such an arrangement could produce up to 750 kW of electricity and could be custom sized for a particular location.

Kutrieb has selected the batch mode rather than the continuous mode of operation for their process primarily because they believe the fire safety problems associated with a continuous supply of oxygen entering the reactor with the rubber feed and the potential escape of a low flash-point liquid with the continuous solids removal are minimized in their batch process.

Potential uses of the product char are expected by Kutrieb to include a fuel as a coal substitute and a filler black for off-road tires.

15. **Garb-Oil Corporation.** Garb-Oil Corporation, Salt Lake City, Utah, operated a 15-TPD plant for 6 months during 1981-82 in Mountlake Terrace, Washington. This plant now is being moved to Salt Lake City. Designs for two commercial plants, each with capacities of 112.5 tons of shredded tires per day, have been prepared for sites in Cleveland, Ohio, and in Scioto County, Ohio. Plans are being prepared for two plants to be built in California to generate 20 MW and 30 MW of electricity using the Garb-Oil technology.

The process is semicontinuous, semiautomated, external fired, direct pyrolysis at 1700 to 2000°F, inert atmosphere with shredded tires as feed. A unique claim for the system is the presence of eight modules which can be operated independently or simultaneously. The pyrolytic chamber is said to need only one gas seal. The reactor is purged before and after operation. The pyrolysis gas is controlled and directed to a condenser to separate the condensable vapors.

The product gas (yield 18%), which consists primarily of propane, methane, and butane with a heat value of 450 Btu/scf, is recycled for process heat. The steel (yield 6%) is sold for scrap. The char (yield 36%) contains 13% ash and 10% volatiles and supposedly has a market for use in any rubber product not requiring tensile strength. The oil (yield 40%) is distilled on site using process waste heat to produce naphtha, diesel fuel, distillate, paint solvent, and asphaltic oil. The oil heat value is 17,800 Btu/lb. Some of the oil is recycled as process fuel. Its sulfur content is less than 1%.

Information on a net energy analysis is available for this process. The estimated process heat required to effect the pyrolysis is 2,800 Btu/lb rubber. Assumptions made include: 439 Btu/lb to raise temperature of the rubber from 50 to 700°F to vaporize the hydrocarbons; 1,800 Btu/lb to activate the decomposition of carbon-carbon bonds; 560 Btu/lb is heat lost in firing the furnace, or 26% of the heat required in the above two steps. The energy outputs total 16,300 Btu/lb input rubber, based on the aforementioned yields and heat values of the products. The difference between the process heat required and energy outputs is the net energy gain of the process, or 13,500 Btu/lb, or 5,598,000 Btu/ton of net rubber weight without metal.

16. **Yokohama Rubber Company, Ltd.** The Yokohama Rubber Company, Ltd., Minato-ku, Tokyo, Japan, in 1973 constructed a prototype pyrolysis plant with a capacity of 2.2 TPD of shredded tires. The process was a dry distillation based on oil shale type technology. The produced oil and gas were recycled and burned internally in the reactor to produce oil (yield, 50 to 56%), char (yield, 30 to 35%), gas (yield, 960 to 1300 scf/ton of tires, with a heating value of 1125 Btu/ft^3), and steel. The reactor was operated at 932°F in the batch mode with a residence time of 3 hr. The char was recovered in a water-sealed basin to eliminate the need for a dust collector. The project was abandoned because of unfavorable economic conditions.

17. **Onahama Smelting & Refining Company, Ltd.** The Onahama Smelting & Refining Company, Ltd., Japan, initiated testing of a tire pyrolysis unit of capacity 1.3 TPH or 825 TPM in April 1981.[26] They had encountered several technical problems and low combustion efficiency with the direct combustion of shredded tires in their furnace, and so they tried pyrolyzing the tires. In Onahama's process, shredded tires are fed continuously into an air-tight, vertical retort heated to 750°F by direct contact with the combustion gas from the combustion of recycled char and gas from the pyrolyzed tires. Air required for combustion is introduced through nozzles located near the bottom of the retort. Particulates are separated from the pyrolysis vapors by a cyclone; the vapors are partially condensed; water is separated from the oil; the gas is recycled for combustion. At the bottom of the retort, the solid residue is recovered by a water-sealed conveyor.

The product yields, including the combustion gases, are: 21% oil, with a sulfur content up to 1.4% and a heating value of 14,200 Btu/lb; 51% gas, with more than 53% nitrogen, 10% carbon monoxide, 7% carbon dioxide, 5% methane, on the order of 1% hydrogen, ethane, propane, ethylene, and oxygen, and a low heating value of 225 to 340 Btu/scf; 13% char, with a heating value of 12,250 Btu/lb; 6.6% carbon particulates from the vapor cyclone, with a heating value of 12,800 Btu/lb; 1.3% water; and 6.6% steel.

Because successful results were obtained with the first unit, Onahama scheduled a second facility, with a capacity of 3.9 TPH, for startup in 1982. They are studying measures to market the carbon products to meet any future rise in the tire collection cost. At present, all the pyrolysis products are burned in their own reverberatory furnace to replace oil and grained coal.

18. **Firestone Tire & Rubber Company.** The Firestone Tire & Rubber Company, Akron, Ohio, and the U.S. Bureau of Mines Coal Research Center in Pittsburgh, Pennsylvania, entered into a cooperative research program in 1968 to study the pyrolysis of shredded scrap rubber using a bench-scale apparatus, and, subsequently, using a pilot system.[27-35] The pyrolysis reactor was an air-tight, cylindrical, steel retort heated externally in an electric furnace to 930 to 1650°F. The gas and vapors were passed through a series of condensers to separate the oils into crude fractions. An electrostatic precipitator separated particulates from the gas. Acid and caustic scrubbers removed basic and acidic components from the gas. The gas was then dried, a portion was analyzed, and the rest was flared.

A series of batch tests were run with about 100 lb of shredded passenger or truck tires, with or without the beads and fabric, at durations of 7 to 14 hr. Each test was discontinued when the evolution of gas no longer supported combustion at a waste gas burner.

The product yields and properties varied somewhat with temperature. At the lower temperature (930°F), less residue (40 to 44%) and gas (3 to 5%) were produced, with nearly 50% of the input rubber being converted to oils. At 1650°F, much less oil (20%) was produced and a much larger portion of the rubber was converted to gas (21%) and residue (52%). The oil aromatic content was significantly higher at 1650°F (85%) than that at 930°F (52%). The heating value of the gas at 1650°F (765 Btu/ft^3) was lower than that at 930°F (922 Btu/ft^3) because of the higher percentage of methane at the higher temperature. The moisture, volatile, ash, and sulfur percentages in the char were somewhat lower at the higher temperature, while the fixed carbon was higher. The char heating value was essentially unchanged at 13,500 Btu/lb. Reinforcing properties, as reflected in the moduli and tensile strength results, also appear to improve with increasing temperature.

Char blacks containing about 10% ash were chemically treated to reduce the ash content to about 4%, with the result that the reinforcing properties were improved. Tests also indicated that the ground char could be activated to some extent by one or two passes of steam treatment at 1800°F.

Some development work was done on the preparation of an acceptable hydro-carbon resin from the product oil, in order to improve the process economics. The presence of such resin-precursors as phenols, indexes, and alkylated styrenes is attractive for the formation of an acceptable resin. Preliminary results indicate that the thermoplastic nature of the resins should be decreased. Also, the staining properties need to be reduced or prevented.

Toxicity studies of the oil and char black were conducted. Based on short-term animal experiments, neither of the products was toxic orally. The oil did produce some skin redness; however, the material is not considered a skin irritant. Neither the oil nor char gave evidence of skin sensitization.

The reinforcing properties of the ground char black were tested in a styrene-butadiene rubber (SBR) and compared with GPF carbon black. The scorch time and cure rate were essentially equivalent. The char black moduli and tensile strength are slightly less. The ash content of the char apparently has little effect relative to changing aging characteristics. Dispersion rating and extrusion properties of the char black are comparable with the GPF.

The type of raw material used in the pyrolysis process does have an effect on the reinforcing properties of the char black. When tire treads are used as process input rather than whole tires, the char that results has slightly less scorch resistance, a faster rate to optimum cure, higher moduli, and higher tensile strength.

Another set of tests was conducted by Firestone to determine the effect of operating the process on a continuous basis instead of a batch basis. The product yields differ for the continuous basis in that the char yield decreases from 40 to 50% for the batch mode to 30 to 40%; the oil yield increases slightly from 20 to 50% for the batch mode to 30 to 50%; the gas yield increases from 5 to 20% for the batch mode to 10 to 20%.

Firestone presently is not interested in operating a commercial tire pyrolysis project, nor are they interested in any joint ventures into pyrolysis.[36] They are investigating the possibilities of licensing their process to upgrade char black to carbon black, for which they claim patentable rights.

19. **Oil-Tec.** In September 1977, Al-jon Company and Sigma Research Associates, Ottumwa, Iowa, set up a partnership to build and operate a 5,000-TPY tire pyrolysis plant, called Oil-Tec. Little is known about the current status or the process details of the project. Apparently, shredded tires were fed continuously into a vertical retort heated by combustion gases from burned tire fragments and the recycled gas product.

Products from the Oil-Tec process are: 51% oil, with a heating value of 18,500 Btu/lb and a sulfur content of 0.76%; 35% char, at 12,500 Btu/lb and with 15% ash, 2.25% sulfur, 28% volatiles, and 0.7% water; 9% gas; and 1.5% steel.

20. **Bergbauforschung.** Bergbauforschung GmbH, West Germany, performed experimental work from 1973 to 1976 on a batch, external-fires, chamber-furnace pyrolysis process with a capacity of 65 to 110 lb/hr of whole tires together with coal. The reaction temperature and residence time were 1470 to 1830°F and 1 to 2 hr, respectively. The product yields were: 35% coke, 5% oil,

30% tar, 20% gas, and 10% steel. The project was abandoned because the coke product was too low in quality compared with the coke produced from coal alone.

21. **DRP.** Deutsche-Reifen-und-Kunststoff-Pyrolyse (DRP) GmbH, West Germany, has a fluidized-bed reactor tire pyrolysis plant under construction at Ebenhausen.[37-42] Two identical, fluidized-bed reactors, each with a capacity of 5,510 TPY of whole tires or plastic waste will give a total plant throughput of 7,716 TPY. Test runs are to start in 1983. The process has been under development at the University of Hamburg since 1970, with successive stages of scale-up at 0.22, 22, and 220 lb/hr.

The pyrolysis zone, a fluidized sand bed or a char black bed is indirectly heated up to 1200 to 1560°F by seven radiating fire tubes, arranged in two layers. One part of the product gas is used to fluidize the bed; the other is burned to heat the process. The whole tires roll through an air lock into the reactor, where they heat up, soften, and gradually sink into the sand. The reduced free cross-section of the bed causes abrasion of small particles and their subsequent decomposition, with a residence time of 2 to 3 minutes. Steel wire is removed by a tiltable grate extended into the fluidized bed.

The products together with the fluidizing gas leave the reactor via a cyclone, where dry char and filler materials are separated. The hot gases are cooled to room temperature by an oil scrubber and then refined in a washer and rectification unit. The noncondensable gas (yield 22% at 1330°F) is mostly methane, ethane, ethylene, propylene, carbon monoxide, carbon dioxide, and hydrogen. Its heat value is about 1200 Btu/ft^3, slightly higher than natural gas.

The oil (yield 27%, sulfur 0.4%) contains the following recoverable products by weight percent: naphtha, 2.7; benzene, 10.8; toluene, 8.6; C_8 aromatics, 15.6; resins, 6.8; naphthalene, 1.3; carbon black oil and technical oil, 36.7; pitch, 17.5. The steel (yield 12%) is sold as scrap.

The char (yield 39%, ash 13%, volatiles 3.6%) is produced in three grades: "coarse soot" 16%, "coarse carbon black" 20%, and "fine carbon black" 4% (<40 μm). Tests with the fine black indicate that it is similar to medium active carbon black types N550 and N660 [comparable with general purpose furnace (GPF) carbon black]; however, it has a much higher ash and volatile content. The volatiles were removed by slight heating before the fine black was mixed in a SBR formulation. The hardness, moduli, and tensile strength were comparable with the N550 black, while the aging characteristics were only slightly more unfavorable. Apparently, the sand and grit were removed successfully during the air separation because the SBR had smooth surfaces. Tests of the suitability of the fine black as color pigments in lacquers were performed with the result that it was suitable for use in primers and as a tinting pigment for grey shades. However, it was not suitable for deep black pure pigment lacquers because of its low blackness.

The significant advantage of the fluidized-bed reactor system is that the temperature gradients within the bed are usually small compared with a rotary kiln. The process parameters, therefore, are more easily controlled at a constant level. Significant disadvantages are the problems of separating char black and sand from the liquid and separating the steel from the bed.

This process apparently is the most favored now in West Germany, since the other West German projects are either switching to household garbage as input or are waiting to see what success DRP has with their present project. More information on the process supposedly will be available after startup in 1983.

22. **Kansas State University.** Kansas State University[43] has conducted pilot plant experiments to examine the feasibility of producing a good quality gas from shredded tires by fluidized bed gasification. The effect of reactor operating temperature on gas composition and product yields was also studied.

Shredded tire particles free of belts and cords were fed continuously by a screw feeder with a slightly pressurized helium atmosphere into the top of the reactor. The fluidizing medium was silica sand. Combustion of propane with substoichiometric air in a burner in the reactor plenum generated a portion of the fluidization gas. Water was injected into the plenum to maintain the temperature below 1790°F and to provide additional fluidization gas. Supplemental heat was supplied by firing natural gas in a radiant jacket surrounding the reactor. Entrained char particles in the offgas were removed in a cyclone. A Venturi scrubber then quenched the offgas and removed condensables. The noncondensable gas was flared. The char remaining in the reactor was sampled and then burned with excess air.

Runs were made with varying feed rates at temperatures of 1155°F to 1450°F. Mass balance closures at the lower temperatures were about 75%. The low closure was ascribed to the fact that not all the product tar could be collected. The gas yield increased linearly with temperature from 20 to 52% over the range of temperature studied. Components in the gas included: hydrogen, carbon monoxide, carbon dioxide, methane, ethylene, ethane, propylene, propane, hydrogen sulfide, nitrogen, and oxygen. The concentration of hydrogen increased with increasing temperature from 25 to 44 vol%. Carbon monoxide and carbon dioxide concentrations increased moderately with increasing temperature. The hydrocarbon concentrations decreased with increasing temperature. The gas concentration changes were approximately linear. The gas heating value decreased linearly with temperature from 1062 to 600 Btu/scf.

The fraction of the feed energy content that was converted to gas increased linearly with temperature from 20 to 40%.

The liquid yield varied between 51 and 17% and the char yield ranged between 25 and 29%. Compositions and properties of the liquid and the char were not reported.

The gas yields were compared with those reported for the Occidental entrained-bed process,[44] the Tosco retort process,[7] and the DRP fluidized-bed process,[45] and it was found that those obtained from Kansas State University were higher.

23. **Occidental Research Corp.** Occidental Research Corp., LaVerne, California, developed an entrained-bed tire pyrolysis process, known as the Occidental Flash Pyrolysis Process, in 1975.[44,46] Pilot plant experiments were done over a wide range of temperatures, 700 to 1600°F, and the economics of a 100,000-TPY (300-TPD) plant were estimated. This particular plant capacity was cited as being the optimum for the U.S. as of 1971 by a study prepared for the Rubber Manufacturers' Association.[44]

The experimental work was performed in a U-shaped, electrically heated, continuously fed reactor. The rubber fragments, ground to a 12 to 16 mesh size, were conveyed through the reactor by nitrogen. The char was collected by a series of cyclones. Liquid product was condensed, and the gas was sampled and analyzed.

The product yields as a function of temperature and feed type are as follows:

Temperature (°F)	Feed Type	Yield (wt%) Char	Oil	Gas	Loss
1000	Tread	41	40.3	14.5	4.2
1000	Ground tire buff	50	30.8	19.2	N/A
1200	Tread	35.1	33.7	30.9	0.3
1200	Ground whole tire	34.3	38.5	22.9	4.3
1600	Ground tire buff	36.3	1.0	62.7	N/A

As expected, the oil yield decreases with increasing temperature, whereas the gas yield increases.

The char black produced at 1200°F was compared with GPF and ISAF (intermediate superabrasion furnace black) in rubber compounding tests. In tests of different rubber formulations using the char and containing different concentrations of zinc and sulfur, performance did not vary significantly. The char produced slower curing times than did GPF, however, and insufficient reinforcement. Char without fiber (tread rubber) had better reinforcing strength than char with fiber (whole tire rubber).

The char black produced at 1400°F compared well with the ISAF black, due in part to the small particle size (the average char particle diameter was less than 0.1 micron).

Tests showed that the product oils performed well as plasticizers. The oil heating values were found to be 17,000 to 18,000 Btu/lb. Their sulfur content was about 1%.

The dry product gas consisted primarily of pentene, butene, ethylene, methane, and hydrogen. Hydrogen sulfide was not detected. Because of the high concentration of pentene and butene, the heating value was 2100 Btu/ft^3.

A conceptual process design was produced. The feed preparation consists of the following operations: sorting and debeading tires, primary shredding to 3-in. size, secondary shredding to 1-in. size, magnetic separation, fine grinding to 24 mesh, drying, and preheating. The entrained-bed reactor operates at low pressure in the absence of air. Recycled product gas would supply process heat. Rapid heating and short residence times are claimed to minimize the product cracking. Char is separated by cyclones and electrostatic precipitators. A quench tower separates the product oil from the gas. Flue gas is scrubbed and vented.

The technology was proven feasible by the experimentation. No efforts were made to optimize the char black quality, which could possibly be improved. Reduction of grinding costs was considered to be an important item to make this process more attractive. The project apparently was abandoned.

24. **Tyrolysis, Ltd.** Tyrolysis, Ltd., a consortium of Foster Wheeler, Ltd., Leigh Investments, Ltd., Industrial and Commercial Finance Corporation, and a group of unnamed stockbrokers, bankers, and insurance companies, is planning to begin construction of a 55,100-TPY tire pyrolysis plant at Four Ashes in South Staffordshire in England. Funding for the plant is supported in part by the U.K. government and the European Economic Community (EEC).[47,48] Startup is scheduled for the end of 1983. This appears to be the only active tire pyrolysis project in the United Kingdom. Batchelor Robinson Metals and Chemicals, Ltd., partially funded a study of tire pyrolysis in 1974 at a U.K. government laboratory. A 6-TPD pilot plant using a vertical-flow reactor system was built. Batchelor Robinson withdrew from the project, and Foster Wheeler, which had purchased a license for a cross-flow reactor system originally designed for general waste pyrolysis, proceeded with development of a process that became a hybridization of the two systems. The Tyrolysis consortium was then formed, and plans were made for the commercial tire pyrolysis plant that is now under construction.

Tires up to 5.75 ft diameter that have been shredded to a nominal 8-in. maximum size enter the top of the pyrolysis reactor through a purged triple-valve, double-chamber sealing system. Preheated, oxygen-free gas enters the base of the reactor, flows upward counter-currently at 1 to 3 ft/sec through the descending tire fragments. The gas and vapor exit at the top of the reactor. The oil is condensed by direct contact in a line quench with a spray of cold product oil. The condensed oil and the sprayed oil are drawn from the base of the quench tower in which the gas is separated. The oil is filtered; the net product oil goes to a stripping tower, then to further filtering, cooling, and finally to storage. The remainder of the oil is circulated to a cooler and back into the line quench. Provision has been made to withdraw lighter fractions of oil from the quench tower as side streams. Overhead gas from the quench tower is cooled to condense water and light hydrocarbons. The condensed lights are either recycled to the quench tower as reflux or pumped to storage. The water is decanted, stripped, and pumped to waste disposal. Gas from the decanter is either flared, recycled as fuel for the gas heater, or passed through the heater and then to the reactor. Large, inclined screws remove the solid residue from the reactor. The residue is cooled and then passed through a triple-valve, lock-hopper system to a magnetic separator. Steel is separated and baled as scrap. Steam is used as a conveying medium to classify the char. The char then is cooled to a temperature just above the dew point by a water spray. The char is separated by a cyclone and bag filters, cooled further, and stored.

The product yields are: a light fuel oil, 45% yield, similar to U.S. No. 4 fuel oil, with 1.2% sulfur and 0.1% ash; char, 39% yield, with 5 to 10% volatiles, 20% ash maximum, 3% sulfur maximum, 11,500 to 13,500 Btu/lb, and 5% zinc; steel, 16% yield. The gas yield is not available, although it could be calculated by difference by assuming no mass loss. With this assumption, the respective yields then would be: oil, 40%; char, 35%; gas, 11%; and steel, 14%.

The char quality has not been satisfactory, and therefore, the char is expected to be used as a coal substitute. Apparently, upgrading of the char to carbon black has been specifically avoided in the U.K. because of excess production capacity for carbon black. The merit of recycling tires to produce a fuel that competes with the considerable coal surpluses in the U.K. has also been questioned.

Information on the expected gas and oil yields for the Tyrolysis process as a function of the reaction temperature for a 3-s residence time indicates that the maximum oil yield of 44.8% (expressed as the weight percent of the dry tire with steel) occurs at 840°F. The corresponding gas yield is about 2%. Gas yield monotonically increases with temperature within the range 900 to 1500°F, and a yield of 15% occurs at 1110°F. The corresponding oil yield is about 38%.

The process requires 1.5 MW power source. A significant proportion of the electricity is used in the shredding process. About 0.5 TPH of sour process water will be discharged. The energy recovery is claimed to be 82% of the available energy in the tires.

William Port & Son, Inc., Geneva, New York,[49] has reviewed most of the available tire pyrolysis technologies and has selected the Foster Wheeler process (see Tyrolysis, Ltd., for the process analysis) for a plant at Geneva, New York. William Port & Son has secured a letter of intent to license from Foster Wheeler, U.K. The process will be adapted to upgrade the char instead of using it as a coal substitute, as Tyrolysis is planning to do. At this time, William Port & Son, Inc., is looking for startup money in the amount of $450,000.

25. **Uniroyal Chemicals, Ltd.** Uniroyal Chemicals, Ltd., Manchester, England, began studies in tire pyrolysis in 1976 when they took over the Rubber Regenerating Company, which operated a rubber reclaiming plant. They were interested in a process (cross-flow pyrolysis) based on the work done by Foster Wheeler and the NRDC. A pilot plant existed at the John Brown Boiler Plant in Hartlepool, but the information available does not clearly identify the operators of that plant. Uniroyal apparently did propose a plant that would produce 50% fuel oil (highly aromatic, about 18,000 Btu/lb), 40% char, and 10% gas, used to fuel the process.

The economics seemed favorable only if the char could be upgraded to carbon black. Uniroyal felt that the value of the products was ultimately related only to their calorific value, and that this simply was not high enough to make any such plant viable. Direct combustion of the tires was considered to be better than pyrolysis. The cost of obtaining tires also was a detriment to the plant economics. After detailed study, the company concluded that the project was not worth pursuing, and they decided to drop it in 1979.

26. **HRI.** Hydrocarbon Research, Inc. (HRI), Trenton, New Jersey, now a division of Dynalectron, Inc., investigated the technical and economic feasibility of the hydrogenating ground waste tire feed.[50-53] The waste rubber was reacted with hydrogen with and without catalysts in an ebullated bed reactor to produce gas, oil, and solids. The technology, called the H-Rubber process, was similar to HRI's processing of coal and petroleum residual feedstocks. Experiments were conducted initially in a 1-liter, magnetically stirred, batch autoclave. Continuous pilot-plant runs then were made using a 400-ml ebullated bed reactor. The research was abandoned in 1977 after a preliminary design of a commercial plant to convert 1,000 TPD was prepared and estimated to cost $9.5 million.

The ebullated bed hydrogenation process was considered the best pyrolysis technique because it was thought that:

- The carbon would not react with hydrogen.
- The rubber would easily convert to low-boiling hydrocarbons as a result of hydrogenation and cracking reactions.
- The extender oil could be recovered for potential reuse.
- The inorganics would not react or change.

The stirred batch autoclave experiments were conducted to determine the optimum range of operating conditions for the H-Rubber process. Ground tires and hydrogen were reacted under high pressure in the presence of a particulate hydrodesulfurization catalyst and a hydrocarbon slurry oil. The levels of the variables investigated ranged as follows:

Temperature	460 to 850°F
Pressure	500 to 2000 psig
Catalysts	None, cobalt molybdate on alumina, nickel molybdate on alumina
Time at temperature	0 to 6 hours
Slurry oils	None, anthracene oil, hydrogenated anthracene oil, tetralin

When the reaction was complete, the gas was vented, measured, and analyzed. The reactor mixture was screened to separate the catalyst and filtered to separate the char. Analysis of the char indicated that its structure was independent of any variables studied. A temperature between 460°F and 660°F was necessary to "spring" the carbon from the rubber. Increasing the temperature increased the relative gas production. A blank run without rubber but with slurry oil showed that one-third of the gas came from the slurry oil at 750°F. In a run with nitrogen instead of hydrogen, a large proportion of the oxygen (presumably in the form of zinc oxide and titanium dioxide) in the rubber was converted to CO and CO_2.

The continuous pilot-plant experiments were made with and without catalysts, at 850°F, at 1000 psig hydrogen pressure, and at a hydrogen flow rate of 34,000 scf/ton rubber (of which 3,560 scf were consumed). The waste rubber was shredded, ground to 24 mesh, separated from the steel magnetically, mixed with the hydro-carbon slurry oil, and added to a charge pot. At the top of the preheater, the rubber-oil slurry, the preheated hydrogen feed, and the internal recycle oil stream from the reactor mixed together and flowed down the preheater counter-currently to the up-flowing hydrogen. The mixture flowed from the bottom of the preheater into the bottom of the reactor. At the reactor top, the major portion of the liquid (internal recycle) was returned to the preheater top. The remainder of the reactor effluent was sent to a 500°F, high-pressure separator. The over-head gas from the separator flowed into an ambient temperature, high-pressure flash, again separating into vent gas and a liquid. That liquid was again flashed at atmospheric pressure. The liquid-solid product from the hot separator was flashed to atmospheric pressure to produce another gas and a slurry. The slurry was filtered, benzene-extracted to remove the remaining oil, and then dried. The liquid filtrate was recycled as slurry oil.

Sustained operation could not be achieved with catalysts and ground tire rubber containing fibers because of sudden reactor pressure drops. Tread peelings were run successfully with catalysts and produced higher quality char black than that from ground tires. A 1-week demonstration run with no catalyst and ground tire rubber was successful. The product yields from that run were: gas (4.4%), oil (59.5%), and solids (37%).

The 200 to 350°F naphtha fraction from the noncatalytic run had 35% aromatics, 32% naphthalenes, 12% paraffins, and 22% dicycloparaffins. Toluene and xylene were the predominant aromatics.

The major product quality difference between the catalytic and the noncatalytic runs was the sulfur content of the gas-oil product. In the noncatalytic operation, this value was in the 0.5 to 0.7% range while, with catalyst, it was generally less than 800 ppm. The naphtha fraction from both operations had nearly the same sulfur content. Apparently this material enters the vapor phase before the catalyst has an effect on it. In fact, the predominant effect of the catalyst appears to be removal of sulfur as hydrogen sulfide.

The char black had an ash content of 16 to 18% and a volatile content of 1.5 to 2.7%. Tests of the char in several types of rubber compounds were compared with commercial blacks. The results were variable, but the char was considered useful as a blend with, or replacement for, FEF, SRF, HMF, and GPF blacks. The char-oil separation procedure apparently had an adverse effect on the char tests. The benzene extraction produced char that had poor dispersibility. No differences were noted in the gross properties of the char produced by catalytic and noncatalytic hydrogenation.

27. **Institut Francais du Petrole.** The Institut Francais du Petrole (The French Institute of Petroleum)[54] has developed a pyrolysis process—originally investigated by the University of Compiegne—in which whole tires are treated with heavy hydrocarbons that transfer heat directly at 700°F and dissolve the oligomers resulting from devulcanization and depolymerization. The first phase of the work, completed in 1979, used a pilot plant operated in a batch mode in an inert atmosphere with a capacity of a few car tires. The results demonstrated the feasibility of treating whole tires.

The second phase started early in 1982 in a large pilot plant suitable for scaling-up studies, with a capacity of 220 to 660 lb of tires. About 160 gal of the hydrocarbon contacting oil—about three times the quantity of rubber by weight—is heated electrically, recirculated in a main loop, and sprinkled into the air-tight vessel, making direct contact with the tires by trickling. The reasons for sprinkling the contact oil onto the tires is that much less liquid than would be needed for total immersion is required to dissolve the tire decomposition products. The contacting oil, which can be waste oil, typically produces no more than 10% vapor fraction by weight when distilled. Heating of the oil is stopped as soon as the rubber has depolymerized at 700°F.

The offgas is cooled in an air-cooled heat exchanger to condense the vapors. Some of this condensate is used in diluting the bulk liquid phase in the main loop to control its viscosity and pour point for subsequent use as a fuel oil. The remainder of the condensate is separated from water, becoming a gasoline (or naphtha) with contents of about 50% olefins, less than 1 wt% sulfur, 500 to 1000 ppm nitrogen, and a distillation end point of about 380°F. The gas product contains predominantly alkanes through pentane, alkenes through pentene, with hydrogen sulfide, water, carbon dioxide, and carbon monoxide. The gas and gasoline could be recycled to provide process heat for an industrial-scale plant.

The bulk oil that remains in the reactor loop contains the nonvolatile tire degradation products along with most of the original contacting oil and the recycled distillate. The properties of this oil will depend significantly on the contacting oil composition. The char from the tires remains in suspension in the oil; no decantation of the char has been observed. The oil has been burned with success in a boiler without noticeable effects on stack effluent. The sulfur content of the oil is about 4 wt% due in part to the 4 to 5% sulfur content of the contacting oil used. The suspended carbon contributes to a rather high oil specific gravity in the 1.0 to 1.025 range. The zinc content was about 0.3 to 0.4%.

The developers claim that since the process operates at a lower temperature than other pyrolysis processes, the products do not suffer as much thermal degradation and, thus, are potentially of a higher value, although no product heat values are available. However, the high sulfur content and the suspended carbon would tend to adversely affect the oil's marketability as fuel. A serious disadvantage could be the large storage volume required for the contacting oil—on the order of three times the weight of the tires to be processed during a given period. The plant site would have to be chosen either near liquid oil storage facilities or near the lowest price scrap tire resource. The batch mode of operation could possibly be improved by using two reactors timed so that one heater and one set of separation equipment would be used twice a shift. The technical problems apparently have been overcome in the pilot plant operation, but there are no plans to build a commercial plant.

No information concerning continuous operation of this process is given. However, several variations are possible, including a conveyor-type process (similar to a plug flow reactor with recycle) or a continuous stirred tank reactor. This process has a high residence time for the evolved decomposition products, a feature thought to be disadvantageous. Also unmentioned, but of concern, are processes for separating the carbon black from the contacting oil.

28. **University of Aston.** The University of Aston, Birmingham, England, started work on pyrolysis about 1976. The process was based on the use of molten salts as the pyrolysis medium. Dunlop sponsored some development work and obtained a patent, but they decided to proceed no further because of a general shortage of capital. Bench-scale experiments were conducted, but a pilot plant was not built. A feasibility study for a 11,000-TPY commercial plant accepting whole tires on a continuous basis was performed.

The process engineering is difficult because the molten inorganic salts are corrosive and require special handling. The advantages of using molten salts are:

- They are nonvolatile, permitting higher reaction temperatures
- They have high heat capacities
- Whole tires can be fed to the process
- Inorganic substances remain in the melt.

The process is claimed to be economic at a much smaller size than the Foster Wheeler process.

The products of the process are: 26 to 33% oil, highly aromatic, with hydrocarbons in the C_6-C_{17} range; 7 to 18% gas, with twice the heat value of natural gas, which could be recycled as process fuel; 30 to 40% char, which could be used as a fuel at natural gas value; and 14 to 17% steel, which would be sold as scrap. The University has talked to other organizations about funding, but no firm plans exist to continue the pyrolysis research.

29. **Plasma Research, Inc.** Plasma Research, Inc., Kingston, Ontario, has conducted laboratory-scale tests of an electrically sustained, transferred arc plasma process to pyrolyze various organic materials, including tires. A dc transfer R-type torch using an electrical source of up to 350 kW has been tested. Commercial equipment designs are available that would use several torches in an air-tight vertical-shaft furnace to pyrolyze up to 5 TPH of unprocessed tires, but the project has been abandoned for lack of financial support. Fuel gas and

char production and quality apparently can be shifted by injecting water into the process while controlling the temperature and collection techniques. Currently, the process technology is being used to dispose of toxic wastes.

The products from this process are: gas (primarily hydrogen and carbon monoxide), char, and iron slag; no oil is formed. The developer claims that no additional processing should be required if the system is correctly operated although information concerning product quality is not known.

30. **Osaka Industrial Laboratory.** The Osaka Industrial Laboratory of MITI, Japan, conducted laboratory tests of a microwave tire pyrolysis process in 1972. The project has been abandoned because of many unsolved scale-up problems such as the high magnetron cost and because of the uncertain marketability of the product gas. The process involved heating a 5- to 10-g tire fragment in a domestic microwave range with 2,450 MHz frequency and 500 to 1100 watts power in a nitrogen atmosphere for a residence time of 0.5 to 8 minutes.

The product gas and vapor were cooled in a dry ice and methanol bath to condense the vapors. The gas (yield up to 45%) consisted of methane, ethylene, propylene, propane, nitrogen, and hydrogen, with no trace of hydrogen sulfide. The liquid (yield up to 22%) consisted of C_4 to C_6 aliphatic hydrocarbons, benzene, toluene, ethyl benzene, styrene, xylene, and sulfurous compounds, but no trace of isoprene or pentane. The char (yield, 42 to 44%) contained about 2% sulfurous compounds. The steel wire turned white hot but apparently had only a slight affect on the process.

Other tests were conducted to verify the effectiveness of water addition. The water becomes superheated vapor in the early stage of pyrolysis and, thus, expels the air from the container, eliminating the need for nitrogen introduction into the system. The water, introduced at about 23% by weight of the rubber sample, reduced the measured residue yield by 5 to 30%. The complete distribution of products with water injection is not known.

31. **USSR.** The All-Union Scientific Research Institute of Petrochemical Processes,[55] USSR, has studied tire pyrolysis in laboratory and pilot-plant units to determine whether pyrolysis tars would meet liquid fuel standard requirements. The process involved heating the tires without air in a batch mode until gas evolution ceased. The resulting tar was highly unsaturated, with a 0.7% sulfur content and a heating value of about 17,700 Btu/lb. The flash point was too low for standard boiler fuel, indicating that the light fraction would have to be removed. The conclusion from the study was that no more than 60% of the tar could be used independently as boiler fuel.

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