CalRecovery Report No. 1364

Final Report

Environmental Factors of Waste Tire Pyrolysis, Gasification, and Liquefaction

California Integrated Waste Management Board

July 1995

Submitted to:

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ACKNOWLEDGEMENT

This report is based upon work performed pursuant to a contract with the California Integrated Waste Management Board. The contract number and dollar amount are as follows: IWM-C2050; $69,627.

DISCLAIMER

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SECTION 1. INTRODUCTION

General

In the United States, each resident discards approximately one waste tire annually [1-1]. Discard of tires resulted in approximately 242 million waste tires nationwide in 1990, exclusive of retreads [1-1]. In California, approximately 28.5 million waste tires were discarded in 1993 [1-2]. Using an average weight of 20 pound/tire[1] (lb/tire), approximately 285,000 tons of waste tires were discarded in California. Waste tires are a minor portion of the California solid waste stream, but represent a major disposal problem. While California is home to a waste tire incinerator, most tires are disposed in landfills or in tire storage piles. Incineration may not "maximize the potential economic recovery of energy and chemical materials" [1-3]. California law requires that tires be shredded prior to disposal in landfills.

Pyrolysis, gasification, and liquefaction (PGL)[2] are three related technologies that could potentially recover usable resources (i.e., energy, chemical feedstocks, steel, and fiber) from waste tires. Tire PGL would also reduce the volume of residue material remaining for disposal; thus, the California Integrated Waste Management Board (CIWMB) wished to study tire PGL as a waste tire management strategy. This report serves as background for assessing PGL in terms of the environmental consequences of the technologies.

Based on an average heating value of 15,000 Btu/pound[1] (Btu/lb), disposed tires represented approximately 8.6 x 10^{12} Btu in California in 1993. This annual energy potential could meet the annual electricity needs of a typical community of 60,000 to 85,000 homes.

Whole waste tires are difficult to dispose in landfills; they tend to collect gas, harbor rodents, and move upward in the landfill over time, as other wastes consolidate and subside. Nonetheless, landfilling, stockpiling, or illegal disposal accounted for 78 percent of waste tire management nationwide in 1990. One in twenty waste tires, i.e., 5 percent, were exported. Recovery for new products or energy production accounted for the remaining 17 percent [1-1].

By January 1991, 23 states including California had enacted environmental legislation addressing waste tire disposal; thirteen other states had adopted regulations dealing with waste tires [1-1].

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1 This value is used for conversions throughout this report.

2 The notation PGL is used throughout this report to indicate simple pyrolysis as well as the more complex processes: gasification and liquefaction.

In 1990, U.S. manufacturers shipped approximately 260.5 million tires. Appendix Table A-1 reports tire production nationwide and in California since 1980. Approximately 81 percent of tires shipped by manufacturers are passenger tires. Bus and truck tires (approximately 5 times the weight of passenger tires) comprise about 18 percent of the tire market. The remainder of the market (about 1 percent) is farm equipment tires.

Figure 1-1 illustrates the typical composition of modern tires. In the United States, tire manufacturing consumes more than half the rubber used nationwide, but new tires contain only approximately 2 percent by weight recycled rubber [1-1].

Because tire disposal involves a waste substream that is generally homogeneous[3] and contains resources, used tire recovery for beneficial reuse is desirable. Pyrolysis, liquefaction, and gasification are potential disposal/recovery technologies that have been applied, or considered for application, to different wastes[4] with varied success. Of these three technologies, pyrolysis is the most common. Entrepreneurs and major firms, including Goodyear, Firestone, Occidental, Uniroyal, Nippon, Foster-Wheeler [1-7], Union Carbide, and Texaco, have invested an estimated $100 million in waste PGL projects.

In terms of the scale of the tire PGL industry, an industry consultant estimated that approximately 1,000,000 tire/year were disposed in 1992 in the United States by PGL [1-8]. Tire PGL systems may process two million tires annually by 1995 and three million tires annually by 1998 [1-8]. Currently, seven commercial-scale pyrolysis or gasification facilities are now operating in the United States, and approximately 130 PGL systems are reportedly operating worldwide. There are two reported tire PGL demonstration[5] projects in California.[6] These two projects may dispose approximately 111,600 tire/year,[7] or an estimated 1,116 tons/year.

Although offering the prospect of substantial financial returns, PGL projects have failed because of a range of reasons [1-7], including:

- operating problems,
- unsafe and dangerous conditions,
- lack of an adequate supply of suitable feedstock,

3 Tires can be separately collected with relative ease.
4 Municipal solid wastes (MSW), sewage sludge, tires, medical wastes, petroleum, and deinking sludges.
5 As defined in Section 2.
6 Homestead Minerals, in Citrus Heights, California; and Texaco, in Montebello, California.
7 Calculated based on the ratio of California disposal to nationwide disposal.

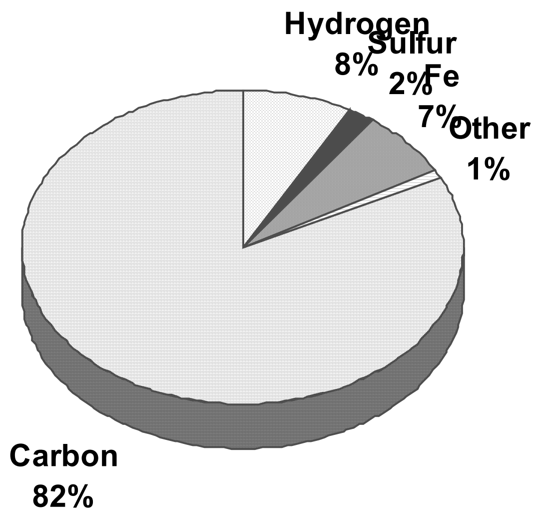

Figure 1-1. Typical Composition of Shredded Domestic Tires

Source: [1-6], and estimates by CalRecovery based on survey information.

- poor product quality,
- lack of adequate environmental controls, and
- high costs.

In its 1991 report on scrap tire markets, the U.S. Environmental Protection Agency (EPA) concluded that no PGL unit had shown sustained commercial operation [1-9]. As a result, the EPA excluded tire pyrolysis as a feasible or potentially feasible market for waste tires [1-9].

This study assesses the current state of the art of waste tire disposal using pyrolysis, gasification, and liquefaction. The report provides technical, environmental, economic, and market information, and includes conclusions and recommendations for future activities.

Technologies

Pyrolysis involves heating organic materials without oxygen to break them down to simpler organic compounds. When organic wastes (e.g., waste tires) are the feedstock, products of the process include char or carbon char, oil, and gas. For example, pyrolysis can convert wood to charcoal and a low-Btu gas.

Gasification of organics occurs at operating conditions between the complete absence of oxygen and stoichiometric (i.e., sufficient oxygen to complete the oxidation reaction). Gasification involves drying and pyrolyzing a feedstock, and oxidizing the solid char to heat the reaction and provide carbon monoxide (CO) to the gas. In the early 1980s, the waste industry saw gasification as promising. Gasification processes maximized the effect of carbon-hydrogen ratios. Furthermore, the product gas was suitable for use in existing boilers [1-10].

Liquefaction is the thermochemical conversion of an organic solid into a petroleum-like liquid. Liquefaction typically involves the production of a liquid composed of heavy molecular compounds from a pyrolytic gas stream. The liquid has properties similar, but not identical, to those of petroleum-based fuels. Essentially, liquefaction is manipulation of the pyrolysis process in order to produce a liquid with characteristics similar to petroleum-based liquids (e.g., fuel oils).

Methods of Analysis

To obtain current information on tire PGL, CalRecovery undertook a comprehensive literature review. We conducted a survey[8] of the known domestic and many international tire PGL operations. Where adequate data were available to draw valid statistical conclusions, the analyses were completed, and this study presents the results. Where quantitative data were sparse or nonexistent, we present qualitative results.

Analyses and interpretation of the environmental and regulatory matters related to PGL processes were made based on the results of the literature review and of the surveys, and after a review of applicable federal and California statutes and regulations, and communications with federal and California regulatory personnel.

Organization of the Report

Following this brief introductory section, Section 2 presents a review of the status of the technologies. Section 3 discusses the preprocessing requirements of tire PGL systems, and the use of additional feedstocks in systems. Section 4 summarizes the operating data for tire PGL projects. Next, Section 5 summarizes environmental impacts of tire PGL. Section 6 discusses the uses of products of PGL systems. In Section 7, the sensitivity of project economics to project variables is discussed. Section 8 presents our conclusions and recommendations related to tire PGL. Finally, appendices are included that contain supporting data.

References

[1-1] United States Environmental Protection Agency, Solid Waste and Emergency Response (OS-301), *Markets for Scrap Tires*, September 1991, EPA/530-SW-90-074B, pp. 15-36.

[1-2] California Integrated Waste Management Board, 1993 Annual Report, Appendix E.

[1-3] Williams, Paul T., S. Besler, and D.T. Taylor, "The Fuel Properties of Pyrolytic Oil Derived From The Batch Pyrolysis of Tyre Waste," *Waste: Handling, Processing and Recycling*; The Institution of Mechanical Engineers, 27 April 1993, pp. 21-30.

8 Telephone interviews and written survey forms. More than 40 telephone contacts with developers were completed successfully.

[1-4] United States Department of Commerce, Economics and Statistics Administration, Bureau of the Census, *Statistical Abstract of the United States 1993*, 113th Edition, Washington, DC, Government Printing Office, 1993, p. 618.

[1-5] California Integrated Waste Management Board, *Market Status Report Tires*, July 17, 1993, 118 p.

[1-6] CalRecovery, Inc., *Handbook of Solid Waste Properties*, New York, Government Advisory Associates, Inc., 1993, pp. 2-19.

[1-7] Pilorusso Research Associates, Inc.; VHB Research and Consulting, Inc.; and T. A. G. Resource Recovery, *Scrap Tire Management in Ontario*, prepared for the Waste Management Branch, Ontario Ministry of the Environment, January 1991, ISBN 0-7729-7830-1, pp. 38-39.

[1-8] Kearney, A.T., Scrap Tire Management Council, *Scrap Tire Use/Disposal Study - 1992 Update*, October 1992, pp. 2-76 - 2-79.

[1-9] United States Environmental Protection Agency, Solid Waste and Emergency Response (OS-301), *Markets for Scrap Tires*, September 1991, EPA/530-SW-90-074B, pp. 8-12.

[1-10] Grayson, Martin and David Eckroth, Ed., *Kirk-Othmer Encyclopedia of Chemical Technology* (New York, John Wiley & Sons, Inc., Third Edition ,1982), Vol 11, pp 406-408.

SECTION 2. CURRENT STATUS

The Tire PGL Industry

The tire PGL industry consists of companies that currently offer the turnkey[1] construction of systems, manufacture process equipment, or offer related services. In the United States alone, about 34 firms in 24 states are developing or marketing tire PGL systems [2-1]. In addition, several European universities are conducting research into PGL technology. Some facilities process waste tires exclusively while others handle a wide range of organic feedstocks.

Classification of waste tire PGL projects based on size and operational status is presented in Table 2-1. Tables and text throughout this report classify projects in planning or design stages as conceptual. It is important to distinguish between the experimental projects designed to test theories and developmental or commercial projects. Developers were asked to classify their projects as conceptual, laboratory, demonstration, or full size. Review of operational status permits the differentiation of projects that have been shut down from those that are operational. For the purpose of this study, a project was defined as fully commercial if it was financially self sustaining, or nearly so. In addition to developer comments, the following criteria were used to differentiate among projects:

Status	Operating Facility	Revenue Producing
Conceptual	No	No
Laboratory	Yes	No
Demonstration	Yes	No
Full	Yes	Yes

The capacity of several projects cited in technical literature was unreported. These projects were classified as demonstration or full-scale based on available information.

Grouping the projects by process type resulted in the frequency distribution provided in Table 2-2. Section 2 provides the descriptions of process types. Data in Table 2-2 indicate that developers pursue the pyrolysis technology most frequently (26 projects out of 35, or 74 percent). Gasification is a distant

1 A single entity designs and builds the complete facility.

Table 2-1. Summary of the Status of Tire Pyrolysis, Gasification, and Liquefaction Projects Worldwide

PROJECT STATUS	PROJECT SCALE: CONCEPTUAL	LABORATORY	DEMONSTRATION	FULL	OTHER
OPERATING		1 AEA-Beven, Harwell (P) 2 Castle Capital (P) 3 Premium Enterprises (P) 4 Wyoming, Univ. of (P)	1 American Tire Reclamation, Inc (P) 2 Champion Recycling (P) 3 ECO 2 (P) 4 Garb Oil & Power (P) 5 Hamburg, Univ. of (P) 6 Heartland (G) 7 Kilborn, Inc (H) 8 Process Fuels (G) 9 Pyrovac Int'l. Inc (P) 10 RT Corporation (P) 11 Texaco, Inc. (L) 12 Thermoselect Inc. (G) (MSW)	1 Conrad Industries (P) 2 International Recycling (G) 3 Jentan (P) 4 NATRL-Wind Gap (L) 5 RMAC International (P)** 6 Wayne Technology Corp. (P) (tire tests only) 7 Worthing Industries (P) (tire tests only)	
INACTIVE		1 Seco/Warwick (P)	1 Horton (P) 2 International Tire Collection (P)		
DISMANTLED			1 Garb Oil & Power (P)	1 Recycling Industries of Missouri (P) 2 Waste Distillation Technology (G)* (MSW tests, not exclusively tires) 3 Leigh plc (G)	
OTHER	1 American Ecological Technologies (P)	1 Kobe Steel (P)	1 Kobe Steel (P)	1 Kutrieb (P)	1 Thermex Energy Recovery System (G) (a)

G = gasification; L = liquefaction; H = hydrogenation; P = pyrolysis
* Classified as "destructive distillation" by developer.
** Classified as "gasification" by developer.
(a) Insufficient information was reported in the survey in order to allow a designation of the project scale.

Source: Survey information.

Table 2-2. Frequency Distribution of Tire PGL Project Developers Worldwide

	Pyrolysis (a)	Gasification	Liquefaction	Total
Conceptual	1	0	0	1
Laboratory	6	0	0	6
Demonstration	12	3	1	16
Full	7	3	1	11
Other	0	1	0	1
TOTAL	26	7	2	35

(a) Includes 1 project classified as hydrogenation by developer.

Source: Table 2-1

second (7 projects out of 35, or 20 percent). Developers attempt to commercialize liquefaction and other processes infrequently. The project status data in Table 2-1 show that of the seven operational, full-scale projects, five (71.4 percent) use pyrolysis. One project uses gasification and one employs liquefaction. Thus, among operating commercial projects, pyrolysis is the most commonly applied of the PGL technologies.

Table 2-1 provides the process description used by the developer. Hydrogenation is included as a separate entry because one developer uses it. Hydrogenation is "a catalytic reaction of hydrogen with other compounds, usually unsaturated" [2-2]. Project representatives provided little information regarding the use of catalysts. Other projects classified as pyrolysis could include reactions in the presence of catalysts.

While the list of processes or developers in the industry was lengthy, several explicit relationships appeared or were inferred. Business relationships included those of new/discontinued company or process names, licensee/licensor, developer or design engineer, financial backer or operator, and shared process research. Appendix Table B-1 lists business relationships identified during this project; others may exist.

The literature included references to several firms and processes that are not discussed further in this report because information was lacking,[2] projects were unfunded, or projects were not PGL-related. These projects are listed in Appendix Table B-2.

The states and countries in which projects listed in Table 2-1 are located are shown in Figure 2-1. Many PGL projects cluster in the middle Atlantic and east north central states. Also, several projects are in the three Pacific coast states and in southern states. Thus, projects may be located near centers of population (and waste generation) or near petroleum producing areas.

PGL Processes

Historic Development

In 1830, a developer successfully commercialized an early application of pyrolysis involving the production of liquid products from wood [2-3]. The production of coke from coal pyrolysis became the most common application of the technology; its use continues today. Using wood pyrolysis to

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2 For example, no responses to telephone messages and/or letters, and no technical articles.

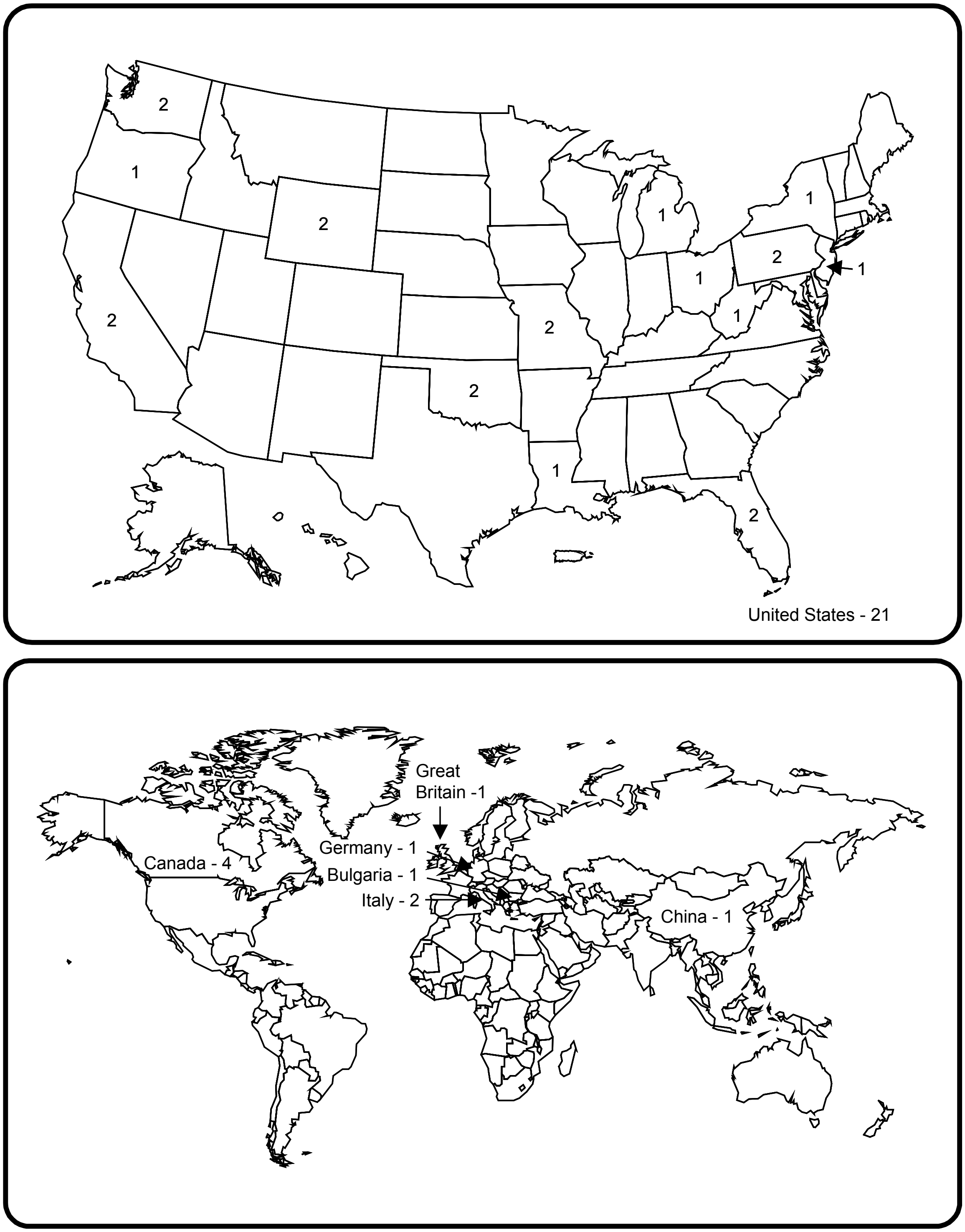

Figure 2-1. Worldwide Locations of Conceptual, Laboratory, Demonstration, Full, and Other Scale Tire PGL Projects

Numbers refer to number of projects.
Source: Survey information.

manufacture creosote oil expanded after the introduction of creosote as a wood preservative in 1838. Pyrolysis of coals and oil shales became common to produce oils in the United States and elsewhere in the mid-1800s (e.g., 55 to 60 plants in Kentucky, Ohio, and Pennsylvania; about 25 in Connecticut, Massachusetts, and New York). Pyrolysis plants to produce illuminating gas became common worldwide until the invention of the electric light bulb in 1879 ended further development [2-3].

The coal industry has applied liquefaction during the past five decades. Coal hydroliquefaction satisfied one third of the German petroleum needs during World War II. By the early 1980s, only the South African Coal, Gas and Oil Company was condensing liquid fuels from coal [2-4].

In addition to coal, wood, and oil shake, feedstocks for PGL processes include municipal solid wastes and organic materials derived therefrom (e.g., plastics, tires, rubber, mixed paper, textiles, etc.); agricultural wastes (e.g., rice hulls, straw, etc.); and wastewater treatment sludges.

Previous Surveys of Tire PGL

A survey of PGL, gasification, and liquefaction processes worldwide as of fall 1977 [2-5] revealed ten projects that had used tires as a feedstock:

1. Pyrotechnic Industries, Ltd., Calgary, AL, Canada
   - fixed bed shaft furnace, (C),[3] mixed feedstock

2. DECO Energy Co., Irvine, CA
   - Agitated solids bed, (C), tires only

3. TOSCO Corp./Goodyear Tire and Rubber
   - Tumbling solids bed, (A), tires only

4. Thermex, Inc., Hayward, CA
   - Static solids bed, (A), tires only

5. Carbon Development Corporation, Walled Lake, MI
   - Static solids bed, (A), tires only

6. Firestone Tire and Rubber Co., Akron, OH
   - Electrically heated, (I), tires only

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3 C = commercial or demonstration, A = active development program, I = inactive.

7. University of Tennessee, Knoxville, TN
   - Molten salt bath, (A), mixed feedstocks

8. Foster Wheeler, London, United Kingdom
   - Moving packed bed, (A), mixed feedstocks

9. Herko Pyrolyse GmbH & Co., Karlruhe, Germany
   - Tumbling solid bed, (C), tires only

10. Firma O. Herbold, Germany
   - Agitated solids bed, (A), tires only

Only one firm described in this early survey remains in business under the same name in 1993 (Thermex) [2-5].

In its 1983 study of tire PGL, the U.S. Department of Energy (DOE) concluded the following [2-6].

1. There were 31 existing plants, of which approximately one half were active.

2. Tire pyrolysis was technically feasible.

3. The economics appeared marginal at best except under special conditions:

   - the cost of competing disposal was high,

   - tax advantages accrued to the project, or

   - high value products were produced.

Current PGL Process

General

Appendix Table B-3 tabulates additional information regarding facilities identified in Table 2-1.

Pyrolysis

PGL processes may operate as either batch feed or continuous feed systems. Batch feed systems process a single charge of feedstock at a time. After required residence time in the batch thermal reactor, solid products and residue are removed. Conversely, in continuous feed systems, feedstock is conveyed through the thermal reactor at a uniform rate, and solid products and residue are continuously discharged.

Pyrolysis relies on the addition of heat to break chemical bonds, providing a mechanism by which organics decompose and vaporize. Most projects operate within a temperature range of 250° - 500°C, although some report operating at up to 900°C. At temperatures above approximately 250°C, shredded tires release increasing amounts of liquid oil products and gases. Above 400°C, depending on the process employed, the yield of oil and solid tire-derived char may decrease relative to gas production, as discussed in Section 4.

A typical commercial operation is described below [2-7, 2-8, 2-9, 2-10].

1. Tires delivered to a site are weighed. Tires are either introduced to systems whole or else halved, chopped, or shredded, as discussed in Section 3. Magnetic separation is often used to remove ferrous metals from size-reduced tires.

2. The feedstock is typically dried and preheated, using tire-derived gas. Oxygen is purged through a combination of the pyrolysis gas preheater and an inert gas system employing nitrogen.

3. Temperature and residence time in the reactor are two key pyrolysis reactor design criteria. Maintaining a positive pressure in the reactor ensures that leaks do not introduce oxygen from the air. Operating characteristics are discussed in Section 4.

4. The liquid stage, tire-derived oil, is condensed and cooled. Light and heavy oil fractions may be handled separately. A separator removes any remaining water vapor. The product is filtered. The characteristics of tire-derived oil are discussed in Section 4.

5. Solid tire-derived char is cooled, typically using a water-cooled stage. The product may be sized and screened to remove fiber. A magnetic separation stage captures magnetic materials remaining in the char. Washing the char and further size reducing it produces the carbon black product. The characteristics of tire-derived char and carbon black are discussed in Sections 4 and 5.

6. Tire-derived gas maintains operating pressure in the system and provides heat to the system. Vented gases pass through a pollution control train, which may include a gas flare. Section 4 discusses gas.

7. Steel shreds are baled for shipment. Separated fibers, when recovery is practical, are baled for shipment. Often, however, fibers are disposed as waste. Reclaimed steel is discussed in Section 4, and fibers are discussed in Sections 4 and 5.

PGL processes investigated generally employed similar flow sheets; variations occurred with respect to the mechanical approaches to material transport, temperature, and pressure control. Peripheral equipment exhibited greater variety than did main process equipment. A typical flow diagram for a tire PGL system is presented in Figure 2-2.

Tire PGL projects have incorporated a variety of equipment. The list of designations and capacities contained in Table 2-3 represents only typical examples, and is not comprehensive. Also, the data have not been adjusted to a consistent fuel basis.

The following descriptions of selected operating, full-scale pyrolysis projects illustrate the range of technical approaches. These descriptions, and the tabulated data in the report, provide detailed introduction to selected projects.

- Conrad Industries, Inc., of Centralia, Washington [2-17], operates a 24 TPD continuous feed, dedicated tire pyrolysis facility that uses the Kleenair[4] process. Conrad reports operation since 1986. The Kleenair process uses neither catalysts nor steam. The process uses a "high temperature reaction tube." Some gas is condensed to yield a medium viscosity pyrolysis oil. Remaining gases are scrubbed, demisted, and then fired to provide process heat. Excess gas can be used for power or compressed and stored.

- The process uses 2 inch tire chips. Conrad planned to retrofit one of its two process lines in 1993 to accept plastic wastes. The market for carbon black is currently weak in the northwest.

- Conrad and Synpro Industries Group employ similar technology. Synpro anticipates using auto shredder fluff as an additional feedstock in planned 96 TPD plants. Synpro plans to use another (unidentified) technology to upgrade[5] the carbon black for sale to the printing and paint industries.

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4 Kleenair Products Co., Portland, Oregon.
5 Expects to achieve 98 - 99 percent purity.

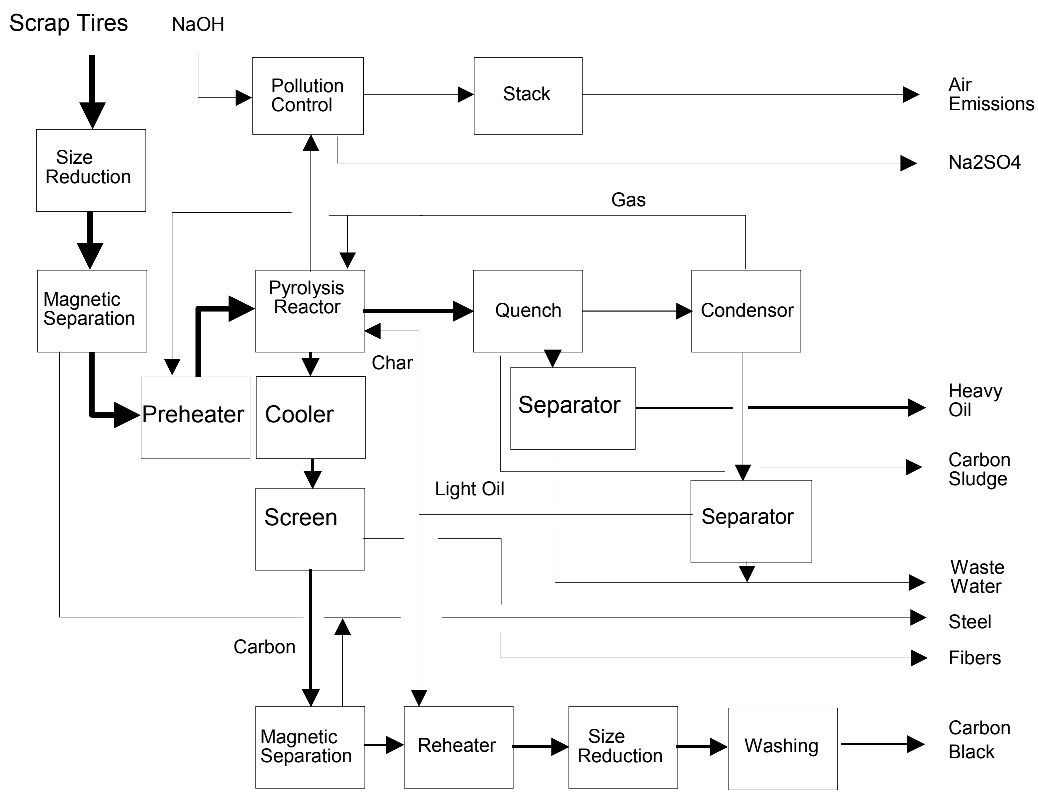

Figure 2-2. Flow Diagram - Typical Tire Pyrolysis System

Some systems may include other equipment, or use alternative flow paths.

Source: [2-8, 2-9, 2-10]

Table 2-3. Designations and Capacities of Selected PGL Equipment

Equipment Types	Units	Reported Capacities
PGL Equipment		
Energy Recovery Chamber	TPH	1.0
Foster Wheeler Cross Flow Pyrolyzer	N/R	
Fluidized-Bed Reactor		N/R
Gas-Purged Static Batch Reactor		N/R
Jentan Recycler	m^3/12-hr charge	60
NATRL (--)	TPH	1.1
Rotary Kiln Pyrolyzer		N/R
Semifluidized Bed (tilting grate)	N/R	
Thermogenics Biomass Gasifier		
Model 103	TPH	0.5
Model 104	TPH	1.0
Model 106	TPH	3.0
Vacuum Tanks	ton/charge	18
Worthing Entrained Gas Reactor		N/R
Post-Processing Equipment		
Post Pyrolysis Reactor		N/R

N/R = not reported.

Source: [2-3, 2-9, 2-11, 2-12, 2-13, 2-14, 2-15, 2-16, 2-17, 2-21, 2-22]

- Jentan Resources, Ltd. [2-16], owns limited worldwide rights[6] to a pyrolysis technology developed in South Korea. Reportedly, about 100 plants are in operation, although there are no domestic projects. These plants range in size up to 20 TPD. Some plants accept tires, but most take medical wastes and plastics. The system employs batch reactors to pyrolyze whole tires.

  The developer claims the process would meet requirements of the Clean Air Act, and that it generates some wastewater.

- RMAC International [2-18], has been conducting tests at its full-scale, continuous feed tire pyrolyzer in Troutdale, Oregon since September 1992. The project achieved a maximum throughput of 2.5 TPH, one half of its design capacity. The average production rate over the 25 weeks of operation through November 1993 was between 0.5 and 1.0 TPH. The developer refers to the system as a gasifier, although it conforms to the definition of a pyrolyzer in this report.

  Shredded tires are introduced at the top of a cylindrical, refractory-lined reactor with capacity to hold 12 to 14 tons of material. Burning scrap wood heats the system to start each cycle; the reaction is self-fueled after startup.

  Utilities buy the solid product, tire-derived char with carbon black content. RMAC plans to upgrade both the carbon black and the oil products in the future.

- Wayne Technology Corporation [2-19] has operated a full-scale, continuous feed plastics pyrolysis plant in Macedon, New York since April 1992. The site adjoins a materials recovery facility (MRF), and accepts industrial and commercial packaging (e.g., plastics and cardboard) from the MRF. Wayne has conducted tests with "chunked" tires, but has not operated commercially on waste tires. Continuously feeding tires would require modification of the existing infeed arrangement.

  The patented Wayne system uses dual rotary drums to pyrolyze the feedstock. Pyrolysis gas, which provides process heat, flows through a caustic scrubber prior to combustion. This system removes the metals that are released by the pyrolysis of plastics. The addition of a co-generation element is being considered. The project is designed to operate 24 hour/day, 300 day/year.

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6 Except Japan and Korea.

If tires were the feedstock, the solid fraction would be sold as fuel or a medium grade carbon black. Reinforcing steel would be removed from the tire-derived char.

New York State Department of Environmental Conservation has issued an air emissions permit. An onsite wastewater treatment plant provides makeup water for use as scrubber water, quench water, and coolant.

- Worthing Industries, Inc. [2-20] markets a mobile, fluid-bed pyrolysis unit, the Encon fast pyrolysis system. Mounted on a 45-foot flat bed trailer, the unit is designed to recover oil from a peat-based absorbent, "Berthinate." This material is sold for use in controlling oil spills. The unit has operated primarily on wood and peat, but is reportedly suitable for tires.

  The solid product, carbon black, will substitute for pulverized coal in utility boilers, although it has a slightly elevated sulfur content. The oil fraction could be a replacement for No. 2 or No. 4 fuel oil, although economics are not currently attractive. The oil retains some moisture, a drawback to marketing. Tire-derived gas meets the process heat requirements; some supplemental operating fuel is necessary. Gas is scrubbed before combustion, and emissions contain some sulfur. The closed-loop cooling system releases little water. The system uses propane for startup.

During the past two decades, tire PGL projects have also included the following process designs [2-4, 2-21]:

- Tosco II - hot (480° - 549°C) ceramic balls in a rotating drum pyrolyzer with a reducing atmosphere.
- Intennco - the Ugland (U.K.), Ltd. technology; two reactors in series, operating at 540°C.
- Steam oxidation.
- Molten salt pyrolysis, developed with the US DOE support by Rockwell International in Canoga Park, CA. Operated at 900° - 1000°C, causing chemical reactions between rubber and salt to produce a gas of primarily carbon monoxide (CO), hydrogen (H_2), and nitrogen (N_2).

Gasification

Gasification is a partial oxidation process. Gasification of organics occurs in an atmosphere that contains some oxygen, but not enough to support complete combustion (i.e., complete oxidation of the feedstock to carbon dioxide and water). In the gasification processes, steam reacts with the solid char in an endothermic (i.e., heat-consuming) reaction, producing gaseous carbon monoxide and hydrogen.

In the 1980s, several developers tested pure oxygen as an alternative to air as the source of oxygen for the reaction. Pure oxygen systems condensed tars from the gas, which resulted in a strong wastewater (i.e., BOD_5 exceeding 50,000 mg/l). Pure oxygen systems operate at higher temperatures than air-supplied systems [2-4]. Further development of oxygen-based systems has been suspended.

Operating, full-scale gasification systems include the following project.

- International Recycling, Ltd. [2-22], of Hammonton, NJ, offers a close-coupled gasification system which is manufactured by Energeco spa and marketed as a Recoverator. Both a rotary kiln system and a stationary system have reportedly operated in Italy since 1989, while a Bulgarian system dates from 1991.

  Systems include a two-chamber combustion system, waste heat boiler, and baghouse, wet scrubber and stack. Steam from the boiler (produced at approximately 8 lb/lb whole tire) can be sold directly, converted to electricity (at 0.8 to 1.2 kW/kg whole tire), or used in co-generation. Larger systems (i.e., 1.1 TPH) employ rotary kilns as the primary combustion chamber while smaller systems use fixed bed reactor technology. The systems accept whole tires.

  No effort is made to recover solid or liquid products. Rather, steel is recovered following the first stage of processing. While Energeco believes that it may be possible to market baghouse ash, there is no supporting domestic experience.

Liquefaction

In the early 1980s, pilot studies evaluated liquefaction of wood wastes. The steps in liquefaction include condensing gas into liquid; ash, sulfur, nitrogen, and oxygen removal; and correction of hydrogen content. The pilot systems employed steam and a catalyst to produce an oil with a higher heating value of 15,000 Btu/lb and a specific gravity of 1.03. The costs of commercial production were estimated to be higher than coal liquefaction.

- NATRL-Wind Gap, formerly J.H. Beers [2-15, 2-23], is the only operating waste tire liquefaction project. The facility started operating one shift in 1986, and expanded to three shifts, five day/week in 1992. The plant consists of two prototype pyrolysis/liquefaction process trains. NATRL-Wind Gap expends to complete a third process line by January 1994.

The process produces a carbon black product. Steel is recovered for the scrap market. Oil and gas are also recovered. Fiber may be sold, once a market is identified.

Permits include a state wastewater discharge permit for the non-contact cooling water that is discharged.

In 1992, AEA Technology and Herbert Beven, Ltd., of Colchester, United Kingdom, announced the sale of a Multi-Purpose Disposer to North American Tire Recycling, Ltd. (NATRL). While no confirmation has been obtained, it seems likely that the modifications at Wind Gap may incorporate the AEA Beven technology, which has operated at laboratory-scale for some time.

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SECTION 3. PYROLYSIS, GASIFICATION, AND LIQUEFACTION PROCESS FEEDSTOCKS

General

This section of the report discusses the preprocessing[1] requirements of tire PGL systems, as well as the supplemental feedstocks that have been used in tire PGL systems. This section also presents the quantities of tires that could be available for processing nationwide and in California.

Characteristics of Feedstocks

The summary information in Table 3-1 permits a comparison of the chemical characteristics[2] and heat content of whole and shredded tires, and several supplemental feedstocks. The combined carbon and hydrogen content of tires exceeds 80 percent by weight (dry basis). These elements form the principal constituents of the solid, liquid, and gaseous pyrolysis products. Waste tires are richer in these elements, and have a higher heat content than either waste plastics or municipal solid waste (MSW), two common feedstocks. Of the common feedstocks, only waste oil has a higher carbon and hydrogen content and greater heating value than waste tires. At least one developer plans to blend shredded tires with an equal amount of waste oil (lubricating oil, transmission fluid, or automotive coolant) to improve economics and operations [3-4].

In addition to natural and synthetic rubber, tires also contain a variety of other materials, including styrene-butadiene copolymers, butyl, EPDM, cis-o-poly-butadiene, aramid, steel, glass fibers, nylon, rayon, polyester, antioxidants, antiozonants, vulcanization accelerators, extending oils, zinc oxide, tackifiers, stearic acid, sulfur, clay fillers, various pigments, and carbon black. As a consequence of containing the above materials, tires contain a variety of chemical compounds, including those of antimony, arsenic, barium, beryllium, boron compounds, cadmium, calcium and magnesium carbonates, cobalt, copper, lead, mercury, potassium, and sodium [3-5].

One developer indicated that a pyrolytic feedstock could be "almost any solid or semi-solid organic ... which by itself has a minimum heating value of 5,000 Btu/lb." This developer reported considering wood waste, dewatered sewage sludge, agricultural wastes, auto shredder fluff, paint sludge, oil field wastes, and soils contaminated with hydrocarbons as suitable process feedstocks [3-6].

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1 Not all systems employ tire preprocessing; some systems accept whole tires.

Table 3-1. Chemical Characteristics of Some Potential PGL Feedstocks

	Units	Tires		Waste	Waste		Mixed
		Whole (a)	Shred (b)	Plastics (c)	Oil (d)	MSW (e)	Paper (f)
Proximate Analysis							
Volatile Matter	%	79.78	83.98	85.84	83.00	58.67	56.85
Fixed Carbon	%	4.69	4.94	1.84	(g)	10.68	8.76
Ash	%	14.39	9.88	5.08	7.00	6.07	10.17
Moisture	%	1.14	1.20	7.24	10.00	24.58	24.22
TOTAL	%	100.00	100.00	100.00	100.00	100.00	100.00
Ultimate Analysis (Dry Weight Basis)							
C	%	74.50	77.60	77.49	87.20	45.65	39.38
H	%	6.00	10.40	12.76	12.50	6.08	5.94
O	%	3.00	0.00	3.51		37.10	40.95
S	%	1.50	2.00	0.18	0.30	0.20	0.09
N	%	0.50		0.03		1.12	0.08
Cl	%	1.00		0.55		0.81	0.15
Ash	%	13.50	10.00	5.48		9.04	13.42
TOTAL	%	100.00	100.00	100.00	100.00	100.00	100.00
Trace Metals							
Lead	mg/kg	51.50	51.50	199	77.80	354.4	13.0
Zinc	mg/kg	45,500	45,500	73	572.60	870.8	96.0
Antimony	mg/kg			10.70		2.7	11.1
Arsenic	mg/kg	2.90	2.90	2.20	<1.00	9.7	0.50
Cadmium	mg/kg	4.80	4.80	0.40	2.00	10.4	0.30
Mercury	mg/kg	0.30	0.30	0.02		0.4	0.05
Molybdenum	mg/kg					23.0	
Selenium	mg/kg			0.002		0.5	0.002
Tin	mg/kg			151		3.8	87.0
Heating Value	Btu/lb	15,000	11,330	15,306	19,430	6,756	5,265
	kJ/kg	34,875	26,342	35,586	45,174	15,708	12,241

(a) Proximate Analysis, calculated, assuming rubber is 95% of tire. Ultimate Analysis and Trace Metals are simple averages of values reported in [3-8]. Heating value reported in [3-1].
(b) As reported in [3-2] for rubber fraction only; trace metals from [3-9]. The reason for the difference between the heating value of whole and of shredded tires is not known, but conceivably could be due to differences in the chemical composition and age of the tires, and to inorganic contamination that may accumulate in waste tires prior to shredding.
(c) Based on the mean value for plastics, reported in [3-2].
(d) Proximate Analysis derived from CalRecovery file data on waste oil; Ultimate Analysis and Heating Value from [3-3] for No. 2 fuel oil; Trace Metals analysis derived simple averages of data from [3-9].
(e) Trace metals for San Diego County CA, as reported in [3-2]. Ultimate Analysis reported for San Diego County CA; Combustible Fraction, as reported in [3-2]. Proximate for Broward County FL [3-2].
(f) Mixed paper fraction for Broward County FL, as reported in [3-2].
(g) Fixed Carbon percentage is included in the above value for Volatile Matter.

2 Proximate and ultimate analysis, and trace metal content.

Relatively few developers provided data regarding preferred feedstock characteristics. Of the developers that provided information, one reported the capability of using either whole or halved tires, and all others required the size reduction of tire feedstocks. Six firms utilized coarse[3] shredding, while three of those further reduced tires to a 2-in or smaller chip. One firm required crumb rubber (i.e., nominal -200 mesh[4]) as a feedstock. For the majority of tire PGL systems, preparation of an acceptable waste tire feedstock includes some degree of size reduction and magnetic separation.

The available data regarding density and size of waste tire feedstocks are summarized in Table 3-2. The density of shredded tires is significantly higher than that of MSW (i.e., 27.5 vs. 8.9 lb/ft^3).

For projects that handle several feedstocks, the pyrolysis of waste tires with waste plastics is most commonly reported, while waste oil is the second more frequently reported supplementary feedstock. Mixed MSW and wastepaper were each reported once. No developer provided a justification for the preference of waste plastics over waste oil. Possible reasons for the preference for waste plastics may include one or more of the following:

1. the ease of handling dry vs. liquid feedstock, or
2. the lower potential for introducing unanticipated hazardous material, or
3. greater potential availability of waste plastics.
4. potential tipping fee revenues

When other materials are blended with tires, high quality additives, including waste plastics and used oil, are preferred by the operators.

Quantities

Residents of the United States disposed approximately 2.42 million tons of waste tires in 1990. Annual tire production has fluctuated between 1.01 and 1.05 tire/capita since 1985. Waste tire generation averaged 0.92 tire/capita for 1990 and 1991.

3 Assumed to result in a nominal 12-in tire chip.

4 200 mesh = 0.075 mm.

Table 3-2. Mean Bulk Densities and Particle Sizes of Waste Tires and Supplemental PGL Feedstocks

	Units	Mean	n
Densities			
Tires, shredded	lb/ft^3	27.5	1
Used oil	lb/ft^3	56 (b)	n/a (a)
MSW, unshredded	lb/ft^3	8.9 (c)	n/a
Particle Sizes			
Tires, shredded	in	< 3.0	5
MSW, shredded	in	< 1	1

(a) n/a = not applicable.
(b) Typical density of used oil, as reported by a re-refiner in California.
(c) Mean value shown is that for Richmond, CA, as reported in [3-2].

Source: Appendix Table C-1

Section 1 provided the estimate that approximately 285,000 tons of waste tires were discarded in California in 1993. The CIWMB reported estimates of diversion (140,000 tons) and disposal (145,000 tons) of tires and other rubber for the same period [3-7]. Appendix Table A-1 provides estimates and projections of tire generation in California for the years 1995 (i.e., 300,000 tons) and 2000 (i.e., 330,000 tons).

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SECTION 4. OPERATING CONDITIONS AND PRODUCTS

General

This section of the report summarizes the operating data for tire PGL projects, and describes the products of their operations. The section presents operating pressures and temperatures for various processes and the predominant products reclaimed by the process. Where data were available, we report historic periods of operation, including startup and shutdown dates. The section summarizes operating schedules for planned facilities. The section includes a summary of the requirements for startup, shutdown, maintenance, and estimated availability. Tables present throughput capacities, based on both experience with actual facilities and planned operations. Pyrolysis, gasification, and liquefaction products are also characterized in this section.

One developer [4-1] of waste pyrolysis systems describes the following five products of PGL and gas cleaning:

1. solids (i.e., inert material, slag, and metals),
2. synthesis gas,
3. metal hydroxide (sludge),
4. gypsum, and
5. industrial grade salt.

Typically however, the tire pyrolysis industry describes the products it produces as a solid (either tire-derived char or tire-derived carbon black), a liquid (oil, often including a naphtha fraction), a gas, steel, and fibers. Wastes from the processes are discussed in Section 5.

Operating Conditions

Temperature and Pressure

Section 2 stated that reactor temperature is one key determinant of overall system performance. Projects may be compared on the basis of reported steady-state operating temperature in the pyrolysis vessel. The range of operating temperatures for the four facilities reporting full-scale pyrolysis projects (see

Section 2) is 460° - 860°C. The single operating full-scale gasifier reports an operating temperature range of 450° - 500°C. Development-scale pyrolysis projects report a range of 250° - 950°C, which is much wider than the range reported by operating systems. The single laboratory-scale project failed to report temperature or pressure.

Only two full-scale operating projects (Wayne and Worthing) reported pressures. This information is considered to be proprietary by most developers.

To a large extent, reactor temperature determines the yield of solid, gas, and liquid pyrolysis products. Over the range of 250° - 500°C, the production of gas increases from 0 - 6 percent by weight, while the quantity of oil and solid fractions are inversely related. Figure 4-1 illustrates the general relationship, and indicates that between approximately 400° and 600°C, the mass fraction of the products is relatively stable. Data provided in Section 2 indicate that between 500° and 800°C, gas production increases from 6 - 31 percent, while over the same range, solid and oil fractions are inversely related. Thus, at higher temperatures, more of the organic content of the tires is converted to the gaseous or liquid phase.

Table 4-1 presents operating temperature and pressure data for various systems, and reports the corresponding product yields for several systems.

Safety

The potential for explosion and fire exists at PGL operations. Operating at high temperatures and in a low oxygen condition increases the risk of fire and explosion through accidental air infiltration. Catastrophic fires have destroyed some facilities [4-5].

Energy Requirements

Most developers report that the pyrolysis process produces an excess of energy. Most developers indicate that the combustion of tire-derived gas provides sufficient heat to drive the reaction. The use of supplemental fuel - propane or natural gas - is limited to the startup period. The electrical usage of systems is estimated to fall between 12.8 and 117.6 kWh/ton of feedstock, based on two survey responses.

The heat required to sustain the pyrolysis reaction appears to be between approximately 630 and 1,025 Btu/lb of feedstock, based on two survey responses.

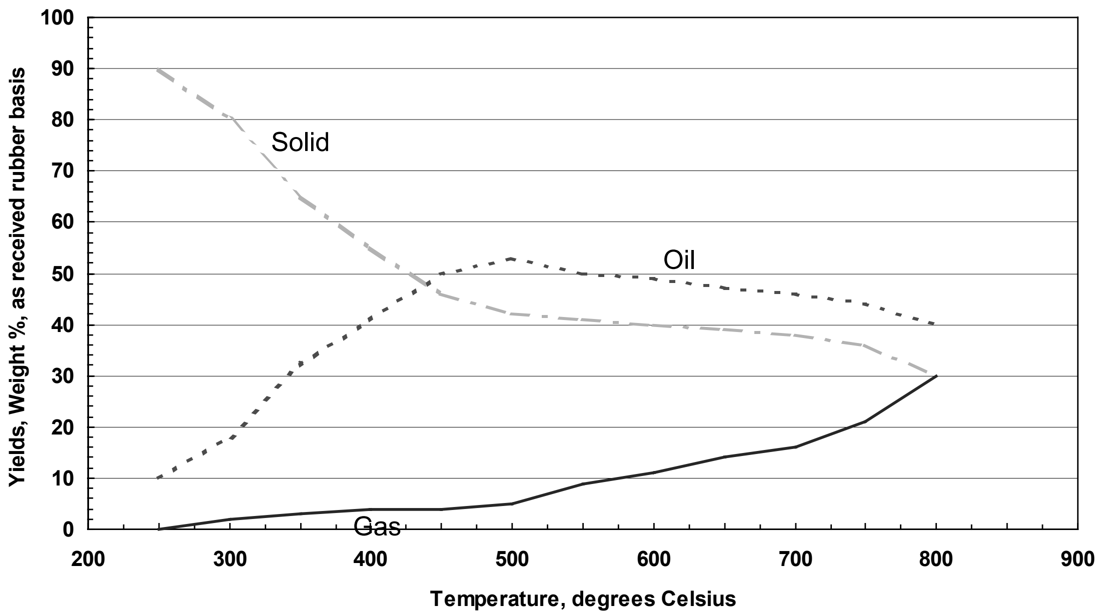


Figure 4-1. Tire-Derived PGL Product Yields vs. Temperature

Source: Constructed from information from [4-2], Table 4-1, and [4-12], and corrected for mass of reinforcing steel, in some cases.

Table 4-1. Operating Conditions - All Tire PGL Reactors

Process	Operating Temperature	Operating Pressure	Products
AEA-Beven	NR (a)	50 mb g	
American Tire Reclamation	500 deg C	NR	Oil 42% Solid 52% Gas 6%
	600 deg C	NR	Oil 50% Solid 40% Gas 10%
	700 deg C	NR	Oil 47% Solid 38% Gas 15%
	800 deg C	NR	Oil 40% Solid 29% Gas 31%
Champion	230 to 500 deg C	slight neg.	
Cheyenne	650 to 760 deg C	low	
Garb Oil	950 deg C	NR	
ITC (planned) Operating: Start-up:	 320 deg C 980 deg C	 62 kPa vac 39.3 kPa	
Jentan	320 to 430 deg C	NR	
Kilborn (b)	454 deg C	17 kPa	
Nippon Zeon (Pilot)	450 to 500 deg C	NR	Oil 52% Solids 33.6% Gas 14.4%
Pyrovac	450 deg C	15 kPa	Oil
Pyrovac/ Laval	415 deg C	2 to 10 kPa	Oil 64% Solids 29% Gas 7%
Recycling Industries of Missouri	480 to 590 deg C	NR	
RMAC	430 to 480 deg C	NR	
Seco/ Warwick	440 to 510 deg C	NR	
Wayne	430 to 590 deg C	6.9 kPa	
Worthing	500 to 550 deg C	30 to 50 kPa	

(a) NR = not reported
(b) Residence time = 60 minutes

Source: Survey information, except Nippon Zeon [4-4]; Pyrovac [4-3]; and Pyrovac/Laval [4-2].

Heating Rate

For a given temperature, the heating rate (°C/minute) has a minor effect on the yield. In general, the faster the feedstock is heated to a given temperature, the less tire-derived char and the more oil and gas that is produced. Under these conditions, higher gas yields are achieved at lower temperatures. Also, at each heating rate, as temperature is increased, the greater the production of benzene, pentane-2, and methanol fractions, and the less the production of pentane-1 and ethanol fractions [4-1].

At a given temperature, the heating value of the gas increases with the heating rate. The surface area of the solid product increases as heating rate or temperature increases [4-1].

Throughput

Throughput capacities vary widely. Table 2-3 provides the design capacities for several pieces of PGL equipment. Appendix Tables B-4 and B-5 tabulate the reported throughput capacities for both actual and planned PGL facilities, respectively. The mean value of reported throughput capacity for both actual operating and planned systems is presented in Table 4-2. The reported throughput capacities of the operating systems averaged 1.24 tons per hour (TPH) for pyrolysis systems. For planned systems, the mean value of anticipated throughput was typically 1.8 TPH. This relatively close correlation between current operating experience and planned operations (i.e., a ratio of 1.45 to 1) indicates that the industry does not expect to scale up the pyrolysis process. Conversely, the ratio of planned to actual capacity is much greater for gasification (i.e., 4.6 to 1) and liquefaction (2.6 to 1). The fact that greater scale-up is anticipated for the two subordinate processes (gasification and liquefaction) may be attributable to the smaller body of experience with these processes.

Operating Schedules

Based on the historic period of operation for developmental and laboratory-scale units, projects report relatively little cumulative operating time. The earliest full-scale operating unit identified in this survey dates from 1987.

With few exceptions, projects anticipate operating 24 hour/day, 7 day/week, as illustrated by the data in Table 4-3. For the estimates that were provided, planned outages for maintenance varied between 36.5 and 65 day/year. Thus, anticipated availability ranges from 82 - 90 percent. While data were unavailable to substantiate the validity of the estimates, an availability of 85 percent is typical for commercial-scale massburn facilities.

Table 4-2. Mean Throughput Capacities - All Tire PGL Facilities

	Pyrolysis n (a)	Gasification n	Liquefaction n
Actual Facilities	19	5	2
Mass-Based			
pound/hour	2,489	3,261	1,625
ton/hour	1	2	1
ton/day	30	39	20
ton/year	9,730	12,914	5,595
Count-Based			
tire/hour	124	163	81
tire/day	2,974	3,913	1,950
1000 tire/year	973	1,291	560
Planned Facilities	19	5	3
Mass-Based			
pound/hour	3,568	15,020	4,100
ton/hour	1.8	7.5	2.1
ton/day	43	180	49
ton/year	14,068	58,478	15,118
Count-Based			
tire/hour	178	751	205
tire/day	4,289	18,024	4,921
1000 tire/year	1,407	5,848	1,512

(a) n = number of projects reporting.

Source: Appendix Tables B-4 and B-5.

Table 4-3. Historic and Planned Periods of Operation and Availability - All Tire PGL Facilities

	Units	Conrad	ECO 2	ITC	NATRL	RTC	Seco/W	Waste Dist.	Wayne
Historic Operating Period of Record									
Start			1991		1987 -				1992
End					present				
Total	Hrs				6, 14, 24	39			
	Days			50	hr/day				
Planned Operating Schedule									
Hrs/Day		24	20	8	24	24			24
Days/Week		7	NR	7	7	7			7
Start-up	Hour				8 - 12		4		
Shutdown	Hour				1				
Planned Maintenance Schedule									
Days/Year		65	NR	NR (b)	NR	36.5	NR	55	65
Planned Availability (a)	%	82%	NR	NR	NR	90%	NR	85%	82%

(a) Availability = (operating days/total days per year); operating days = total days per year - maintenance days.
(b) NR = not reported

Source: Survey information.

Estimates of the duration of the startup period vary between 4 and 12 hours. Typically, a propane or natural gas ignition system brings the initial reactor vessel charge to the operating temperature of the system, although one developer reported the use of waste wood as startup fuel. The mass of material to be heated includes the feedstock, the suspension medium (in a fluid bed system), and the reactor vessel itself.

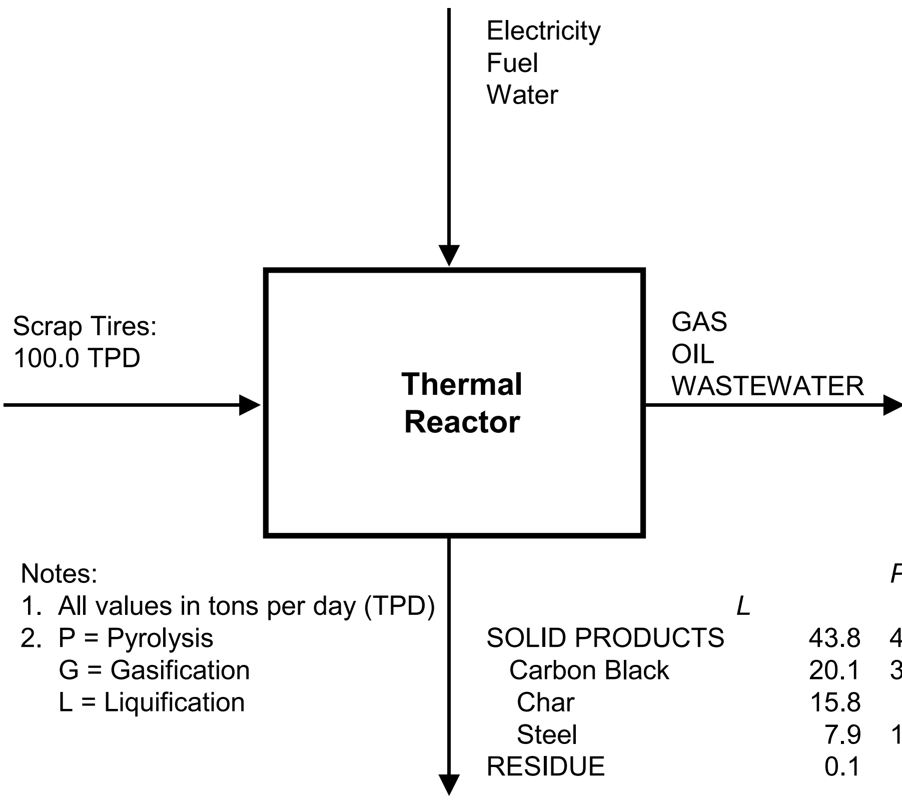
Material Balances

Typical material balances for the pyrolysis, gasification, and liquefaction of waste tires, based on a feed rate of 100 ton/day, are illustrated in Figure 4-2. These material balances were calculated by using mean values where multiple data points (i.e., multiple project reports or estimates) were available for each technology. These data represent steady state conditions. These data could be quite different from the experience of any specific project during commercial acceptance testing, during its startup cycle, or while operating under steady state conditions. Nonetheless, the balances provide additional insight into the material flows that might be anticipated from any tire PGL project.

PGL Products

Quantities

The quantities of PGL products produced nationwide and in California have not been reported in the literature. CalRecovery estimated production, based on available system throughput estimates and projections that were described in Section 1, and product materials balance data, shown in Figure 4-2. Because these estimates are based on average values, and the industry is highly variable, actual results for a particular facility could be quite different from the average. The projected increases in the application of the PGL technologies could fail to materialize. This shortfall would result in fewer tires being processed through PGL systems than anticipated, reducing both input quantities and outputs. Alternatively, a technical innovation widely adopted by the tire PGL industry could have an impact on future projections. An innovation could result in more or less product being produced (i.e., more or less residue for disposal), or a variation in the product mix. Because California has few projects at present, a technical innovation could have a greater relative impact in the state than in the nation as a whole. Also, the potential need to dispose of materials produced when markets are not found, as discussed in Section 5, could decrease the amount of revenue producing product while increasing the amount of waste produced by the operation of PGL projects. Nonetheless, estimates of quantities presented in Table 4-4 may be considered to reflect the order of magnitude of production through 1998.



	P	L	G
GAS	16.1	28.8	6.0
OIL	39.0	27.4	47.0
WASTEWATER	1.0	0.0	0.0

Notes:
1. All values in tons per day (TPD)
2. P = Pyrolysis
   G = Gasification
   L = Liquification

	P	L	G
SOLID PRODUCTS	43.8	43.8	47.0
Carbon Black	20.1	32.9	43.0
Char	15.8	0.0	0.0
Steel	7.9	10.9	4.0
RESIDUE	0.1	0.0	0.0

Figure 4-2. Typical Material Balance for Tire PGL Processes

Source: Estimate of CalRecovery, based on survey and literature information.

Table 4-4. Estimated Current and Projected Quantities of Tire PGL Products - Nationwide and California

	Units	Nationwide			California		
		1992	1995	1998	1992	1995	1998
Tires Processed							
	million	1	2	3	0.11	0.22	0.33
	ton	10,000	20,000	30,000	1,116	2,232	3,348
Products and Wastes							
Char	ton	1,583	3,165	4,748	177	353	530
Carbon Black	ton	2,005	4,010	6,015	224	448	671
Oil	ton	3,902	7,803	11,705	435	871	1,306
Gas	ton	1,612	3,223	4,835	180	360	540
Steel	ton	789	1,578	2,366	88	176	264
Ash	ton	14	28	42	2	3	5
Wastewater	ton	96	193	289	11	21	32
TOTAL	ton	10,000	20,000	30,000	1,116	2,232	3,348

Calculations assume all projects operate as pyrolysis projects, and that the projects generate the output streams shown in Figure 4-2.

Source: Calculated, based on data presented in Section 1 and Figure 4-2.

Characteristics

Oil

The mean ultimate analysis of four pyrolytic oils is reported in Table 4-5. Also, the mean heating value of seven oils is provided. The ultimate analysis indicates an oil product well within the range of that of a No. 2 to No. 6 fuel oil, while the heating value is characteristic of No. 6 oil. However, as discussed in Section 6, pyrolytic oil must be economically competitive with fuel oil refined from crude oil.

Laboratory analysis has indicated that in excess of 10 percent of pyrolytic oil may be polyaromatic hydrocarbons (PAH), some of which are toxic. Process conditions can be optimized to decrease or increase PAH production [4-12]. The principal chemical constituents of the ash fraction of one pyrolytic oil are shown in Table 4-6. If subjected to fractional distillation, the oil would reportedly yield a naphtha fraction (boiling point < 210°C) [4-2]. The naphtha fraction would reportedly contain dipentene (dl-limonene), a powerful, non-toxic solvent [4-2]. Other researchers have reported that toluene, xylene, and styrene isomers would be obtained from the oil at yields exceeding 0.5 percent by weight of feed (see Appendix Table D-4).

Char and Carbon Black

A solid product termed tire-derived char or tire-derived carbon char is produced by most PGL processes that use tires or other solid organic feedstocks. The solid product can be further processed to enhance specific characteristics and to meet specifications for carbon black,[1] or can be marketed directly, as discussed in Section 6. Virgin carbon black can reportedly be produced more economically and with better quality control than carbon black from tire char [4-20].

The proximate and ultimate analyses of tire-derived char and tire-derived carbon black are provided in Table 4-5. The data shown in Table 4-5 are for all projects reporting, and do not differentiate among the PGL technologies. The mean concentrations of chlorine and the moisture content of the solid product are also indicated. The data in the table include the mean heating value for the solid product, which is within the heating value range of coal. However, the mean sulfur content (i.e., 2.36 percent) would not permit its substitution for a low sulfur coal (typically less than 1 percent sulfur).

Little information is available with respect to the constituents of the ash produced by the combustion of tire-derived char or tire-derived carbon black. Based on two reports, the major component of the ash is

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1 Carbon black is a petroleum based product, and has ASTM specifications.

Table 4-5. Mean Values of Chemical Characteristics of Tire-Derived PGL Products

		Solid (a)		Oil		Gas	
	units	Value	n (b)	Value	n	Value	n
Ultimate Analysis (c)							
Carbon	%	91.5	3	86.6	4	85.76	1
Hydrogen	%	2.0	3	10.3	4	14.24	1
Nitrogen	%	0.4	3	0.6	4	trace	1
Oxygen	%	0.2	3	0.8	4	trace	1
Sulfur	%	2.1	3	1.2	4	trace	1
Chlorine	%	0.11	1				
Chloride	mg/Nm—u3			0.06	1	0.3	1
HF	mg/Nm—u3					<0.06	1
SO—d2	mg/Nm—u3					<1.35	1
Moisture	%	0.205	2				
Proximate Analysis (c)							
Volatile Solids	%	1.0	2				
Fixed Carbon	%	84.8	3				
Ash	%	11.5	3				
Sulfur	%	1.8	3				
Other	%	1.0	3				
Heating Value							
	Mj/Kg	30.5	4	42.2	7	44.6	3
	Btu/lb	13,131	4	18,145	7	19,167	3
	Btu/scf (d)	n/a (e)		n/a		958	3

(a) Solid products are char and carbon black.
(b) n = number of data points.
(c) Ultimate and proximate analyses may not total 100% because of incomplete data reporting.
(d) scf = standard cubic foot.
(e) n/a = not applicable.

Table 4-6. Mean Concentrations of Trace Elements and Characteristics of Ash in Tire-Derived PGL Products

		Solid		Oil		Gas	
	units	**Value**	**n (a)**	**Value**	**n**	**Value**	**n**
Analysis of Ash							
SiO_2	%	22.3	2				
TiO_2	%	0.1	2				
MgO	%	1.4	2				
ZnO	%	37.8	2				
Na_2O	%	1.2	1				
K_2O	%	1.0	1				
CaO	%	5.7	1				
Fe_2O_3	%	7.4	1				
Al_2O_3	%	2.2	1				
SO_3	%	7.0	1				
Not reported (b)		13.9	2				
TOTAL		100					
Residual Elements							
Ca	ppm			0.3	1		
Cd	ppm			<0.01	1		
	mg/Nm^3					<0.001	1
Cr	ppm			0.67	1		
Hg	mg/Nm^3					<0.006	1
Na	ppm			0.3	1		
Pb	ppm			<0.1	1		
	mg/Nm^3					<0.005	1
V	ppm			<0.1	1		
Va	%			<0.1	1		

(a) n = number of data points
(b) by difference

zinc oxide, ZnO. Zinc oxide represents approximately 37.8 percent of ash by weight, as data in Table 4-6 show. Because zinc is a significant component of the ash, the potential for recovery exists.

The second most common component (at 22.3 percent of ash by weight) is silica oxide, SiO_2. Other compounds with relatively high concentrations are lime (CaO, 5.7 percent), ferric oxide (Fe_2O_3, 7.4 percent), and sulfate ions ($S0_3$, 7.0 percent). Because these substances are usually common minerals, the potential for their recovery has generated little interest. Taken together, the above substances account for approximately 42.2 percent of the ash by weight.

Minor constituents of the ash include oxides of titanium, magnesium, sodium, potassium, and aluminum. While the recovery of these substances might be attractive, their concentrations are small (combined 5.9 percent by weight).

Mean values for important physical characteristics of solid PGL products are summarized in Table 4-7. Since these values are mean values, actual test results could be substantially different. Insufficient data were available from which to calculate a meaningful statistical confidence interval about the mean values.

Gas

Little information is available on the composition of PGL gas. Because most systems consume some of the gas for energy and flare the excess, it is likely that little attention has been paid by developers to characterize the composition of the gas. The ultimate analysis values of a single pyrolytic gas product is reported in Table 4-5. Also, the heating value of the gas is provided. The composition of one tire-derived pyrolytic gas is reported in Appendix Table D-6. The carbon content of the tire-derived gas is higher than that expected for most natural gas (i.e., 85.76 percent vs. approximately 70 - 75 percent), whereas the hydrogen content is lower (14.24 vs. 23 percent).

Steel and Fiber

Single stage magnetic separation recovered 95.6 percent by weight of the wire in tire chips, in one case. A two-stage separation process recovered 99.86 percent by weight of the wire [4-4].

The principal contaminant of the recovered steel is adherent rubber or carbon as a result of its having been embedded in the tire. No quantitative data are available with respect to the concentration of contamination.

Table 4-7. Mean Physical Properties of Tire-Derived Char or Carbon Black

	units	Value	n
Specific Gravity	-	1.7	3
Bulk Density	lb/ft—u3˜	32.4	3
Particle Size	micron	40-50	1
Surface Area			
BET (a)	m—u2˜/g	40.0	1
CTAB (a)	m—u2˜/g	85	1
Void Volume			
DBP (a)	ml/100g	85.5	2
Pellet hardness	g/pellet	23	1
Toluene Discoloration	-	90.0	1

(a) BET = Braunauer, Emmett and Teller procedure;
CTAB = cetyltrimethylammonium bromide adsorption procedure;
DBP = dibutyl phthalate method.

Source: Appendix Table D-5.

No data are available with respect to the quantity or composition of fibers that might be recovered from used tires. As noted in Appendix Table B-3, few operations make any attempt to recover fiber.

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SECTION 5. ENVIRONMENTAL IMPACTS OF TIRE PGL

Introduction

General

This section of the report presents the potential environmental impacts of tire PGL processes. Most of the environmental impacts discussed are common to pyrolysis, gasification, and liquefaction, rather than specific to any of the three technologies. This section characterizes the available information on solid and liquid wastes and air pollutant emissions, methods for treating these wastes and controlling the emissions, and the resources used by tire PGL processes. The amount and characteristics of potential wastes and air pollutant emissions can be influenced by several factors, including the ability to market materials from the PGL process. Generally, the environmental impacts of tire PGL processes are not substantial; one reason is the relatively low capacity of tire PGL systems. Based on a survey of the tire PGL industry and a review of the literature, most of the PGL operations that have shut down did so because of reasons other than difficulties in complying with environmental requirements.

As discussed in Section 2, tire PGL is the thermal degradation of whole or chipped tires to recover carbonaceous material (including ash), oil, gas, steel, and fiber. As discussed in Section 4, the amount of each component produced varies depending on the feedstock, temperature, and residence time of the process. A factor that affects the analysis of potential environmental impacts from tire PGL processes is the variability of the composition of tires. Composition varies from manufacturer to manufacturer, with the exact composition of each company's tires being a trade secret.

The results of the analysis presented in this section must be used cautiously because the available environmental data are limited and lack detail. Furthermore, many data are from small-scale or pilot projects. The types of potential waste streams or air pollutant emissions and/or their characteristics could change significantly when full-scale versions of the technologies are built. For example, differences between pilot- and full-scale versions could occur in cooling requirements, product separation processes, and air pollution control processes. A full-scale process might generate wastewater that would not be generated by the pilot-scale version because of the need to use a wet-scrubber to control air pollutants in the case of the full-scale system.

The remainder of this section first provides information on the potential environmental concerns of tire storage at a tire PGL facility. Subsequently, the characteristics and potential environmental impacts of solid, liquid, and gaseous emissions are described. Based on the available information, wastes are characterized and management practices analyzed. Finally, a discussion of resource utilization is provided.

Tire Storage Management

Process feedstocks are discussed in Section 3. The only raw material required for many tire PGL processes is scrap tires. Most processors prefer to maintain a 10 - 30 day stockpile of raw materials as a protection against market and seasonal fluctuations, transportation problems, or work stoppages. If a typical facility uses between 1,000 and 10,000 tires daily (i.e., 10 - 100 tons per day (TPD)) and a 10 - 30 day stockpile is maintained, then the number of tires which must be stored is 10,000 - 300,000 tires (i.e., 100 - 3,000 tons). Storage of whole tires requires proper management to prevent potential health problems. Whole tires stored outdoors may be treated with pesticides or insecticides for vector control (e.g., mosquito or other insect larvae, rodents, water snakes).[1] Rain may wash dirt, road oil, and pesticides or insecticides off the tires. Tires, whole or in chips, may also leach substances into the soil. Thus, stormwater runoff could potentially contaminate soils, groundwater, or nearby surface water [5-1].

Stormwater runoff from tire storage areas and other surficial areas at a tire PGL facility is regulated. In November 1991, the California Water Resources Control Board adopted general industrial stormwater permit requirements to comply with federal requirements for stormwater discharges [5-2, 5-3]. These general permit requirements apply to all industrial stormwater dischargers, including recycling (e.g., tire PGL) facilities. A facility must develop pollution prevention plans and implement best management practices (BMPs) to control stormwater discharges, and may be required to establish a monitoring program. Control of runoff through containment (e.g., berms) and capture (e.g., settling ponds) may be acceptable BMPs.

In addition, tire stockpiles represent fire hazards. Open burning of scrap tires could emit pollutants of health concern, including benzo(a)pyrene, benzene, lead, zinc, and numerous aromatic organic compounds [5-4]. Aisles and berms between and around piles provide emergency access for fire fighting equipment and serve as fire breaks.

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1 Tires, when exposed to the elements, have the potential to cause significant environmental and public health concerns. Whole tires collect water and the black color causes tires to act as heat sinks. Therefore, tires make an excellent incubator for mosquitos. In addition, rodents, water snakes, and other pests may seek refuge in tire piles.

Under the California Integrated Waste Management Act, a tire PGL facility would probably be required to comply with the requirements for a major waste tire facility [5-5].[2] The facility would be required to obtain a major waste tire facility permit. To obtain this permit, a facility would need to submit an operations plan that provided for fire prevention methods, fencing and security measures, and vector control; a closure plan; and financial assurance for closure and third-party liability coverage.

Potential Solid Wastes

General Background

The tire PGL processes reviewed in this analysis typically generate the following solid materials: char, scrap steel, and fiber (e.g., fiber, nylon, and rayon). In general, tire PGL processors and vendors identified these materials as products. However, these materials were also considered by some processors as wastes or potential wastes. In addition, survey data identified the ash residue separated from the char as another potential waste. Consequently, for the purpose of this section, all of the solid tire-derived products are considered to be potential solid wastes.

Any of the solid tire-derived products and wastes generated by tire PGL could be classified as solid waste if not sold, utilized, or recycled to the PGL process. If classified as solid wastes, products or wastes might also be classified as hazardous wastes if they: 1) exhibit any of the characteristics of hazardous waste, or 2) are listed as hazardous wastes in Chapter 11, Article 4 of the California Hazardous Waste Regulations [5-6].[3] While some of the tire-derived PGL products and wastes may exhibit some characteristics of hazardous waste (e.g., toxicity), none is specifically listed as a hazardous waste.

Overview of Applicable Solid Waste Statutes and Regulations

The California Porter-Cologne Water Quality Act establishes management requirements for any solid waste generated by a tire PGL facility. If a waste is considered a hazardous waste, the California Hazardous Waste Control Law establishes requirements for hazardous waste management [5-7]. In addition to the adoption of the federal Resource Conservation and Recovery Act (RCRA) hazardous waste identification criteria, California has implemented a greatly expanded system of health-based

2 "Major" refers to a facility storing more than 5,000 tires at any time.

3 For the purposes of this discussion, no distinction is made between a RCRA hazardous waste and non-RCRA hazardous wastes (not a RCRA hazardous waste but the waste exhibits at least one of the state's more stringent corrosivity or toxicity characteristics).

toxicity characteristics and has augmented the federal corrosivity characteristic to include non-liquid wastes [5-8].

In order to determine whether a material is considered a hazardous waste in California, it is necessary to determine whether it is considered a waste under California law. The California definition of waste states that a waste is a discarded material that is not specifically excluded (e.g., certain refinery wastes) [5-9]. The facility generating a waste is responsible for properly classifying its waste stream. To aid waste generators, California developed a list of 791 chemical names and approximately 70 common names for hazardous wastes and materials. If a substance is listed, the waste is presumed hazardous [5-10]. This list contains none of the tire PGL materials.

The criteria used to identify characteristic hazardous wastes in California are found in Chapter 11, Article 3 of the California Code of Regulations. In brief, the criteria are as follows.

- Ignitability. Is capable of being set afire, or of bursting into flame spontaneously or by interaction with another substance or material

- Corrosivity. Has a pH of less than 2 or greater than 12.5, or causes destruction of living tissue or steel surfaces by chemical action

- Reactivity. Having properties of explosivity or of chemical activity which can be a hazard to human health or the environment

- Toxicity. A solid waste exhibits the hazardous characteristic of toxicity if:

  - any of the 40 Federal toxicity characteristic (TC) constituents have Toxicity Characteristic Leaching Procedure (TCLP) concentrations above the regulatory levels;

  - any of the California List of Inorganic Persistent and Bioaccumulative Toxic Substances are at or above their respective soluble threshold limit concentrations (STLC) or total threshold limit concentrations (TTLC);

  - any of the California List of Organic Persistent and Bioaccumulative Constituents are at or above their respective STLC or TTLC;

  - it has an acute oral LD_{50} < 5,000 mg/kg;

  - it has an acute dermal LD_{50} < 4,300 mg/kg;

- it has an acute inhalation LC_{50} < 10,000 ppm as a gas or vapor;
- it has an acute aquatic 96-hour LC_{50} < 500 mg/l in soft water;
- it contains any of 16 organic substances at a single or combined concentration exceeding 0.001 weight percent (10 ppm); or
- it has been shown to pose a hazard to human health or the environment.

Characterization of Solid Wastes

Very few data are available on the composition of the materials generated by tire PGL processes. For some processes, the data do not appear to have been collected, while in others the process developers were unwilling to provide them. The information available on the generation rates, hazardous characteristics, and management options for the potential wastes from the 17 responding PGL processes is summarized in Table 5-1. As discussed earlier, none of the materials produced by tire PGL is a listed hazardous waste. Because of the limited amount of available composition data, we were only able to evaluate the char for the hazardous characteristic of toxicity with any degree of confidence. The char from the processes of AEA-Beven, RMAC International, and Worthing Industries was found to exhibit the characteristic of toxicity for zinc (i.e., the California List of Inorganic Persistent and Bioaccumulative Substances).

While char has a fuel value similar to pulverized coal, no information reviewed suggested that char under normal conditions could cause a fire through friction, absorption of moisture, or spontaneous chemical changes, and burn so vigorously when ignited as to create a hazard. None of the PGL processes that provided data discussed ignitability as a potential problem. For this reason, char probably would not be considered a hazardous waste based on the ignitability characteristic.

Under the federal RCRA corrosivity definitions, char would not be considered corrosive because the characteristic does not apply to solid materials. However, California regulations expand the corrosivity characteristic to include those solids which, when added to an equal weight of water, have a measure of pH less than 2 or greater than 12.5 [5-11]. California expanded the corrosivity characteristic for nonaqueous waste because of the high probability that improperly disposed waste would come into contact with water. Char is mostly carbon and would probably be closer to neutral than either being acidic or alkaline. No references raised the issue of char being considered corrosive. Therefore, char probably would not be considered a hazardous waste as a result of the corrosivity characteristic.

Table 5-1. Mean Values of Potential PGL Waste Quantities and Management Options - All Tire PGL Projects

Potential Waste	n (a)	Units	Mean Generation Rate	N(a)	Management Option
Char	10	lb/ton tires	664	10	Dispose or sell as carbon black,
		lb/ton char			fuel, filler, or pigment.
	10	lb/ton oil	1,926	10	
	10	lb/ton gas	4,150	9	
Scrap Steel	12	lb/ton tires	212	11	Dispose or sell
	12	lb/ton char	716	11	
	12	lb/ton oil	612	11	
	12	lb/ton gas	1,708	10	
Process Wastewater	3	lb/ton tires	63	3	Off-site treatment
	3	lb/ton char	188	3	
	3	lb/ton oil	275	3	
	3	lb/ton gas	524	2	
Fiber	2	lb/ton tires	100	1	
	2	lb/ton char	400	1	
	2	lb/ton oil	182	1	
	2	lb/ton gas	1,667	1	
Ash	3	lb/ton tires	55	2	Dispose
	3	lb/ton char	185	2	
	3	lb/ton oil	153	2	
	3	lb/ton gas	327	2	
Cooling Tower Blowdown	1	lb/ton tires	2,390	1	Off-site treatment
	1	lb/ton char	7,836	1	
	1	lb/ton oil	5,975	1	
	1	lb/ton gas	15,933	1	
H—d2˜S	1	lb/ton tires	NR (b)		
	1	lb/ton char	NR		
	1	lb/ton oil	NR		
	1	lb/ton gas	NR		
Carbon Black	2	lb/ton tires	525	2	Sell
	2	lb/ton char	NR		
	2	lb/ton oil	1,140	2	
	2	lb/ton gas	9,920	2	
Other	1	lb/ton tires	160	1	
	1	lb/ton char	790	1	
	1	lb/ton oil	318	1	
	1	lb/ton gas	3,917	1	
Hydrogen, Ammonia, and Methanol	1	NR	NR		
Sulfur	1	NR	NR		

(a) n = number of projects reporting the indicated type of waste material; N = number reporting quantities.
(b) NR = no, or insufficient, data were reported.

Source: Appendix Table F-1.

To be considered a hazardous waste based on the characteristic of reactivity, a waste would have to be extremely unstable and have a tendency to react violently or explode during management. No data suggest that char is reactive.

Though some PGL materials may be considered a hazardous waste because of high levels of zinc, most of the tire PGL processors surveyed did not characterize char as a potential hazardous waste. Most sources of tire PGL did not discuss the issue of the PGL materials potentially becoming a hazardous waste. References to char found in other reports conclude that char from the PGL of tires is not a hazardous material [5-12].

Table 5-1 summarizes survey information on the generation rate of each potential waste, any hazardous waste characteristics, and management options reported by each process developer. Some additional information on the wastes generated by each PGL process follows.

- AEA-Beven. The char has been reported to contain 44,500 mg/kg zinc oxide, which could result in its exceeding the total threshold limit concentration of 5,000 mg/kg for zinc, and exhibiting the hazardous characteristic of toxicity [5-13].

- Premium Enterprises, Inc. There are probably intermediate materials (e.g., pyrolysis oil) generated by this process, but our contact at Premium Enterprises was not willing to identify or discuss them. He indicated that the only products were carbon black and electricity [5-14].

- Texaco, Inc. The products associated with this PGL process are speculative at this time [5-15].

- Worthing Industries. The char has been reported to contain 310,000 mg/kg zinc oxide, which could result in its exceeding the total threshold limit concentration of 5,000 mg/kg for zinc, and exhibiting the hazardous characteristic of toxicity [5-16].

Solid Waste Management Options

A variety of management options are available for each of the solid PGL materials which potentially may be generated as wastes. The most economical option is to sell, utilize, or recycle the materials to avoid having to dispose of them as wastes (for a more detailed discussion of the marketing of products, see Section 6). The management options for each of the potential materials are summarized below.

If the char cannot be sold or used as fuel, carbon black, asphalt, or roofing filler, it may have to be managed as a either a solid waste or a hazardous waste. Only American Ecological Technologies stated that a management option for char included landfilling. If the char is a non-hazardous solid waste, landfills permitted to accept commercial and industrial solid waste would probably accept this material. Due to the high cost of building a dedicated landfill, a tire PGL facility would probably transport the waste to a commercial facility. Alternatively, char could be used for waste stabilization. Through its absorption capacity, char can de-water contaminated materials and reduce the presence of free leachate. As an example of waste stabilization, char could be used in treating municipal sewage sludge, thereby rendering such sludges more conducive to handling. This management method may also be considered a beneficial use that could generate revenues.

If the char is characterized as a hazardous waste, more stringent management requirements would be required than if it were designated as solid waste. The waste would have to be manifested and could only be sent to Class I landfills that comply with specific design and operating requirements. Though two facilities in the survey might have char characterized as hazardous because of high zinc concentrations, no information exists on whether these facilities have ever managed char as hazardous waste.

Scrap steel, fiber, and ash can probably be disposed in a landfill permitted to accept commercial and industrial solid waste if the materials cannot be sold as products. Scrap steel is reportedly contaminated with carbon in some processes but this should not prevent the scrap steel from being managed as a solid waste.

Potential Liquid Wastes

General Background

Eight of the tire PGL processes reported generating wastewater. Two of these processes use the water only for cooling, and the water does not appear to come into contact with any of the PGL products or wastes. Three of the PGL processes generate water as a by-product and this wastewater is likely to be contaminated with whatever constituents are found in the pyrolysis oil (e.g., benzene and toluene). One process uses water to condense the pyrolysis gas, after which the water is separated and reused. The process is likely to generate a large volume of wastewater, and the water is likely to be contaminated with the pyrolysis products. Another PGL process uses water to lubricate the tire shredders. Lastly, one PGL process uses water in its char separation process. No process identified pyrolysis oil as a potential waste.

Overview of Applicable Liquid Waste Statutes

The basic framework for state water pollution control is the Porter-Cologne Water Quality Control Act [5-17]. Under the Porter-Cologne Act, the discharge of a pollutant from a point source into any waters of California, except as authorized by permit, is illegal. California has been delegated responsibility for implementation of the federal National Pollutant Discharge Elimination System (NPDES) program to regulate discharges to surface waters within California. Generally, a tire PGL facility may have two types of discharges: process wastewater and stormwater runoff.

Process wastewaters might be produced from once-through cooling or cooling tower blowdown, or from process waters that come into contact with tires prior to PGL or with the products after PGL. Examples of specific references to process wastewaters are discussed below.

- BBC Engineering and Research. The cooling water is used in a closed-loop system and reportedly does not come into contact with any of the pyrolysis products or wastes [5-18].

- Pyrovac. The process water comes into contact with the char, steel, and fiber; water may also be used in two air pollution control scrubbers. The process wastewater is discharged to a wastewater treatment plant. The nature of the treatment was not reported [5-19, 5-20].

- RMAC International. The process water is used to lubricate the tire shredders. The water may come into contact with tires prior to pyrolysis. The composition of the wastewater and its possible treatment were not reported [5-21].

General permit requirements apply to stormwater discharges from tire PGL facilities. For further discussion, see the Tire Storage Management section.

Liquid Waste Management Options

For facilities that directly discharge process wastewaters, a state NPDES permit would establish specific effluent limitations and conditions regarding discharges to surface waters. Monitoring and reporting requirements ensure compliance with the applicable effluent limitations and water quality standards. Certain processes generate wastewater that may contain some of the PGL products (e.g., benzene and toluene) because the wastewater comes into contact with the PGL gas and/or char. If a process wastewater contains a significant amount of organic PGL products, some onsite pretreatment would be required. In addition, if a facility discharges to a publicly owned treatment work (POTW), these indirect discharges would be regulated by pretreatment standards [5-22]. Pretreatment standards protect the operation of POTWs (e.g., prohibit the introduction of pollutants that create fire or explosion hazards) and prevent the discharge of pollutants that might pass through POTWs without receiving adequate treatment.

Information on the stormwater requirements for a tire PGL facility can be found in the discussion on Tire Storage Management.

Air Pollutant Emissions

General Background

The tire PGL process generates a gaseous product in addition to the char and oil products mentioned earlier. This product gas typically contains low molecular weight hydrocarbons, including simple alkanes and alkenes. This gas is often used to fuel the process after startup, because its similarity to methane and propane allows for easy substitution. Alternatively, the product gas may be sold to local utilities for similar heating purposes, or flared onsite. Emissions from a PGL facility could result either from the burning of natural or product gas to heat the reactor or from leaks from imperfect joints in the equipment, i.e., fugitive emissions. Therefore, a tire PGL plant as a first-order approximation will have an impact on the surrounding air quality similar to industrial processes that combust natural gas to provide heat.

The survey revealed little data regarding air emissions. The discussion that follows is based on qualitative or quantitative information obtained via the survey or from the literature.

The stack emissions are likely to parallel common natural gas stack emissions, because the product gas is high in small straight-chained hydrocarbons, such as methane, ethane, propane, and similar alkenes. Constituents of concern for stack emissions would be products of incomplete combustion, such as carbon monoxide, carbon dioxide, as well as sulfur and nitrogen oxides and particulates. The carbon monoxide formed in the product gas is of some concern, because it is a relatively stable compound and considerable energy and oxygen are needed to convert it to carbon dioxide. If excess product gas is flared, similar constituents of concern exist.

A large percentage of the universe of chemical compounds that are considered toxic contain one or more of the halogen family (i.e., fluorene, chlorine, bromine, and iodine). The products of tire PGL are unlikely to contain halogenated compounds, because tires do not contain halogens. However, if tires are pyrolyzed with other materials, a much wider range of potential pollutants could be expected.

Another source of air pollutants is fugitive emissions from joints and valves and from the handling and processing of char. No quantitative estimates of fugitive emissions could be found in the literature.

Fugitive emissions may contain volatile organic compounds (VOCs) and may be caused by worn or loose packing, valves, or pipe connections. The composition of the fugitive emissions is a combination of pyrolytic gas and non-condensed light oils [5-23]. The primary constituents of pyrolytic gas would be hydrogen, methane, ethane, propane, and propylene. Constituents of light oil include toluene, benzene, hexane, styrene, and xylene [5-24]. Based on an estimated model plant with a capacity of 100 tons per day, a typical PGL facility would emit about 100 pounds of VOCs per day, or 21 tons per year [5-25]. Fugitive emissions of particulate matter occur during screening, handling, and processing of char. The emissions contain carbon black, sulfur, zinc oxide, clay fillers, calcium and magnesium carbonates, and silicates, all of which may produce particulate matter emissions less than or equal to 10 microns in diameter.

Overview of Applicable Air Pollutant Statutes and Regulations

The California Clean Air Act establishes the basic requirements for air pollution control [5-26]. The regulatory process that a PGL facility would have to go through, in order to operate in California, will vary depending on the size of the facility, its total emissions, specific stack emissions, the air basin in which the facility is sited, and the health risk posed to the surrounding area. Monitoring requirements, emissions offsets, best available control technology (BACT), and other requirements would be established in the permitting process. Some of the programs and regulations that the facility will have to comply with are described below.

California established ambient air quality standards at which no adverse effects would be experienced. Areas that meet or are below these levels are considered attainment areas. Areas that have ambient air concentrations above these levels are non-attainment areas. Currently, California ambient air quality standards exist for the following pollutants:

- ozone (O_3);
- carbon monoxide (CO);
- nitrogen dioxide (NO_2);
- sulfur dioxide (SO_2);
- particulate matter (PM_{10});
- sulfates (SO_4);

- particulate lead (Pb);
- hydrogen sulfide (H_2S); and
- visibility reducing particles [5-27].

If the area in which a facility is to be located is an attainment area, the facility would have to go through Prevention of Significant Deterioration (PSD) and New Source Review. The PSD program seeks to prevent facilities from lowering the air quality in an area that has acceptable air quality. If the facility were to be located in a non-attainment area, the facility would have to obtain emission offsets [5-28]. These offsets must be somewhat greater than the potential emissions of the new facility such that a net air quality benefit is produced in the non-attainment area.

Actual emission limitations and operating requirements would be established in a two-staged permitting process [5-29]. The first permit required would be the authority to construct and the second would be the authority to operate. In addition, under California's Air Toxic "Hot Spots" Information and Assessment Act, a facility that either emits any toxic air pollutant (that is, any substance listed in Section 112 of the Federal Clean Air Act or on the AB 2588 List of Substances in California's regulations) or specific criteria pollutants (e.g., particulate matter or nitrogen oxides) above certain levels must prepare an emissions inventory [5-30]. This inventory must be updated every two years. The local air quality district also may require a facility to perform a risk assessment based on this inventory.

Characterization of Air Emissions

The information available on product gas from the 17 responding PGL processes is summarized in Table 5-2. Very little information is available, and it is reported in such a variety of formats that comparing the different processes is difficult. The product gas is never released directly to the atmosphere and should not be confused with stack emissions. The product gas is burned for fuel in the PGL process, in a flare, or as fuel by some other process. These uses appear to adequately destroy the hazardous organic air pollutants typically found in the product gas.

Additional information on the PGL gas from Conrad's process can be found in Table 5-3. Specifically, the pyrolytic gas is reported to contain a variety of hazardous air pollutants: chromium, manganese, mercury, nickel, bis-(2-ethylhexyl) phthalate, naphthalene, phenol, benzene, ethylbenzene, toluene, and xylenes, all of which are considered hazardous air pollutants under Section 122 of the Federal Clean Air Act. In addition, aluminum, zinc, and butyl benzyl phthalate, which were also found in the gas, are listed in California air regulations under the air toxics hot spots listing [5-31].

Air Pollutant Control Options

Based on a review of the literature and results from the survey, two primary methods are available for controlling the emission of air pollutants from the PGL facility: burn the PGL gas in an incinerator (e.g., burn it as fuel in the PGL process) or burn it in a flare. Both of these options have been successfully used to reduce the potential air emissions from the PGL gas [5-33]. It appears that no air pollution control devices or scrubbers have been required in order to comply with emission limits. In most of the literature, the flare is considered the pollution control equipment. Conrad's facility does not have any pollution control devices except for the outside flare for the excess pyrolysis gas [5-34].

One potential concern with relying on a flare to manage excess pyrolysis gas is the difficulty in accurately monitoring emissions or establishing parameters for emissions. Continuous emission monitoring systems (CEMS) are not available for flares. Another pollution control option would be to use a fume incinerator to burn the excess pyrolysis gas. With the use of a fume incinerator, stack monitoring ports would allow the use of CEMS to more closely monitor air pollutant emissions. Air pollution control measures also could reduce fugitive emissions at a tire PGL facility. Fugitive VOC emissions could be reduced by the use of components (e.g., pumps, valves, and compressors) specifically designed to minimize fugitive emissions. Proper operating procedures that provide for training and good maintenance practices could also reduce fugitive emissions. Finally, operations which generate fugitive emissions, such as screening, grinding, and processing, could be controlled with dust collectors and baghouses.

Potential Environmental Impacts from the Storage of PGL Products

California does not require any beneficial use approvals for the tire PGL products [5-35]. In addition, no testing is required for products. Testing of products will probably occur, however, to the extent necessary to determine if a product meets industry specifications (e.g., specifications for carbon black and for oil).

The storage of pyrolysis products such as oil may cause environmental impacts. The typical size of a tire pyrolysis oil storage tank is 10,000 gallons. Fugitive emissions of VOCs and spills and releases of oil from these tanks are regulated by California's Aboveground Petroleum Storage Act [5-36]. State regulations control fugitive emissions through requirements for vapor recovery systems and design and operating standards. Similarly, design and operating requirements (e.g., dikes and monitoring) can control releases and spills.

Table 5-2. Mean Values of Air Pollutant Emissions - All Tire PGL Projects

Pollutant	Units	Rate	n (a)
SOx	lb/ton tires	9.7	3
	lb/ton char	34.8	3
	lb/ton/oil	19.6	3
NOx	lb/ton tires	11.0	3
	lb/ton char	37.9	3
	lb/ton/oil	22.6	3
Particulate	lb/ton tires	0.5	2
	lb/ton char	1.2	2
	lb/ton/oil	1.3	2
HCl	lb/lb tire	$< 3.6 \times 10^{-7}$	
		0.00027	1
H_2SO_4	lb/lb tire	0.44	1

(a) n = number of projects reporting quantities.

Source: Survey information

Table 5-3. Hazardous Constituents in Conrad's Tire-Derived Gas

Pollutant	Concentration ug/m^3
aluminum	1.51
chromium	0.82
mercury	0.05
nickel	2.95
manganese	0.09
zinc	0.65
benzene	20.2
bis-(2-ethylhexyl) phthalate	10.2
butylbenzyl phthalate	1.7
ethylbenzene	24.1
naphthalene	2.87
phenol	1.4
toluene	30.8
xylenes	16.2

Source: [5-32]

Resource Utilization

The tire PGL processes examined require relatively few resources because the current processing capacities are small (i.e., less than 47 TPD) and the processes are not resource intensive on a unit capacity basis. Some of the processes use water for cooling and the separation of products (see Table 5-4), but the volumes are quite small, as illustrated by the generation rate for process wastewater in Table 5-1. Most of the processes use natural gas or propane during startup and shutdown, but burn pyrolysis products to provide heat during normal operations. The information available on water and external energy use is summarized in Table 5-4. Feedstocks are discussed in Section 3.

References

[5-1] Energy Task Force of the Urban Consortium for Technology Initiatives (Energy Task Force), *Waste Tire Recycling by Pyrolysis*, October 1992, p. 23.

[5-2] California Resources Control Board, *Fact Sheet for National Pollutant Discharge Elimination Permit: General Permit for Storm Water Discharges Associated With Industrial Activities Excluding Construction Activities*, December 18 1991.

[5-3] The United States Environmental Protection Agency's requirements for stormwater discharges associated with industrial activity can be found at 40 CFR § 122.26.

[5-4] United States Environmental Protection Agency (U.S. EPA), *Burning Tires for Fuel and Tire Pyrolysis: Air Implications*, December 1991, p. 1-11.

[5-5] Cal. Pub. Res. Code §§ 42800-42855.

[5-6] Cal. Admin. Code tit. 22, Chapter 11 (also referred to as the California Code of Regulations). For the purposes of this discussion, no distinction is made between a RCRA hazardous waste and non-RCRA hazardous wastes (not a RCRA hazardous waste but the waste exhibits at least one of the state's more stringent corrosivity or toxicity characteristics).

[5-7] Cal. Health and Safety Code §§ 25100-25250.25.

[5-8] Christopher Marxen, California Environmental Protection Agency, *Classification of Hazardous Wastes in California*, undated, p. 160.

[5-9] Cal. Health and Safety Code § 24124.

[5-10] Cal. Admin. Code tit. 22, §§ 66261.30-66261.33.

Table 5-4. Summary of the Water and External Energy Use by Tire PGL Processes

	Resources Used	
Company/Process	**Water**	**External Energy**
AEA-Beven		Electricity
American Ecological Technologies	Used in char separation	Natural gas or propane for startup
American Tire Reclamation	Cooling water	Natural gas or propane for startup and shutdown
BBC Engineering and Research	Cooling water (closed-loop)	Propane or nuartual gas for startup
Champion		Natural gas or propane for startup
Cheyenne Industries		Natural gas for startup
Conrad Industries		Natural gas or propane No. 2 fuel oil for startup
Hamburg, Univ. of		Propane for startup
Pyrovac	Cooling water	Gas
RMAC International	Used in tire shredding	Scrap wood for startup
Seco/Warwick	Cooling water and boiler make-up water (200 gpm)	Propane (5,000 cfh at 1 psi) Electricity (200 kW)
Worthing	Cooling water (closed-loop)	Propane for startup

Source: Survey information

[5-11] Cal. Admin. Code tit. 22, § 66261.22.

[5-12] U.S. EPA, p. 8-16.

[5-13] *The Tire Recycler*, MDP Model TP-2000, AEA-Beven, February 23, 1993.

[5-14] Rogers, John D., Premium Enterprises, Inc., ICF, telephone conversation, July 1993.

[5-15] Card, Richard, Texaco, Inc., ICF, telephone conversation, July 1993.

[5-16] Fransham, Peter, Worthing Industries, ICF, telephone conversation, July 1993.

[5-17] Cal. Water Code §§ 13370-13389.

[5-18] Black, John, BBC Engineering and Research, ICF, telephone conversations, July 1993.

[5-19] Roy, Christian, "Vacuum Pyrolysis of Scrap Tires," Presented at Waste and Scrap in the Rubber Industry: Treatment and Legislation, Brussels, Belgium, September 23, 1992, page 4.

[5-20] Roy, V.; de Caumia, B.; and C. Roy, "Development of a Gas-Cleaning System for a Scrap-Tire Vacuum-Pyrolysis Plant," *Gas Separation and Purification* (1992, Vol. 6, No. 2), pp. 83-87.

[5-21] Weege, Don, RMAC International, ICF, Telephone conversation July 1993.

[5-22] 40 CFR Part 403.

[5-23] U.S. EPA, p. 8-15.

[5-24] U.S. EPA, p. 8-18.

[5-25] U.S. EPA, p. 8-16.

[5-26] Cal. Health and Safety Code §§ 39000-44384.

[5-27] Cal. Admin. Code tit. 17, § 70200.

[5-28] Emission Offset Interpretive Ruling, 40 CFR Part 51, Appendix S.

[5-29] Cal. Health and Safety Code § 40506.

[5-30] Cal. Health and Safety Code §§ 44300-44384.

[5-31] Cal. Admin. Code tit. 17 Subchap. 3.6, Appendix A.

[5-32] Roy F Weston, Inc., Detroit, MI; Willmington, MA; and West Chester, PA, *Draft - Phase I Due Diligence Evaluation of the Detroit Tire Reclamation, Inc., Project, Section 3 - The American Tire Reclamation Technology Including Product Markets and Environmental Impacts*, prepared for the City of Detroit Policemen and Firemen Retirement System, May 24, 1993.

[5-33] U.S. EPA, p. 8-13.

[5-34] U.S. EPA, p. 8-13.

[5-35] Dietsch, Tom and Diana Range, Cal. Integrated Waste Management Board, ICF, telephone conversation, January 1994.

[5-36] Cal. Health and Safety Code §§ 25270-25270.13.

SECTION 6. PRODUCT MARKETS

General

This section of the report discusses the uses and potential uses of products from PGL systems. Their technical and economic viability as marketable products is examined. Based on the data available, end uses for the products are explored. Potential market size and required product specifications are presented.

Materials Derived from Tire PGL

As presented in Section 4, the products are a solid (either tire-derived char or tire-derived carbon black), a liquid (oil, often including a naphtha fraction), and a gas. Waste products from the PGL processes are discussed in Section 5.

Oil

Oil derived from the tire PGL process is similar to No. 6 fuel oil, as noted in Section 4. No. 6 fuel oil is a low-grade petroleum product with some contamination.

Carbon Black

Carbon black, an important industrial carbon, is any of various finely-divided forms of amorphous (non-structured) carbon. The partial combustion of hydrocarbons produces carbon black. Its uses depend on its chemical composition, pigment properties, state of subdivision, and adsorption activity.

The basic process for manufacturing carbon black is the combustion of fuels with insufficient air, i.e., the partial combustion or thermal decomposition of hydrocarbons in the vapor phase. This combustion produces small carbon black particles, which, when separated from the combustion gases, comprise a fluffy, intensely black powder. In contrast, cokes and chars are formed by the pyrolysis of solids. For the purpose of this section, the material derived from tire PGL will be referred to as carbon black, although the material often resembles a char.

Gas

Gas generated in tire PGL is a product high in carbon dioxide and carbon monoxide content, as shown in Appendix Table D-6.

Steel

Steel scrap extracted from the feedstock of the tire PGL process contains carbon and fiber contaminants but is usually considered a fairly clean scrap iron ready to be marketed.

Variability of End Products

The type of pyrolytic process is an important factor in the quality of the end products. When a batch process is used, removing the steel and carbon black is fairly simple. Continuous tire PGL systems usually grind the tires into chips before processing. Grinding may result in steel and fiber contamination (from the tire belting) of the end products [6-1].

Market Assessment for Materials Generated from Tire PGL

Oil

Tire PGL systems can be operated to generate an oil-based liquid that is approximately 30 - 50 percent of the product derived from the organic content of the tire feedstock. Because different types of tires are pyrolyzed together, the oil generated consists of a combination of oil grades and carbon black. Isolation of a single oil from the mixture for reprocessing is reportedly difficult [6-2].

A source from the Clean Washington Center indicated that there are few tire companies, major reclaimers, or paper mills that will reuse or reprocess oil generated from tire PGL [6-3].

Potential Uses

Use as a Fuel

Oil derived from tire PGL is similar to No. 6 fuel oil. In December 1993, No. 6 fuel oil was selling for approximately $8/barrel [6-4]. No. 6 oil can be fired in burners with preheaters which accept high viscosity fuels. The heating value of an oil determines its value as a fuel. Table 6-1 compares the properties of No. 4 and No. 6 fuel oils with those of tire-derived oil.

Pyrolytic systems presently in operation have provided some insight into possible fuel uses for tire-derived oil.

- American Tire Reclamation, Inc. (ATR) has reported two uses for its tire-derived oil. One use is to fuel an engine-generator using a 50/50 blend of tire-derived oil with diesel fuel. The other use is to fuel a delivery truck with a 10/90 blend of a tire-derived oil and diesel fuel. Emissions from both uses have been reported to be within EPA guidelines [6-6].

- According to the president of ECO2, the company is upgrading the tire-derived oil to meet a No. 4 fuel oil specification. No. 4 is used by industrial boilers and cement kilns [6-2].

- Conrad Industries generates a pyrolytic oil with a heating value of 18,500 Btu/lb. Data are not available on the quantity of oil that Conrad is selling.

  Conrad Industries calculates that 0.39 pounds of oil is generated for every pound of tire input. Thus, based on data presented in Table 4-3, Conrad's 1 ton/hour PGL operation would yield a calculated 2,800 ton/year of oil. Data are not available on the price at which Conrad is selling this oil.

One processor of waste hydrocarbons in California indicated that the pyrolytic oil from PGL systems might have potential as a component of slurry fuels. However, a charge would be imposed for accepting and processing the pyrolytic oil in this application.

Use as a Lubricant

Re-refineries process used oil into a variety of products, including heating oil, gasoline, jet fuel, chemical feedstocks, and plastic feedstocks [6-7]. Pyrolytic oils contain approximately 1 - 1.2 parts hydrogen to every one part carbon.[1]

Lubrication oil contains at least two parts hydrogen for every one part carbon. Upgrading used oil to meet lubricating oil specifications entails adding hydrogen to the hydrocarbon molecule, which requires the use of a pump and a catalyst. This upgrading, according to one source [6-8], is uneconomical and chemically unfeasible for a crude chemical feedstock such as tire-derived oil.

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1 See Table 4-5 for ultimate analysis of tire-derived oils.

Table 6-1. Comparison of Tire-Derived Oil with Fuel Oils

	Units	Tire-Derived Oil	No. 4 Oil	No. 6 Oil
Flash point, min	°C		65	60
Pour point, max	°C		6	
Water and sediment, Max	% by vol.		0.50	1.00
Ash, max	% by wt	0.099	0.1	
Viscosity				
Min	mm^2/g = cST	3.1	5.8	
Max	mm^2/g = cST	6.3	26.4	

Source: Appendix Table D-2 and [6-5].

Furthermore, most re-refiners do not have the technology necessary to process the oil derived from tire PGL. A source at the National Petroleum Refiners Association (NPRA) noted that two technologically-advanced re-refiners in the United States are Evergreen, of Irvine, CA, and Safety Kleen (formerly Preslube), headquartered in Elgin, IL [6-9]. These two companies provided the following analysis of the potential of tire-derived oil as a re-refining feedstock.

- Evergreen Industries examined Appendix Tables D-2 and D-4 and concluded from the limited data that the oil was not suitable for re-refining because of its low viscosity. Evergreen requires an oil with a viscosity of at least 20 centistokes at a 40 degree Celsius temperature [6-10].

- Discussions with Safety Kleen concluded that their operation does not have the distillation technology to attain the necessary boiling range to convert the tire-derived oil to a saturated oil [6-8].

Four other re-refineries were using motor/lubrication oils and/or hydraulic oils as feedstocks, and reportedly lacked the technological capabilities to process the tire-derived oil.

Market Assessment

Tire-derived pyrolytic oil has four potential uses, none of which appears economically feasible at this time, except perhaps in limited, special circumstances. Blending the oil with other fuels to produce a useable fuel is in the research stage. Upgrading the oil to a lubrication oil is technically and economically unattractive. The possibility of upgrading the oil to a higher quality product (e.g., a No. 4 grade), using distillation, is being explored, but the economics are unknown for a commercial-scale operation. Marketing the oil as a fuel is not feasible, because cheaper and cleaner fuels exist.

Carbon Black

General

Carbon exists in two crystalline forms, and numerous amorphous,[2] less-ordered forms. The crystalline forms are diamond and graphite, and the less-ordered forms are mainly cokes and chars.

Carbon blacks have industry standards and they differ in particle size, surface area, average aggregate mass, particle and aggregate mass distributions, structure, and chemical composition. The ultimate

2 Characterized by degenerate or imperfect graphitic structures.

colloidal units[3] of carbon black are called aggregates (i.e., fused assemblies of particles). Carbon black's various uses depend on chemical composition, pigment properties, state of subdivision, adsorption activity, and other colloidal properties.

Conformity with industry standards determine the marketability of the tire-derived carbon black. Researchers at the University of Laval (Ste-Foy, Quebec) state that the main disadvantage of recycling the char from tire PGL as carbon black is its high inorganic (ash) content [6-11]. Furthermore, recent improvements in virgin carbon black production have fostered markets for many specialized grades of carbon black. Recovered carbon char from tire PGL units reportedly does not meet these new standards [6-11].

Surface Area

Based on discussions with two of the larger manufacturers of carbon black in the United States, the most important property of carbon black is surface area[4] since surface area has a substantial impact on the performance of carbon black in its applications. Mean surface area for tire-derived char is reported in Table 4-7. Standard carbon blacks containing sub-micron particles have a high surface area to volume ratio, as shown in Appendix Table E-1. The average particle size of a commercial carbon black ranges from approximately 5,000 angstroms for a low-cost thermal carbon to approximately 100 angstroms for the most expensive high-color paint carbon. Conversely, the surface area for thermal carbons is approximately 7 - 15 m^2/g, while that of high color carbon is approximately 1,700 m^2/g, as shown in Appendix Tables E-1 and E-2. Surface areas are measured by both gas and liquid phase adsorption techniques and depend on the amount of adsorbate required to produce a monolayer.

Structure

The second most important property of carbon blacks is structure. Structure is determined by aggregate size and shape, the number of particles per aggregate, and their average mass. These characteristics affect aggregate packing and the volume of voids in the bulk material. The measurement of void volume, a characteristic related to structure, is used to assess structure. Mean values of void volume are shown in Table 4-7. Values are within the range of rubber grade carbon blacks.

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3 The smallest dispersible entities in elastomer, plastic, and fluid systems.

4 The industry uses the term "surface area" rather than the more precise "surface area per unit of mass" to describe the parameter measured in m^2/g.

Potential Uses

Use in the Manufacture of Plastic Products

A plastic products manufacturer reported testing tire-derived carbon black as follows.

- Rapco is a southern California business which is testing the use of carbon black generated from PGL to manufacture a plastic product. Rapco is commercializing a plastic and coating technology. Its manufacturing process includes grinding plastic with a chemical formulation and mixing the ground plastic with carbon black. Rapco has been using carbon black derived from plastic, but prefers tire-derived carbon black as it is cleaner and more abrasive in their manufacturing process [6-16]. Rapco is pursuing tire PGL operations which will sell the carbon black material to them for $0.07 - 0.08/pound. Rapco examined the data provided in Appendix Tables D-1 and D-5 and found them to meet the specifications of its manufacturing process.

  In December 1993, Rapco was actively pursuing the purchase of a tire pyrolysis unit. The company reported an interest in developing a joint venture tire PGL project. The company estimated that it will need 20 ton/day of tire-derived carbon black [6-16].

Upgrading to Carbon Black

Most commercial rubber-grade carbon blacks contain over 97 percent elemental carbon, with bulk densities between 16 and 32 lb/ft^3 [6-5]. Generally, the percentage of elemental carbon is a relatively less important consideration than surface area or structure. In addition to chemically combined surface oxygen, carbon blacks contain varying but minimal amounts of moisture, solvent-extractable hydrocarbons, sulfur, hydrogen, and inorganic salts.

Although none of the product data available to this study met the 97 percent elemental carbon requirements of a rubber-grade carbon black, PGL operators have reported possibilities for beneficiating their carbon black material. The mean value of reported carbon content is 91.5 percent, as shown in Table 4-5.

- American Tire Reclamation, Inc. (ATR) refines tire pyrolyzed carbon black residue to produce a carbon-rich powder with semi-reinforcing characteristics similar to virgin carbon blacks for use in rubber goods. A graphitic powder is also produced which can be used in modified asphalts as a compatible additive for road construction [6-6].

- The president of ECO2 reported that buyers of carbon black from its system include manufacturers of low-grade carbon products such as hoses and solid rubber tires [6-2]. ECO2 sells tire-derived carbon black to commodity companies and brokers at $0.10/pound, or $200/ton [6-12].

- Conrad Industries indicated that their PGL operation is also upgrading the tire-derived char material to a carbon black product [6-13].

Industry experts estimate that virgin carbon black production capacity worldwide exceeds demand by 10 percent [6-7]. Virgin carbon black sells for between $0.25 and $0.30/pound ($500 - 600/ton), with 1.65 million tons sold in the United States each year [6-5]. While the potential exists to upgrade tire-derived char to carbon black, there is insufficient data in the literature to judge the cost of upgrading tire-derived char to any specific grade and specification of carbon black.

Use as Special Carbon Blacks

Tire-derived carbon char is produced in the size range of 10 - 100 microns, as shown in Table 4-7. This particle size range limits the ability of the material to be substituted for standard carbon blacks containing sub-micron particles. However, some special carbon black grades containing particles with lower surface areas (i.e.., larger particle sizes) may be used for applications in plastics to improve weathering resistance, or to impart antistatic and electrically conductive properties [6-5]. Appendix Table E-2 lists the types and applications of special carbon blacks.

- The data from Laval University show a surface area of 85 m^2/g (using the CTAB method), a DBP result of 95 ml/100g, and a volatile content of 2.8 percent. Given its low surface area and high volatile content, the tire-derived carbon black from Laval University does not fit the properties of special carbon blacks in Appendix Table E-2, but more closely resembles carbon blacks used for inks, paints, and plastics in Appendix Table E-1.

- The material sampled from NATRL contains a surface area of 40 m^2/g, a DBP result of 76 ml/100g, and an unknown volatile content. Given these properties and an appropriate volatile content, the sampled material may fall under the "low color" type, a blue toned tinting black, to be used for inks, paints, sealants, plastics, and cements.

Given the appropriate volatile content, the reports from Laval University and NATRL indicate that the carbon black from their PGL units may be marketed for special carbon black usage.

Use as a Printing Ink

Over 40 special black grades have been developed having a broad range of properties from 20 m^2/g surface area grades used for inexpensive inks and tinting to oxidized, porous low-aggregation grades of approximately 500 m^2/g used for high color enamels and lacquers [6-14]. A few of these special pigment grades have carbon contents below 90 percent [6-5]. Appendix Table E-1 illustrates properties of carbon blacks which can be used for inks, paints, and plastics.

The 87.5 percent fixed carbon content of ATR tire-derived carbon black suggests that it may fall under an HCF category of carbon blacks (i.e., "high color furnace" - a virgin carbon black category). Given the appropriate surface area, aggregate size, and tinting strength of the material, this material could be marketable as an ink, paint, or plastic.

Use as an Activated Carbon

Activated carbon is a microcrystalline, nongraphitic form of carbon that has been processed to develop internal porosity. Whereas standard carbon blacks are characterized by a surface area of between 20 - 500 m^2/g, activated carbons are characterized by a higher surface area, ranging from 300 - 2,500 m^2/g. This large surface area allows the physical adsorption of contaminants from gases and the dissolved or dispersed substances from liquids.[5] Commercial grades of activated carbon are designated as either gas-phase or liquid-phase adsorbents. Liquid-phase carbons are generally powdered or granular in form; gas-phase, vapor-adsorbent carbons are hard granules or pellets. Activated carbons are widely used to remove impurities from liquids and gases and to recover valuable substances or control pollutants from gas streams [6-5].

Tire PGL reduces carbon char to micron size particles. The 100 m^2/g and lower surface areas of tire-derived carbon char indicate that the carbon black falls outside the required 300 - 2,500 m^2/g range of an activated carbon. Technically, PGL carbon char may be upgradable to activated carbon. However, economic data and analyses are lacking that would allow an accurate definition of the costs to achieve specific grades of activated carbon versus the properties of PGL carbon char feedstocks.

Use as a Fuel

The char or carbon char material generated from PGL can be used as a source of fuel. Table 4-5 indicates the mean heating value of tire-derived solid (char) (i.e., 13,131 Btu/lb). The heat content of

5 Including potable water.

domestic coals and cokes ranges from approximately 7,200 Btu/lb for lignite to approximately 15,000 Btu/lb for petroleum coke. Some operators have indicated that they are using the char material as a source of fuel. Carbon char from PGL systems could potentially serve as a coal substitute in California. However, the market is limited.

- Conrad Industries reported the heating value of the company's tire-derived carbon black as well as the quantity generated. The company's PGL unit produces 0.37 pounds of carbon for every pound of tire input. Based on operating data in Table 4-3, 2,664 tons of tire-derived carbon black would be generated per year [6-15]. The material has a heating value of 12,000 Btu/lb., or one fourth of the amount of energy required to operate the pyrolysis unit. Thus usage as a fuel in this system would require other substantial energy inputs (e.g., from tire-derived gas).

- Wayne Technologies indicated that they use the tire-derived carbon black material produced by its PGL unit as a fuel to operate the system [6-1].

The emission of particulate matter, sulfur compounds, nitric oxides, hydrocarbons, and other gases resulting from the combustion of fuels is regulated. Because of the concentrated nature of carbon black, atmospheric release is carefully controlled [6-5]. Thus, environmental control should be considered when planning the use of tire-derived carbon black as a fuel.

Coal and coke fuels are usually less expensive and of a higher quality than tire-derived carbon char fuel. Therefore, the ability to compete in these specific markets does not appear feasible at this time.

Market Assessment

Four possible markets exist for the carbon black material derived from tire PGL, although none is presently viable. Upgrading the material for use in rubber products is still in the research phase. Using the carbon black for plastic product manufacture is also in the research stage. Carbon black may be marketed as a fuel. At this time, however, cheaper sources of fuel are available. Finally, marketing the tire-derived carbon black material as a special grade carbon black or for use in inks, paints, or plastics may be possible under certain conditions.

Gas

As shown in Appendix Table D-6, tire PGL produces a gas that contains relatively high concentrations of methane and ethane, and thus resembles a natural gas. Most pyrolytic operations use this gas as a fuel.

The large amounts of carbon monoxide and carbon dioxide in the gas are not conducive to blending with a natural gas. Thus, the gas is best used solely as a fuel for process [6-2].

- Wayne Technologies reported that the PGL process yields three to five times more energy than needed to fuel the process. Most facilities flare the excess. It would be possible to use a steam generator to capture the excess through co-generation, but the throughput of the PGL system would need to be large in order to make this alternative economically feasible [6-1].

Potential Uses

- Conrad Industries generates a gas from its PGL operation with a heating value of 1,000 Btu/scf, which heats the firing chamber of the PGL unit. The company estimates that once the tires are fed into the unit, the pyrolytic gas produced takes over and sustains the machine. The system then runs on 10 - 15 percent of the gas it produces and generates 8,000 ft^3/hour of gas. The excess gas can be directly piped to burners, boilers, or internal combustion engines or compressed and stored for future use, for example as a fuel in a manufacturing process.

Market Assessment

The gas generated by tire PGL is most efficiently used to fuel the process of PGL.

Steel

Due to the variability of the quality of steel and fiber extracted in the pre- or post-pyrolyzing process, specific issues related to the marketability of steel generated from pyrolytic systems could not be examined. However, scrap metal industry sources were surveyed.

- Most scrap metal brokers and processors accept only clean scrap iron and steel. Markovits and Fox, a scrap metal recycling firm in California, confirmed this concept and indicated that steel prices range from $10 - 20/ton based on the cleanliness of the material [6-17].

Estimates on quantities of steel extracted from tire PGL differ. The Scrap Tire Management Council and a source from Resource Recycling reported that the 2.5 pounds (12.5 percent) of steel obtained from a 20-pound tire is clean enough to market [6-18]. Conrad Industries reported generating 50 - 60 lb (2.5 percent) of steel and fiber per ton of tires [6-15]. This variation likely represents the differing emphasis placed on steel recovery by different developers, probably in response to local market conditions or technical considerations.

- The president of ECO2 reported that 2,500 pound bales of scrap have been sold to scrap processors for between $30 and $60/ton [6-12].

In cases where the tires are shredded, steel may be generated in small pieces. One way to increase the economic efficiency and marketability of it would be to bale the steel. The cost of a baler affects the feasibility of selling the scrap material.

- At the operation rate of Conrad's unit shown in Table 4-3, 180 tons of steel are generated per year [6-15], and given the higher selling price of $60/ton, Conrad could collect a calculated $10,800/year selling the steel, excluding processing and transportation costs.

Market Assessment

The scrap steel generated from tire PGL is clean enough to be sold to scrap processors. The feasibility of marketing the steel is based on a number of factors: cleanliness (e.g., fiber contamination), quantity, packaging, and transportation and storage costs.

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SECTION 7. COST SENSITIVITY ANALYSIS

Introduction

This section reports cost and revenue information compiled during the study, presents data collected on tire tip fees in various parts of the state, and then discusses the sensitivity of project economics to changes in key project variables. The sensitivity analyses were performed on project alternatives considered by CalRecovery to be representative of the state of the PGL technology.

Reported Project Economics

Cost information was assembled from survey responses and literature. Costs for both tire-only projects and mixed feedstock PGL systems were used. Because the PGL industry has little full-scale experience, costs presented represent both actual laboratory-, pilot-, or demonstration-scale experience, and also estimates of the economics of planned systems. Those few operators with actual full-scale operating experience were reluctant to share information with an audience that could include competitors.

Four mixed-feedstock PGL systems that did not handle tires were included in the analysis. These systems had been developed through research into processes that produce liquid fuels from biomass, i.e., wood [7-1, 7-2]. Two liquefaction systems included in the analysis were atmospheric flash pyrolysis (AFP)[1] and liquefaction in pressurized solvent (LIPS). Liquefaction involved primary liquefaction to a crude product, catalytic hydrotreating to deoxygenate the crude, and refining to gasoline or diesel oil [7-2]. The two pyrolysis systems included in the analysis were a pyrolysis oil hydrotreating process developed at Georgia Tech and elsewhere, and a zeolite-catalyst upgrading[2] process based on research by the National Renewable Energy Laboratory. The analysis included cost estimates for typical 1000 dry metric ton/day plants. Also, four MSW PGL projects were included, based on survey results.

Estimates that follow include capital costs, annual operating and maintenance costs, product revenues, tire tip fees, and project economics.

Capital Cost Estimates

For purposes of the study, capital costs were defined to include the following:

---

1 A liquefaction process.

2 Applied to pyrolysis vapors.

- land acquisition;
- site preparation (site grading and drainage, roads, utility interconnections, and landscaping);
- process equipment (purchasing and installing fixed and mobile equipment to process the feedstock, as well as auxiliary equipment, e.g., startup reactor heating systems, air pollution control systems);
- structures (buildings to enclose the process equipment and store the feedstock); and
- indirect costs (engineering, design, permitting, legal, and administrative costs of construction).

Some developers provided the costs of process equipment only. These developers did not report the costs of necessary buildings or other structures.

The mean reported capital costs for the tire pyrolysis, gasification, and liquefaction systems surveyed are presented in Table 7-1. The reported costs are based on both operating and planned PGL projects. Data were unavailable for capital costs for mixed feedstock PGL projects.

Cost subcategories are also presented in the table, when available. As shown in the table, the number of facilities reporting data varies for each cost subcategory. All capital costs in this section are presented in 1993 dollars.

Operating Cost Estimates

Complete reports of the operating costs included the following categories:

- labor (cost of plant staff and labor overhead; excludes corporate management costs);
- feedstock purchases (e.g., tire or wood buying) -- occurred in only a few of the projects selected for the analysis;
- equipment maintenance (lubricants and spare and replacement parts);
- process operations (electricity, gas, water, wastewater disposal, and fuel for space heating and on-site mobile equipment); and
- general and administrative (G&A) costs (non-labor insurance, permits, environmental monitoring services, taxes, and corporate management).

Table 7-1. Mean Values of Reported Capital Costs - Tire Projects

	Pyrolysis		Gasification		Liquifaction	
	N	Cost	N	Cost	N	Cost
Total Number Reporting (a)	14		4		2	
Mean Throughput (TPY)	12	17,629	3	16,631	2	17,082
Capital Cost Categories (b)						
Land	2	$1,100,000		N/R (c)		N/R
Site Work	1	$340,000		N/R		N/R
Process Equipment	5	$3,360,552	1	$3,500,000		N/R
Structures	2	$1,002,563		N/R		N/R
Indirect Cost	3	$1,581,043		N/R		N/R
Total Capital (d)	12	$6,533,395	3	$4,527,500	2	$2,500,000

Source: Survey information.

(a) Total number of projects reporting data. Values in "N" columns indicate number of data points for each reported cost category.
(b) Represents the mean value of individually reported cost categories.
(c) N/R = not reported.
(d) Represents the mean value of all reported capital costs, including individually reported total costs. Due to differences in the number of projects reporting in each category, may not equal the sum of individually reported values.

Table 7-2 presents the mean reported annual operating costs for tire PGL projects and compares the costs with those for mixed feedstock projects. The reported costs are based on both operational and planned PGL projects. Operating cost data were unavailable for tire liquefaction projects. For tire gasification projects, only estimates of the total annual costs of operation were available. For the other gasification projects, data were unavailable.

Cost subcategories are also presented in the table, when available. As shown in the table, the number of facilities reporting data varies for each cost subcategory. All operating costs in this section are presented in 1993 dollars.

Estimates of Revenues

The mean annual revenues (in 1993 dollars) from the tire PGL projects are presented in Table 7-3. As indicated by the number of projects reporting for each product, the types of products produced varied among the projects.

The product revenues presented in Table 7-3 are calculated based on the unit sales price for the product (as reported by the facility) and the estimated quantity of product produced per ton of throughput. Consequently, the revenues reported in the table assume that the entire product stream is sold at the reported unit sales price.

Based on the data in Table 7-3 for tire pyrolysis projects, solid carbon products account for the majority of the product revenues (approximately 78 percent). Fuel oil accounts for about 20 percent of product revenues, and scrap steel for approximately 2 percent. Tire tip fees yielded a mean value of $1,271,300 annually.

The reported unit sales prices (mean, maximum, and minimum) for each tire-derived product stream are presented in Table 7-4. The table also lists the sales prices for comparable virgin commodities.

Project Economics

The costs and revenues of the reported tire PGL projects are presented in Table 7-5 on a $/ton of throughput basis, and are compared with those of mixed-feedstock PGL projects. The product revenues presented in the table are based on the revenues presented in Table 7-3, and thus assume that the entire product stream is sold at the reported unit sales price.

Table 7-2. Mean Values of Reported Operating Costs - Tire Projects Compared with Estimates for Similar Projects

	Tire Projects						Other (a)					
	Pyrolysis		Gasification		Liquifaction		Pyrolysis		Gasification		Liquifaction	
	N	Cost	N	Cost	N	Cost	N	Cost	N	Cost	N	Cost
Total Number Reporting (b)	14		4		2		4		2		2	
Mean Throughput (TPY)	12	17,629	3	16,631	2	17,082	4	171,394	2	121,250	2	330,000
Operating Cost Categories (c)												
Labor	4	$398,570		N/R (d)		N/R	2	$2,410,453		N/R	2	$7,784,683
Feedstock Purchases	2	$216,930		N/R		N/R	2	$15,454,886		N/R	2	$27,568,033
Equipment Maintenance	4	$183,505		N/R		N/R	2	$756,844		N/R	2	$2,035,211
Process Operations	5	$311,763		N/R		N/R	2	$699,604		N/R	2	$8,795,929
General & Admin. (G&A)	3	$223,250		N/R		N/R	2	$2,967,416		N/R	2	$3,408,979
Total Operating Cost (e)	7	$2,049,571	1	$176,471	N/A		2	$22,279,204	N/A		2	$49,592,835

Source: Survey information

(a) Includes projects using MSW or wood as feedstocks.
(b) Total number of projects reporting data. Values in "N" columns indicate number of data points for each reported cost category.
(c) Represents the mean value of individually reported cost categories.
(d) N/R = not reported; N/A = not applicable.
(e) Represents the mean value of all reported operating costs, including individually reported total costs. Due to differences in the number of projects reporting in each category, may not equal the sum of individually reported values.

Table 7-3. Mean Values of Reported Annual Revenues - Tire Projects (a)

	Pyrolysis		Gasification		Liquefaction	
	N	Revenue	N	Revenue	N	Revenue
Total Number Reporting (b)	14		4		2	
Mean Throughput (TPY)	12	17,629	3	16,631	2	17,082
Product Revenues (c,d)						
Fuel Oil	6	$747,814		N/R	2	$2,423,303
All Solid Carbon Products	5	$2,919,681		N/R	2	$1,226,452
Gas		N/R		N/R	1	$128,544
Energy		N/R	1	$505,882		N/R
Steel	5	$77,667		N/R	2	$108,540
Fiber		N/R	1	$35,294		N/R
All Product Revenues (e)	7	$3,498,431	2	$541,176	2	$3,822,567
Tip Fee	2	$1,271,300	2	$469,584	2	$499,200
All Revenues (f)	7	$3,861,659	2	$740,172	2	$4,072,187

Source: Survey information.

(a) Product revenues are calculated based on the unit sales price for the product as reported by the facilities, and the estimated quantity of product produced per ton of throughput. Thus, revenues reported assume the entire product stream is sold at reported unit sales prices.
(b) Total number of projects reporting data. Values in "N" columns indicate number of data points for each reported revenue category.
(c) Represents the mean value of individually reported revenue categories.
(d) N/R = no reported revenues.
(e) Represents the mean value of all reported product revenues. Due to differences in the number of projects reporting in each category, may not equal the sum of individually reported values.
(f) Represents the mean value of all reported revenues.

Table 7-4. Unit Prices of Tire-Derived Products Compared with Unit Prices of Virgin Products

		Tire-Derived Products (a)					Virgin Products	
Product	**Units**	**No. of Entries**	**Mean Price**	**Standard Deviation**	**Maximum Price**	**Minimum Price**	**Price**	**Source**
Fuel Oil	$/lb	12	$0.065	$0.054	$0.232	$0.032	$0.027	A
	$/bbl	12	$21.19	$17.56	$75.60	$10.50	$8.000	A
	$/gal	12	$0.504	$0.418	$1.800	$0.250	$0.190	A
Activated Carbon	$/lb	2	$0.210	$0.141	$0.310	$0.110	$0.280	C
Carbon Black	$/lb	7	$0.176	$0.121	$0.430	$0.100	$0.275	A
Filler Carbon	$/lb	1	$0.080	N/A (b)	$0.080	$0.080	$0.080	A
Gas	$/ccf(c)	1	$1.000	N/A	$1.000	$1.000	$0.680	D
Electricity	$/kWhr	1	$0.060	N/A	$0.060	$0.060	$0.100	D
Steel	$/ton	8	$74.38	$25.42	$120.00	$45.00	$32-45	B

Source: Tire-derived product prices from survey. A, from Section 6. B, from Recycling Times, August 1993, West baled steel can prices. C, based on discussions with Calgon Carbon, Barneby-Sutcliffe, and Sorb-Tech, activated carbon manufacturers, regarding value of low-quality activated carbon. D, from Pacific Gas & Electric, typical rate for small industrial customers.

(a) Prices reported by two projects for fiber were $22.50 and $140/ton.
(b) N/A = Not applicable.
(c) ccf = 100 cubic feet.

The data in the table indicate the following for tire pyrolysis projects:

- The annual unit costs for tire pyrolysis systems are high ($156/ton of throughput, equivalent to $1.56/tire). A significant revenue stream is required from the sale of products, tire tip fee, or both.

- If all products are sold at the reported prices, tire pyrolysis projects will produce net revenues, even without the revenue from a tip fee on tires.

- If all products are sold at 50 percent of the reported prices, a tire tip fee of over $61/ton ($0.61/tire) would be required to result in a net profit.

The sensitivity of the economics of tire pyrolysis projects to key variables (i.e., carbon product sales, tire tip fee, and annual costs) is discussed later in this section.

Tire Disposal Costs in California

Tire disposal costs in the state vary widely. In southern California, one landfill charged approximately $38/ton at the end of 1993 to dispose of tires. A San Joaquin Valley landfill charged more than three times that amount ($125/ton). A landfill near San Jose charged $1,500/ton (equivalent to $15/tire). At most disposal sites, tip fees were higher for truck tires than for car tires. In the San Francisco Bay Area, tip fees varied by a factor of nearly six to one, from $350/ton to $2,000/ton.

Some facilities accepted only small loads of tires, or collected an additional charge for mixed loads containing tires. Some facilities determined charges based on inspections of the loads for size and quality. This sliding scale approach was used frequently for larger loads.

Some facilities accepted only shredded tires. Tip fees in these cases were $65 to $175/ton. The lower tip fees for shredded tires are expected, inasmuch as the cost of tip fees for whole tires must cover the cost of shredding prior to landfilling.

A crumb rubber-producing tire processor reported that a pickup truck load of tires would be charged approximately $1/tire ($100/ton). The Oxford Energy incinerator in central California estimated that a large load of tires would be charged approximately $1.25/tire ($125/ton).

For tire PGL projects to offer an attractive disposal alternative, facilities need to be conveniently located and charge less than landfill or other competing disposal. Assuming that a 25 percent differential tip fee would be attractive, a tip fee range for tire PGL should be in the range of $30 to $1,500/ton ($0.30 to $15/tire).

Sensitivity Analysis

The sensitivity of project economics to changes in key project variables was analyzed for tire pyrolysis projects. Cost and revenue data from the survey and professional judgments of CalRecovery, where appropriate, were used to assess the sensitivity of tire pyrolysis project economics to variations in annual capital costs, O&M costs, and product revenues. The survey and available information in the literature revealed too few data to permit a similar determination of the sensitivity of either tire gasification or tire liquefaction project costs.

Assumptions

A baseline scenario was developed for purposes of analysis based on data reported by the facilities and our judgment. The assumptions used in constructing the baseline scenario are as follows:

- Annual capital costs of $38.37/ton of throughput.
- O&M costs of $118.06/ton of throughput.
- Residue disposal costs of $20/ton.
- Carbon black sales price of $0.128/lb; 75 percent of product sold.
- Char sales price of $0.08/lb; 75 percent of product sold.
- Fuel oil sales price of $0.027/lb; 90 percent of product sold.
- Steel sales price of $0.019/lb; 90 percent of product sold.
- Reported tip fees were not included.

Project costs (capital and O&M) were calculated from mean data for the reporting tire pyrolysis projects (see Table 7-5). The mean value of capital cost was calculated as $101,328/TPD of throughput. For purposes of this analysis, 100 percent of the capital costs were amortized using 8 percent interest over a 15-year period. Operating costs were as presented in Tables 7-2 and 7-5.

Table 7-5. Reported Unit Costs and Revenues - Tire Projects Compared with Estimates for Similar Projects

		Tire			Other		
	Units	Pyrolysis	Gasification	Liquefaction	Pyrolysis	Gasification	Liquefaction
Number of Projects Reporting		14	4	2	4	2	2
Capital Cost	$/TPD throughput	$101,328	$84,845	$48,298	$74,648	$161,938	$67,798
Annual Costs ($/ton)							
Capital (a)	$/ton	$38.37	$30.04	$17.10	$26.43	$57.33	$24.00
O&M	$/ton	$118.06	$20.21	N/R (b)	$67.51	N/R	$150.26
Total	$/ton	$156.43	$50.25	N/A	$93.94	N/A	$174.26
Product Revenues	$/ton	$189.92	$61.98	$223.78	N/R	N/R	N/R
Net Revenues (c)	$/ton	$33.49	$11.73	N/A	N/A	N/A	N/A

Source: Calculated, based on information from Tables 7-1, 7-2, and 7-3.

(a) Amortization of capital costs, 15 years at 8%.
(b) N/R = not reported; N/A = not applicable.
(c) Excludes tip fee.

Product sales prices were determined based on the responses from the project surveys for tire-derived products, data compiled on virgin commodity prices, and our judgment. For char, fuel oil, and steel, the unit sales price was assumed to be the lesser of the mean survey price and the virgin commodity price. The sales price for carbon black was assumed to be at the mid-point between the reported sales prices for carbon black and for char, based on our judgment that a high-quality carbon black would not be produced in all cases. The percentage of product marketed was assumed to be 90 percent for fuel oil and steel, and 75 percent for carbon black and char, because of the fact that recovery (i.e., process yields) in commercial operations is less than 100 percent. The percentages for the carbon products were set at a more conservative level because of the uncertainty of the markets for those products.

Sensitivity to Variations in Costs

The sensitivity of tire pyrolysis economics to variations in capital costs and in O&M costs is presented in Figure 7-1. The analysis presents the tip fee that would be required for a project to break even at various costs, ranging from -20 percent to +20 percent of the baseline scenario.

The capital costs represented in the figure range from \$31 to \$46/ton of throughput; capital costs reported in the survey range from \$10 to \$129/ton. The O&M costs in the figure range from \$94 to \$142/ton of throughput; O&M costs reported in the survey range from \$32 to \$296/ton.

According to the data presented in the figure, a tire pyrolysis project would require on the order of \$0.80/tire tip fee to break even based on capital and O&M costs of approximately \$159/ton of throughput and assumed product revenues of \$79/ton of throughput. Also as depicted in the figure, project economics are significantly more sensitive to variations in O&M costs than in capital costs.

Sensitivity to Variations in Revenues

The sensitivity of tire pyrolysis economics to variations in product revenues is depicted in Figure 7-2. The analysis presents the tip fee that would be required for a project to break even at various revenues, ranging from -20 percent to +20 percent of those assumed for the baseline scenario.

As shown in the figure, project economics are most sensitive to variations in sales prices of carbon products, particularly carbon black. This finding is significant because of the uncertainty of markets for carbon products, especially the higher quality grades of carbon black.

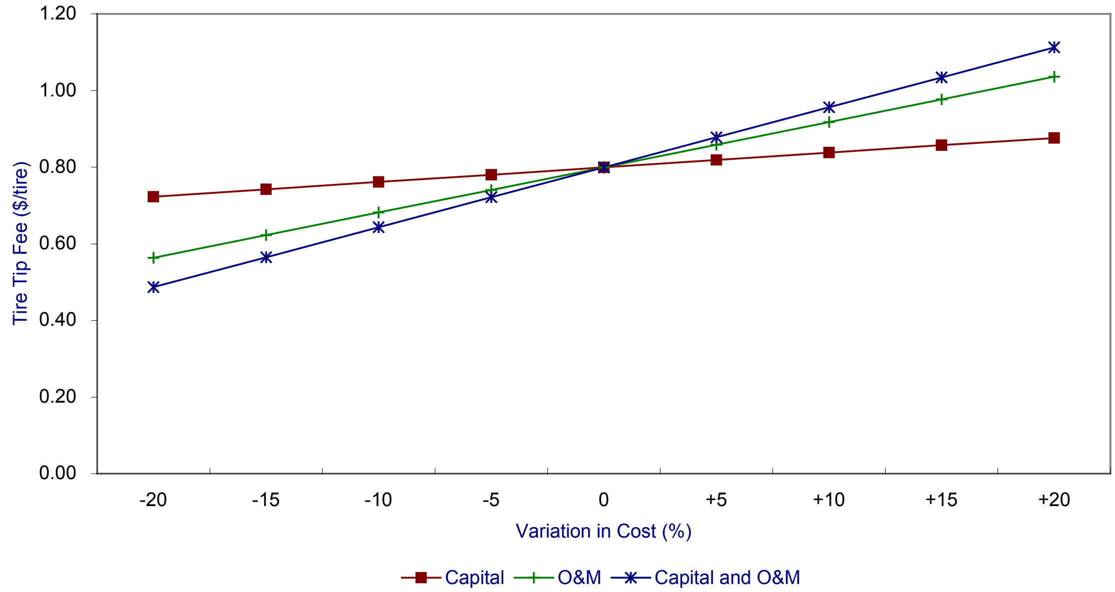

Figure 7-1. Sensitivity of Tire Pyrolysis Economics to Cost Elements -- Required Tire Tip Fee to Break Even at ±20% Variations in Cost

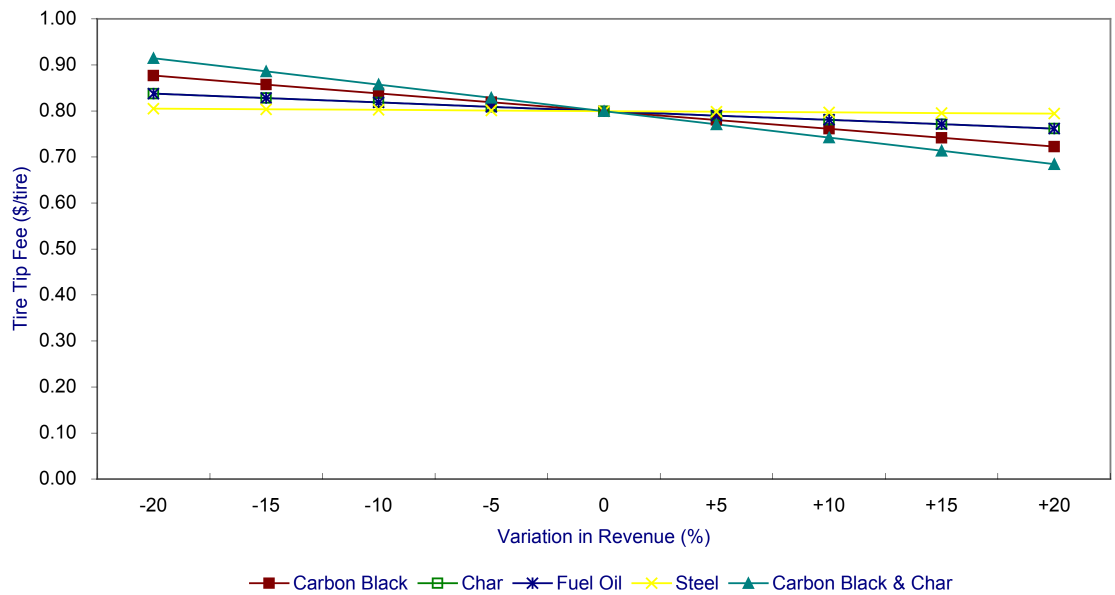

Figure 7-2. Sensitivity of Tire Pyrolysis Economics to Product Revenues -- Required Tire Tip Fee to Break Even at ±20% Variations in Revenues

Sensitivity to Carbon Black Sales

The market survey in Section 6 indicated that char from PGL processes usually is not of a quality sufficient over the long-term to command high sales prices, except under some special conditions, and that limited viable markets exist for solid carbon products. The results of the sensitivity analysis presented previously demonstrate the sensitivity of project economics to carbon product revenues. Consequently, additional sensitivity analyses were conducted on the effect of carbon black sales on the economics of tire pyrolysis projects.

The effect of variations in carbon black sales price is presented in Figure 7-3, and the effect of variations in percent of carbon black sold, in Figure 7-4. In both cases, the results are presented for three tire tip fees -- $1.00, $0.80, and $0.60/tire. The analyses also assume that product revenues from the other three products (char, fuel oil, and steel) are constant at the levels assumed for the baseline scenario.

As shown in Figure 7-3, at a tip fee of $0.80/tire, the profitability of the project ranges from -20 percent if the carbon black is sold for $0.026/lb to +20 percent if the product is sold for $0.23/lb. The analysis assumes that 75 percent of the carbon black is sold. At a tip fee of $1.00/tire, the likelihood of a profitable project is greater.

The data in Figure 7-4 demonstrate that project economics are also very sensitive to the percentage of the carbon black that is sold. The analysis assumes a selling price of $0.128/lb. At a tip fee of $0.80/tire, the project is profitable if greater than 75 percent of the product is sold. If the tip fee is increased to $1.00/tire, the project becomes profitable when about 40 percent of the product is sold.

Summary

The economics of tire pyrolysis projects are difficult to project with reasonable accuracy because of the lack of history for commercially viable operations. Nevertheless, the analyses conducted as part of this study indicate that the projects are particularly sensitive to three variables: tire tip fee, O&M costs, and product revenues. Recognizing that the tip fee cannot be set at an amount greater than what is being charged at other facilities, and also that O&M costs will likely remain high (due to the type of process and typical processing rates at tire pyrolysis facilities), it becomes evident that product revenues are critical to the viability of a tire pyrolysis project. Based on the uncertainty of markets for the products (as discussed in Section 6), it becomes clear that emphasis must be placed on the production of high quality products and the development of markets for those products.

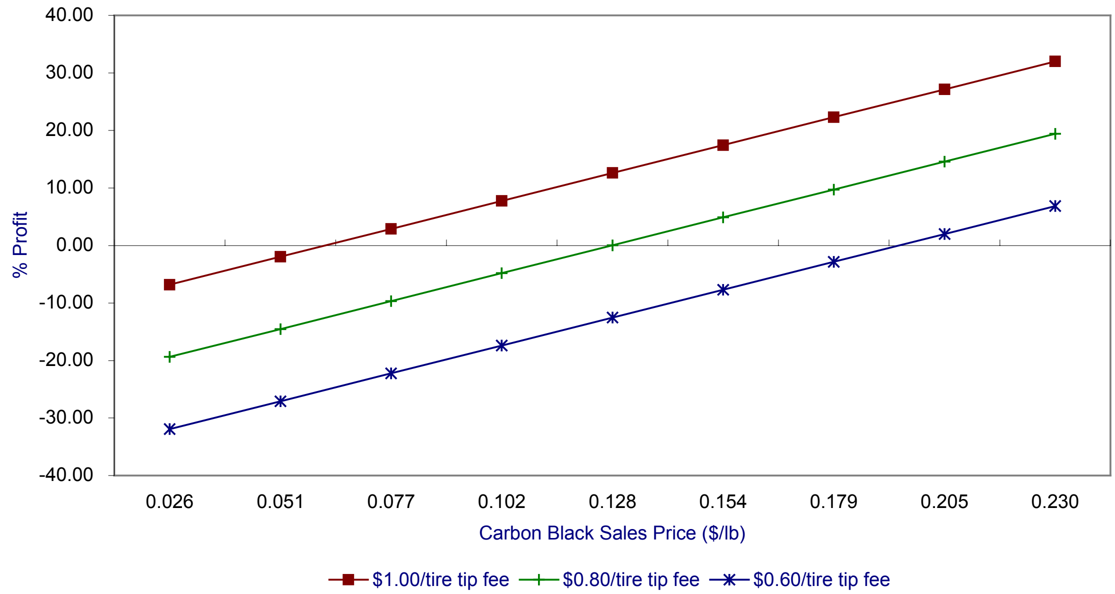

Figure 7-3. Sensitivity of Tire Pyrolysis Project Profitability to Carbon Black Sales Price at Various Tire Tip Fees

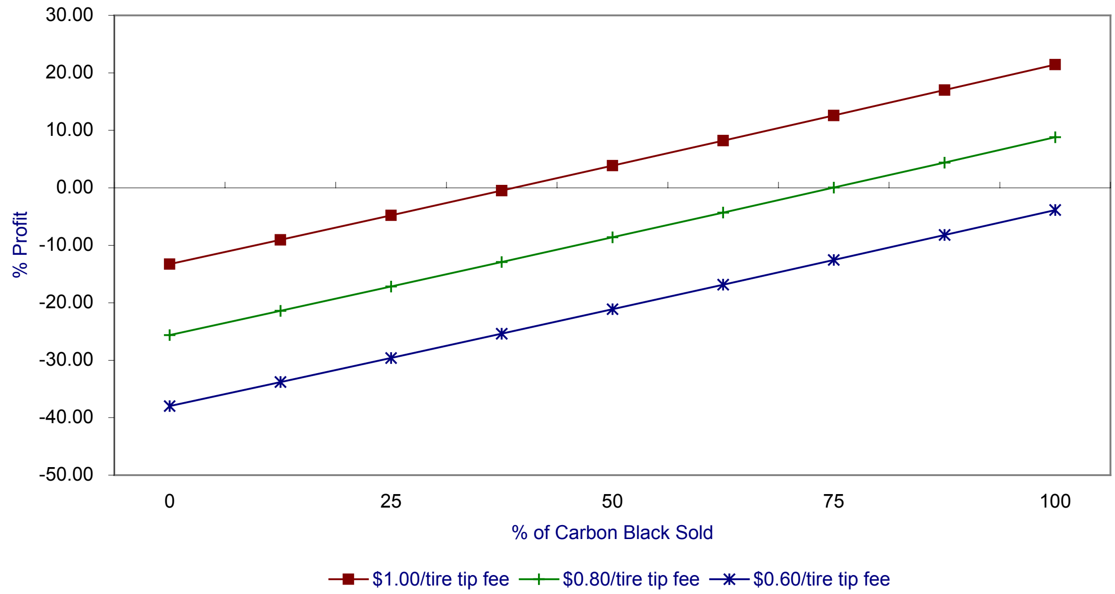

Figure 7-4. Sensitivity of Tire Pyrolysis Project Profitability to Percent of Carbon Black Sold at Various Tire Tip Fees

References

[7-1] Elliot, Douglas C., et al., "A Technical and Economic Analysis of Direct Biomass Liquefaction," published in *Energy from Biomass and Wastes XIII*, Institute of Gas Technology, Chicago, IL, 1990, pp. 743-767.

[7-2] Stevens, Don J. and Edward I. Wan, "Production Costs of Hydrocarbon Fuels from Biomass," published in *Energy from Biomass and Wastes XII*, Institute of Gas Technology, Chicago, IL, 1989, pp. 1209-1235.

SECTION 8. CONCLUSIONS AND RECOMMENDATIONS

This study was based on a literature review and a survey of more than 40 firms in the tire PGL industry. The following conclusions and recommendations can be drawn from this study.

Conclusions

General

- The tire PGL industry has been subjected to critical evaluation a number of times over the past decade. In 1983, the U.S. Department of Energy concluded that pyrolysis was technically feasible, but that its economics were marginal at best. In 1991, the U.S. Environmental Protection Agency reported no sustained commercial operation of PGL facilities. In the United States in 1993, approximately 34 firms (nearly double the number active in 1977) in 24 states were developing or marketing tire PGL systems. Because of industry volatility, only one firm active in 1977 remained in business under the same name in 1993. Industry members are often related through licenses, common technology, or subordinate corporate relations.

- Information and data available on commercial PGL systems is predominantly that provided by the system developers. Few, if any, third-party evaluations of technical and financial aspects of PGL processes have been conducted, especially in the past five years.

- Approximately 285,000 tons of waste tires were generated in California in 1993. Nearly 10 times that amount was generated nationwide. Tire PGL projects are located near centers of population (and of waste generation), or near petroleum producing areas. Approximately 1,100 tons of tires were processed by PGL projects at two demonstration facilities in California in 1992.

Technology

- The PGL process consists of feedstock reception, feedstock drying, and the thermal (pyrolysis) process to produce oil, one or more solid products, and a gas. Air emissions are controlled, and wastewater is treated.

- In undertaking PGL by batch processing, a reactor is charged, heated to operating temperature, and held at that temperature for a specific period. After decomposition is complete, wastes and products are discharged. In continuous operations, feedstock moves steadily through a reactor.

Feedstocks

- Of the three typical supplemental feedstocks (i.e., waste plastic, waste oil, and municipal solid waste), only waste oil has a higher heat content per unit of mass and a higher hydrocarbon content per unit of mass than waste tires.

- For the majority of tire PGL systems, preparation of an acceptable feedstock includes magnetic separation and size reduction. Many systems operators prefer the use of a supplemental fuel to facilitate tire decomposition or to improve operating economics.

Operating Conditions and Products

- Full-scale PGL projects operate within the temperature range of 460° - 860°C. At higher temperatures, more of the organic content of the tires is converted to gas or liquid.

- Most systems are net energy producers. Nonetheless, electric use is estimated at between 12 and 120 kWh/ton. The required heat input to the system is 1.2 - 2 million Btu/ton throughput. Most systems use propane or natural gas to achieve operating temperatures, although one system uses wood waste.

- Operations are typically planned for 24 hour/day, 7 day/week, with an expected availability of 82 - 90 percent. The throughput rates of planned and operating PGL systems correlate quite closely. This agreement indicates that the pyrolysis industry expects to improve economies of scale by installing multiple units, rather than by scaling up equipment sizes. Conversely, both gasification and liquefaction projects expect substantial scale-up in equipment size.

- Products are tire-derived oil (27.4 - 47.0 percent by weight of products), char or carbon black (32.8 - 43.0 percent), gas (6.0 - 26.8 percent), and scrap steel (4.0 - 10.9 percent). No significant quantities of fibers are recovered.

- The heating content of tire-derived oil is in the range of No. 6 oil, approximately 18,000 - 20,000 Btu/lb. The ultimate analysis of the oil is similar to that of No. 6 oil. However, small amounts of hazardous chemicals can be present in tire-derived pyrolytic oil.

- Advantages of converting tires from a solid to a liquid fuel include:

  - compatibility with hydrocarbon fuels produced from petroleum,

  - the energy density of tire-derived liquid fuels is higher than that of tires,

  - the bulk density of whole tires is much less than that of conventional liquid fuels, and

  - liquid fuels are transported easily.

- The heating value of the solid products generated by tire PGL processes (whether tire-derived char or carbon black) is within the range of coals. However, use of char as a fuel may be restricted by a high sulfur content. Mean physical characteristics of tire-derived char are similar, but not identical, to those of some grades of carbon blacks. Zinc oxide is the principal recoverable constituent of the ash.

- The heating value of tire-derived pyrolytic gas is similar to that of natural gas. The principal component of the gas is methane.

Environmental Impacts

- Tire PGL units produce minimal air pollution emissions because most of the PGL gas generated by the PGL process is burned as fuel. When complete combustion occurs, the decomposition products are carbon dioxide, sulfur dioxide, and water. The primary sources of emissions are fugitive sources (e.g., particulate matter emissions generated during the handling and processing of char) and equipment leaks (for volatile organic compound emissions). If markets for char cannot be developed, the char becomes a potential solid waste management concern. Analysis of char indicates that it generally would not be considered a hazardous material. However, at some tire PGL facilities, high levels of zinc in char could subject some char to the hazardous waste management requirements. Tire PGL also produces some non-flammable by-products, such as steel, fiber, or ash. If these by-products cannot be marketed, they also would need to be managed as solid wastes. Process wastewater and stormwater runoff from tire PGL facilities should be minimal. The tire PGL processes examined for this analysis require relatively few resources on a unit capacity basis. Most of the processes use natural gas or propane during startup and shutdown, but burn PGL products to generate heat during normal operations.

Markets

- Oil: Tire-derived oil has four possible uses, none of which is commercially viable at this time, except perhaps under some special circumstances. Blending the oil with other fuels to produce a fuel is in the research stage. Upgrading the oil to a lubrication oil is technically and economically unfeasible. Upgrading the oil to a No. 4 fuel oil grade is being explored. Tire-derived oil must compete with cheaper and cleaner fuels.

- Tire-derived carbon black: Four possible uses exist for marketing the char material derived from tire pyrolysis, although markets are limited and not presently viable overall. Upgrading the material for use in rubber products is still in the research phase. Using the tire-derived char for plastic product manufacture is also in the research stage. Tire-derived char may be marketed as a fuel, but cheaper sources of solid fuel exist. Marketing the tire-derived char as a special grade of carbon black or for use in inks, paints, or plastics has not been demonstrated commercially, although some tire-derived chars approach or meet some of the specifications for certain of grades of carbon black. Tire-derived char is inferior to virgin carbon black. Given the slight current worldwide oversupply, the marketability of tire-derived char is considered minimal at this time.

- Gas: Within the temperature range of operation of most commercial systems, 6 - 30 percent of the material generated from tire pyrolysis is a gas. Gas generated by tire pyrolysis is most effectively used to fuel the PGL process.

- Steel: The scrap steel generated from tire PGL processes may be sufficiently clean to be sold to scrap processors. The feasibility of marketing the steel is based on a number of factors: cleanliness (fiber contamination), quantity, packaging, and transportation and storage costs. Only limited quantities of steel scrap have been marketed by tire PGL facilities. Costs of baling the steel and operating a baler may be a factor in determining the feasibility of marketing the steel from tire pyrolysis. Large pyrolysis operators may be able to justify the purchase of a baler if the quantity of the steel they are generating is high and the market prices for the steel are substantial and stable.

Economics

- The mean capital costs for surveyed tire PGL systems are between approximately $48,298 and $101,328/ton per day of throughput.

- The mean annual operating and maintenance costs for surveyed tire PGL systems are between $20.21 and $118.06/ton of throughput, excluding the annual cost of capital and the effects of offsetting revenues.

- The mean annual revenues from the sale of products for surveyed tire PGL projects are reported to range from approximately $62 - 224/ton of throughput.

- Results of the facility survey indicate that tire pyrolysis will produce net revenues. However, if all products are sold at 50 percent of the reported prices, a tire tip fee of over $61/ton ($0.61/tire) would be required to result in a net profit.

- The economics of tire pyrolysis projects are particularly sensitive to three variables: tire tip fee, O&M costs, and product revenues. Because tip fees cannot be set at an amount greater than what is being charged at other facilities, and because O&M costs will likely remain high for these types of processes, product revenues are critical to the economic viability of a tire pyrolysis project.

- Product revenues are affected both by the sales price of the products and by the percentage of each product sold. Because of the uncertainty of markets for the products, emphasis must be placed on the product of high-quality products and the development of markets for those products.

Recommendations

- Monitor the tire PGL industry. Watch for developments in universities (e.g., University of Wyoming, Leeds, Laval, University of Hamburg), signs of technological breakthroughs (e.g., improvement in the quality of tire-derived carbon black), or growing commercialization of current technologies.

- Monitor changes in the economics of oil and coal production and use that could favor the development of markets for tire PGL products.

- Monitor changes in federal regulations (e.g., federal mandates regarding tire disposal, recovery goals, special provisions of legislation such as the Clean Air Act, changes to the Internal Revenue Code, etc.) that could support the development and growth of the tire PGL industry.

- Monitor and/or support federal or state financial assistance becoming available that could improve the current unattractive economics of the tire PGL industry. Make available low-cost development capital to firms that wish to initiate projects in California.

- Support federal and state market development initiatives that will provide price supports, etc. for tire PGL products.

- Monitor firms that own and operate PGL projects in California and advise them of availability of discarded tires and of tire stockpiles that, if otherwise abandoned, represent the potential of causing environmental damage and waste management problems in the host community.

- Since the economic feasibility of PGL processes is in general very sensitive to and dependent upon the sale of char as a product (e.g., carbon black), research and development in the area of upgrading of char to valuable products is warranted. Relatively little research effort is being conducted in this area at this time.

Appendix Table A-1. Tire Production and Waste Tire Generation - Nationwide and California

		1980	1985	1990	1991	1993	1995	2000
Tire Production (a)								
Passenger Car	million	145.9	200.9	213.6	214.5			
Truck & Bus	million	31.1	41.1	46.9	42.4			
Total		177.0	242.0	260.5	256.9			
Population (a)								
United States	million	226.546	237.924	248.71	252.16			
California	million	23.668	26.441	29.76	30.38		33	36
Unit Production (b)								
United States	total tire/capita	0.781	1.017	1.047	1.019			
Waste Tire Generation								
United States (c)	million		218.497	242.496	231.201			
(d)	million ton		2.18	2.42	2.31			
California (e)	million		24	27	27.5	28.3	30	33
(d)	ton		240,000	270,000	275,000	285,000	300,000	330,000
Unit Generation (f)								
United States	tire/capita	(g)	0.903	0.931	0.917	0.917	0.917	0.917
California (f)	tire/capita	(g)	0.917	0.917	0.917	0.917	0.917	0.917

(a) Reference [1-4].
(b) Calculated, dividing tire production by population.
(c) Reference [1-1].
(d) Calculated, using number of tires times 20 lb/tire.
(e) Reference [1-5].
(f) Calculated, using number of tires generated and population nationwide for 1985 and 1990.
California rate was assumed to be equal to the calculated national rate.
(g) Since calculated waste generation rate exceeds production, value is unknown.

Appendix Table B-1. Explicit or Inferred Corporate Relationships

Related Entities/Former Names	
AEA-Beven, Harwell	Herbert Beven & Co., Ltd.; Leeds, University of; Multi-Purpose Disposer (MPD); NATRL
American Tire Recycling & Recovery	ABB Raymond
Castle Capital	BBC Engineering & Research, Ltd.; Ireton
Champion Recycling	Tire Recycling Technologies
Conrad	H.O. Argus Ecological, Inc.; Kleenair Pyrolysis System; Synpro
Hamburg, University of	Deutsche Reifen und Kunstsoff - Pyrolyse GmbH
Heartland	Jarrell; Thermal Recovery and Processing; TIRE, Inc
Horton, Norman P.	Art Wilson Co.; Homestead
International Recycling Ltd.	Energeco; Marangoni Group; Recoverator technology
International Tire Collection	Oconco; Thermogenics
Jentan	Korean Pyrolysis Co., Ltd.; Pace Treadmore
Kilborn, Inc.	Canadian Energy Development, Inc.; PARR process
Kutrieb	Bergey's Tire Service
NATRL-Wind Gap	Cheyenne Industries; J.H. Beers, Inc.; North American Tire Recycling, Ltd. (NATRL)
Process Fuels	International Tirecycle Corp.
Pyrovac International, Inc.	Laval University
Recycling Industries of Missouri	Recycled Energy, Inc.
Seco/Warwick	Eastern Shale Research
Thermex	Yamagata Canada
Tyrolysis, Ltd	Foster Wheeler; Warren Spring Laboratory
Waste Distillation Technology, Inc.	Suffolk Waste Distillation
Worthing Industries	ENCON Enterprises; fast pyrolysis process; Waterloo, University of

Source: Survey information

Appendix Table B-2. Firms, Processes, or Projects Eliminated from Analysis with Comments

Firm Name	Comment
American Tire Recycling & Recovery, Inc.	No information available
Babcock-Krauss-Maffei	No information available
Carbon OIl & Gas Co., Ltd	No information available
CLE Management (formerly Emery)	No information available
Colinas Tire Recovery	No information available
Cyclean, Inc	No information available
Deutsche Reifen und Kunstsoff - Pyrolyse GmbH	No information available
Energy Conversion Ltd	No information available
Environmental Disposal Systems Ltd.	No information available
Ferrostall	No information available
Foster Wheeler	No information available
Hyban Recycler	No information available
Intennco	Limited information
Kienerp Pyrolyse	No information available
Kobe Steel	No information available
Kutrieb Corp.	Limited information
Long Island Waste	No information available
Mannesmann Veba Umelttechnick GmbH	No information available
Mfgr. & Tech. Conv. Inter., Inc.	No information available
Morgan Group	No information available
Onahama Smelting & Refining	No information available
Oxford Energy	Tire combustion
Pan-American Resources	No information available
Phoenix Recycling	No information available
Pilquist	No data on abandoned pyrolysis project
PTL Tire Warehouse	Tire shredding; no operating pyrolysis project
Reid Corporation	No information available
Scientific Development	Rubber shred, thermal process, remold
Sobeit-Sodoit Ltd.	No information available
TecSon Corp. Ltd.	No information available
Thermogenics	Future project only
Tire Tech. Recycling	Crumb rubber production. Considering a project using Yamagata Canada gasification technology
Tork Landfill	No information available
Tosco II	Limited information
Tyrolysis, Ltd.	Limited information
VBC Engineering	No information available
Waste Conversion Corp.	No information available
Wolf	No information available

Source: Survey information

Appendix Table B-3. Survey Summary - Facility Descriptions and Products

Status	**Laboratory**	**Conceptual**	**Demonstration**	**Lab**	**Demonstration**
Facility Description					
Owner/Operator					
Company Name	AEA-Beven, Harwell	American Ecological Technologies	American Tire Reclamation	Castle Capital	Champion Recycling Industries
Address	Cochester, Eng.	Shreveport, LA	Detroit, MI	Halifax, NS, Can.	Apple Valley, CA
Contact Person	Herbert Bevan	Wallace "Lyn" Stanberry	Jack Fader	John Black	Chuck Wages
Phone Number	-	(318) 221 3957	(313) 895 1200	(416) 297 7584	(619) 247 0755
Site Location	Cochester, Eng.	Krotz Springs, LA	Toledo, MI	Halifax, NS, Can.	Oklahoma
Technology					
Type	Pyrolysis	Pyrolysis	Pyrolysis	Pyrolysis	Pyrolysis
Continuous or Batch	Batch	Continuous	-	Continuous	Continuous
Throughput, Actual	2.2 tons/day	5k - 20k tires/day	-	0.25 TPD	100 TPD
Operating Years	-	-	Toledo: '89-present	1989-present	1991-present
Products					
Solid	Char	Char/carbon black	Char	Carbon black	Carbon black
Liquid	Oil	40 gravity oil	Oil (like #6 crude)	Oil (like #2 F.O.)	Oil
Gas	Gas	Yes	Yes	Yes	Yes
Reclaimed Steel	Yes	Yes	Yes	Yes	Yes
Reclaimed Fiber	No	Yes	No	No	No

Appendix Table B-3. Survey Summary - Facility Descriptions and Products (cont.)

Full	Demonstration	Demonstration	Demonstration	Demonstration
Conrad Industries	ECO 2	Garb Oil & Power	Hamburg, Univ. of ITMC	Heartland Industries
Centralia, WA	Hawthorne, FL		Hamburg, Ger.	Malden, MO
Philip Bridges	Charles Ledford	John C. Brewer	Walter Kaminsky	Dan Tirey
(206) 748 4924	(904) 481 0187	(801) 332 5410	-	(314) 624 0097
Centralia, WA	Hawthorne, FL	WV	U. of Hamburg; Ebenhausen, Ger.	Campbell, MO; Nara, Japan
Pyrolysis & Liquefaction	Pyrolysis	Pyrolysis	Pyrolysis, (fluid bed)	Gasification
Continuous	Continuous	-	-	Batch
1 TPH	35-60 tires/hr	10 TPD	Max: 120 kg/hr	17-19 tons/charge
1986-present	1991-present	1987-present	-	MO: '89-; Japan: '94+
Carbon	Carbon black	Carbon black	Carbon black	Char
Oil	Oil (like #4 F.O.)	Oil	Oil, Water	Oil
Yes	Yes	Yes	Yes	Non-condensible gas
Yes	Yes	Yes	Yes	Yes
No	Yes	No	No	No

Appendix Table B-3. Survey Summary - Facility Descriptions and Products (cont.)

Demonstration	Full	Demonstration	Full	Demonstration
Homestead Minerals	International Recycling, Ltd.	International Tire Collection (Oconoco)	Jentan Resources, Ltd.	Kilborn, Inc
-	Hammonton, NJ	Oklahoma City, OK	Vancouver, BC, Can.	Toronto, ON, Can.
John Mahan	George Arslanian	Mort Resnick	Brent Singbeil	Norman Anderson
	(609) 561 7770	(505) 296 0799	(604) 875 8677	(416) 252 5311
Citrus Heights, CA	Rovereto & Feltre, Italy; Bulgaria	Oklahoma City, OK	Japan. Korea	Unk
Pyrolysis	Close-coupled Gasification	Pyrolysis	Pyrolysis	Hydrogenation
-	Continuous	Continuous	-	Continuous
	-	100 TPD	17 TPD	Unk
-	1982-present	1982-1984	-	1989
Carbon black	No	Carbon black	None	Residue
Diesel oil	No	Oil	None	Light oil
Yes	Yes	Yes	Yes	Yes
Yes	Yes; and zinc powder	Yes	None	Unk
No	No	No	None	No

Appendix Table B-3. Survey Summary - Facility Descriptions and Products (cont.)

Status	**Laboratory & Demonstration**	**Full**	**Full**	**Lab**	**Demonstration**
Facility Description					
Owner/Operator					
Company Name	Kobe Steel	Leigh Interests plc	NATRL-Wind Gap	Premium Enterprises, Inc	Process Fuels
Address	Unk	Staffordshire, U.K.	Wind Gap, PA	Longmont, CO	Spokane, WA
Contact Person	Unk	K. Griffiths	Blaine Masemore	John Rogers	Joe Munger
Phone Number	Unk	09 02 790 011	(215) 862 7933	(303) 772 1253	(509) 534 6939
Site Location	Ako City, Japan	Unk	Wind Gap, PA	Florida	Spokane, WA
Technology					
Type	Pyrolysis	Pyrolysis	Pyrolysis, Liquefaction	Pyrolysis	Pyrolytic Gasification
Continuous or Batch				Continuous	Batch
Throughput, Actual	7,700 ton/yr	55,000 ton/yr	0.5 TPH	-	0.067 TPH
Operating Years	1970s	Aug 1985 - 1991	1986-present	1992-present	1988-present
Products					
Solid	Crabon black	Char	Carbon	Carbon black	None
Liquid	Oil	Light and heavy oil	Oil	No	Oil
Gas	Yes	Yes	Yes	No	Yes
Reclaimed Steel	Unk	Yes	Yes	No	Yes
Reclaimed Fiber	Unk	Unk	Yes	Yes	No

Appendix Table B-3. Survey Summary - Facility Descriptions and Products (cont.)

Demonstration	Full	Full	Demonstration	Demonstration
Pyrovac International Inc.	Recycling Industries of Missouri	RMAC International	RT Corporation	Seco/Warwick
Sillery, PQ, Can.	Fulton, MO	Troutdale, OR	Laramie, WY	Meadville, PA
Christian Roy	Charles Wentz	Don Weege	Bob Rucinski	Keith Boeckenhauer
-	(314) 642 7596	(503) 667 6790	(307) 742 5452	(814) 724 1400
Quebec, PQ, Can.	Fulton, MO	Troutdale, OR	Laramie, WY	Shelbyville, IN
Vacuum pyrolysis	Pyrolysis	Gasification	Pyrolysis	Pyrolysis
Continuous	Continuous	Continuous	Continuous	Batch
500 kg/hr	1.7 million tires/yr	2.5 TPH	50 TPD (tires)	0.004 TPH
-	1983-1985	1992-present	1991-present	Mid-1970's
Carbon black	Carbon black	Char	Carbon	Char
Oil, water	Fuel oil	Light oil	Oil	Oil
Yes	Yes	Yes	Yes	Yes
No	Yes	Yes	Steel	No
No	Nylon, rayon	No	No	No

Appendix Table B-3. Survey Summary - Facility Descriptions and Products

Demonstration	Unk	Demonstration	Full	Full
Texaco, Inc.	Thermex Energy Recovery System	Thermoselect Incorporated	Waste Distillation Technology, Inc.	Wayne Technology Corporation
Tarrytown, NY	Montreal, PQ, Can.	Troy, MI	Irvington, NY	Rochester, NY
Richard Card Paul Curren	Michael Handfield	David J. Runyon	Willliam Friorito	Scott Arrington
(914) 253 7325	(514) 849 7391	(313) 689 3060	(914) 591 5080	(716) 264 5900
Montebello, CA	Montreal, PQ, Can.	Fondotoce, Italy	Elmwood, NJ	Rochester, NY
Liquefaction	Gasification	Gasification - Degasification	Destructive Distillation	Pyrolysis
Batch	Batch, Double	Continuous	Continuous	Continuous
-	1,200 tires/day	4.4 TPH	50 TPD	3 TPH
1993-present	None	1992-present	1982-l985	1992-present
-	Carbon black	Salts, gypsum, metal oxides, slag	Carbon	Char
Petroleum Products	No	No	No	Oil (lighter than #6)
-	No	Yes	Yes	Yes
Yes	Yes	Yes	Yes	Yes
No	No	No	No	No

Appendix Table B-3. Survey Summary - Facility Descriptions and Products (cont.)

Full	**Lab**
Worthing Industries	Wyoming, University of
Calgary, AL, Can	Laramie, WY
Peter Fransham	Henry Plancher
(403) 284 5302	(307) 766 2500
Mobile plant	Laramie, WY
Pyrolysis	Pyrolysis
Continuous	Batch
5.5 tons/day	0.3 TPD
1990-present	1991-present
Carbon black	Carbonous residue
Oil	No
Yes	Yes
Yes	No
No	No

Appendix Table B-4. Throughputs Reported for Actual Facilities

Process	ton/year (a)	ton/day (a)	ton/hour (a)
AEA-Beven	726	2.2	0.28
AET	41,250	125	5.2
American Tire Reclamation	13,000	39	1.6
Castle Capital	83	0.3	0.01
Champion	11,550	35	1.5
CLE	no data	no data	no data
Conrad	7,920	24	1.0
Cyclean	no data	no data	no data
Ecology Enterprises	no data	no data	no data
ECO 2	3,762	11	0.48
Garb OIl	100 #/batch	not reported	not reported
Hamburg, U of	1,048	3	0.1
Heartland	18 ton/charge	not reported	not reported
Homestead	not reported	not reported	not reported
ITC	no data	no data	no data
Oconco	33,000	100	4.2
Thermogenics	0	0	0.0
International Recycling	8,732	26	1.1
Jentan	5,610	17	0.7
Kobe	87	0.3	0.01
and	1,048	3	0.13
Kilborn Tech	no data	no data	no data
Kutrieb	no data	no data	no data
Leigh	no data	no data	no data
LI Waste to Energy	no data	no data	no data
NATRL-Wind Gap	6,240	24	1.0
Cheyenne	0	0	0.0
Oxford	N/A (b)	N/A	N/A
Phoenix	no data	no data	no data
Premium	not reported	not reported	not reported
Process Fuels	531	2	0.07
Pyco	21,094	64	2.7
Pyrovac	4,366	13	0.6
Recycle Industries of MO	17,000	52	2.1
RMAC	18,600	61	2.5
RT Corp	119	0.4	0.02
Scientific Development	N/A	N/A	N/A
Seco/Warwick	32	0.10	0.004
Texaco	4,950	15	0.6
Tire Tech Recycling	N/A	N/A	N/A
Thermex	3,960	12	0.5
Thermoselect	34,848	106	4.4
Waste Distillation	16,500	50	2.1
Wayne Technologies	23,760	72	3.0
Wolf	no data	no data	no data
Worthing	1,815	6	0.2
Wyoming, U of	99	0.3	0.01

(a) Where limited data were available, estimates were prepared based on 330 operating days per year, 24 hours per day.
(b) N/A = not applicable

Source: Survey information

Appendix Table B-5. Throughputs Reported for Planned Facilities

Process	ton/year (a)	ton/day (a)	ton/hour (a)
AEA-Beven	13,000	39	1.6
AET	41,250	125	5.2
American Tire Reclamation	16,500	50	2.1
Castle Capital	not reported	not reported	not reported
Champion	27,923	85	3.5
CLE	no data	no data	no data
Conrad	7,920	24	1.0
Cyclean	no data	no data	no data
Ecology Enterprises	no data	no data	no data
ECO 2	3,534	11	0.4
Garb OIl	100 #/batch	not reported	not reported
Hamburg, U of	1,048	3	0.1
Heartland	18 ton/charge	not reported	not reported
Homestead	not reported	not reported	not reported
ITC	24,900	75	3.1
Thermogenics	22,320	68	2.8
International Recycling	8,732	26	1.1
Jentan	5,610	17	0.7
Kobe	4,000	12	0.5
and	14,000	42	1.8
Kilborn Tech	277,200	840	35.0
Kutrieb	no data	no data	no data
Leigh	no data	no data	no data
LI Waste to Energy	no data	no data	no data
NATRL-Wind Gap	12,480	48	2.0
Cheyenne	27,923	85	3.5
Oxford	N/A (b)	N/A	N/A
Phoenix	no data	no data	no data
Premium	not reported	not reported	not reported
Process Fuels	37,200	113	4.7
Pyco	21,094	64	2.7
Pyrovac	20,000	61	2.5
Recycle Industries of MO	17,000	52	2.1
RMAC	18,600	61	2.5
RT Corp	16,425	50	2.1
Scientific Development	N/A	N/A	N/A
Seco/Warwick	10,000	30	1.3
Texaco	4,950	15	0.6
Tire Tech Recycling	N/A	N/A	N/A
Thermex	3,960	12	0.5
Thermoselect	165,000	500	20.8
Waste Distillation	77,500	250	10.4
Wayne Technologies	23,760	72	3.0
Wolf	no data	no data	no data
Worthing	1,815	6	0.2
Wyoming, U of	99	0.3	0.01

(a) Where limited data were available, estimates were prepared based on 330 operating days per day, 24 hours per day.
(b) N/A = not applicable

Source: Survey information.

Appendix Table C-1. Physical Characteristics of Waste Tires and Supplemental Feedstocks

	Units	Champion	ITC	NATRL	Premium	Texaco	Mean
Densities							
Tires, shredded	lb/cf			25 - 30			27.5
Used motor oil	lb/cf					X	56 (b)
MSW, unshredded	lb/cf		X (a)				8.9 (c)
Particle Sizes							
Tires, shredded	in	6	< 1	< 2	No. 4	< 6	< 3.04
MSW, shredded	in		< 1		sieve (d)		< 1

(a) X = value expected, since feedstock applies, but not reported. n/a = not applicable.
(b) Mean value shown is that of lubricating oil, as reported in [3-6].
(c) Mean value shown is that for Richmond, CA, as reported in [3-2].
(d) No. 4 sieve = 4.75 mm opening.

Source: Survey information

Appendix Table D-1. Chemical Characteristics of Tire-Derived Char and Carbon Black

	units	AEA-Beven	American Tire Reclamation	Conrad	Laval U.	NATRL	Nippon Zeon	Worthing
Kiln Temperature	deg C				500			
Product		coke	ATR-077	carbon black		Low structure tire reclaim carbon black		carbon black
Volatile Content	%	Incl. below	0.25		2.8			
Fixed Carbon	%	87.5	81		85.8			
Ash	%	10.1	13		11.4	9-11		
Sulfur	%	2.5	2.8		0			
Not Reported	%	0	2.95		0			
Total (a)		100.1	100		100			
Analysis of Ash								
SiO_2	%	15.7						28.93
TiO_2	%	0.2						0
MgO	%	1.2						1.6
ZnO	%	44.1						31.52
Na_2O	%							1.2
K_2O	%							0.96
CaO	%							5.74
Fe_2O_3	%							7.44
Al_2O_3	%							2.16
SO_3	%							7.04
Not reported		38.8						13.41
Total		100						100
Moisture	%	0.41						
Chlorine	%	0.11						
Loss at 105° C	%				0.2	0.15		
Ultimate Analysis								
Carbon	%				94.78		85.6-88.0	74.6
Hydrogen	%				1.11		0.03-0.68	4.08
Nitrogen	%				1.19			0.12
Oxygen	%				0.56			0
Sulfur	%				2.36		2.22-2.24	1.28
Moisture	%				0			13
Ash	%				0		8.36-11.8	7.4
Total								100.48
Heating Value (a)	Mj/Kg	31.4		27.9			30.9	31.9
	Btu/lb	13,498		12,000			13,292	13,733
	Cal/gr						7,385	7,630
pH			7.8					
Sources:		[4-6]	[4-7]	[4-8]	[4-2]	[4-9]	[4-4]	[4-10]

(a) Values in some cases were converted from values presented in source using [4-11], or are totals or differences.

Appendix Table D-2. Chemical Characteristics of Tire-Derived Pyrolytic Oil and Commercial Fuels

						Pyrolytic Oil							Petroleum Products	
		Conrad	Heartland	Kilborn	Laval U.	Leads University Lo	Leads University Hi	NATRL-Wind Gap	Nippon Zeon	RMAC	RTC	Worthing	Kerosene	Heavy Fuel Oil
Kiln Temperature	deg C			400 13.1 MPa		700	950						n/a	n/a
Carbon Residue	%					0.5	2.2						<0.15	-
Hydrogen Content	%					10.58	9.42						13.6	11.8
Sulfur	%	0.49				0.5	1.1						0.1	2.1
Ash	%	0.099				-	-							
Ultimate Analysis	%			85.3	85.94				77.1		86.97	88.33		
H	%			11.2	10.62				10.06		9.79	9.56		
N	%			0.5	1.35						0.36	0.18		
O	%			0.8	1.2							1.06		
S	%			2.2	0.89				1.39		0.69	0.87		
	%			100	100						97.81	100		
Chloride	%										0.06			
Residual Metals														
Va	%				<0.1									
Ni														
Na														
Na	ppm							0.3						
Cr	ppm							0.67						
Cd	ppm							<0.01						
PB	ppm							<0.1						
V	ppm							<0.1						
Ca	ppm							0.3						
Heating Content	MJ/kg	43.0	45.4		43	42.9	42.1	42.1	39.8	45.3		36.2	46.6	44
	Cal/g								9500			8,637		
	Btu/lb	18,500	19,500		18,490	18,447	18,103	18,100	17,104	19,486		15,550	20,038	18,920
Initial Boiling Point	deg C	132			112	80	100						140	252
	deg F										181			
90% Boiling Point	deg C	364				340	355						315	-
	deg F										>779			
Viscosity	centipoise				-	-	-				20.5		-	-
60 deg C	centistokeas					2.15	2.38				-		0.65	24
40 deg C	centistokeas					3.1	6.3				-		1.2	30
20 deg C	MPa											6.34		
100 deg F	ssu	45.8						35						
Density	kg/m—u3˜			0.9		0.91	0.96						0.84	0.95
API Gravity					17.8	21.81	15.51	14.7			18.4	18.8	47	17.5
Source:		[4-8]	[4-15]	[4-14]	[4-2]	[4-12]	[4-12]	[4-9]	[4-4]	[4-16]	[4-13]	[4-10]	[4-12]	[4-12]

Appendix Table D-3. Chemical Composition of Tire-Derived Gas and Federal Air Emissions Regulations

	units	Conrad	Heartland	Laval U.	RMAC	Thermo-select	40 CFR (a) Part 60
PM(dust)	mg/Nm—u3˜					<0.25	69
Cd	mg/Nm—u3˜					<0.001	n/a
Hg	mg/Nm—u3˜					<0.006	n/a
Pb	mg/Nm—u3˜					<0.005	n/a
SO2	mg/Nm—u3˜					<1.35	80
HCl	mg/Nm—u3˜					0.3	30
HF	mg/Nm—u3˜					<0.06	n/a
Ultimate Analysis							
C	%			85.76			
H	%			14.24			
N	%			trace			
O	%			trace			
S	%			trace			
Heating Value	Btu/scf	1000	1275		500 - 700		
	Btu/lb (b)	20,000	25,500		12,000		
Dioxins/ Furans	ng.Nm3					N/D	125
Source:		[4-8]	[4-15]	[4-2]	[4-16]	[4-17]	[4-17]

(a) 40 CFR Part 60 refers to air emissions performance standards in Reference [4-18].
(b) Calculated, using 20 ft—u3˜/lb.

Appendix Table D-4. Selected Compounds in Tire-Derived Oil

	Yield % of feed
Limonene-Id	2.26
Toluene	1.05
o-,m-,p-Xylene	0.93
Styrene	0.82
Benzene	0.38
4-Vinyl-1-cyclohexene	0.25
Dimetylcyclopentadiene	0.24
Methylpentene	0.23
2,4,4-Trimethyl-1-pentene	0.22
alpha-Methylstyrene	0.19
Dimethylpentane	0.16
Cylcopentanone	0.15
Isopropylbenzene	0.15
Ethylhexadiene	0.13
Trimethylpentadiene	0.07
Methylhexadiene	0.06

Source: [4-19]

Appendix Table D-5. Physical Properties of Tire-Derived Char or Carbon Black

	units	American Tire Reclamation	Laval U.	NATRL	Worthing	n	Mean
Product		ATR-077					
Form		Black Pellet					
Specific Gravity		1.83		1.8	1.34	3	1.7
Bulk Density	lb/ft—u3˜	31		30	36.2	3	32.4
(a)	onne/m—u3˜				0.58		
Particle Size							
Measured	micron	40-50				1	40-50
Effective (b)	micron	0.05-0.1				1	0
Surface Area							
BET	m—u2˜/g			40		1	40.0
CTAB	m—u2˜/g	85				1	85.0
Void Volume							
DBP	ml/100g	95		76		2	85.5
Iodine Index	mg/g	156	151.5			2	153.8
Pellet hardness							
	g/pellet	23				1	23.0
Toluene							
Discoloration				90		1	90.0
Wettability			hydrophonic				
Sources		[4-7]	[4-2]	[4-9]	[4-10]		

(a) Values in some cases were converted from values presented in source using [4-11].
(b) Reportedly based on reinforcing properties in rubber; equivalent particle size is shown.

Appendix Table D-6.
Tire-Derived Gas Composition

		Mole %
Hydrogen	H—d2˜	19.87%
Nitrogen	N—d2˜	3.65%
Oxygen	O—d2˜	0.71%
Carbon monoxide	CO	3.27%
Carbon dioxide	CO—d2˜	5.24%
Methane	CH—d4	35.70%
Ethylene	C—d2˜H—d	9.69%
Ethane	C—d2˜H—d	8.61%
Propylene	C—d3˜H—d	5.34%
Propane	C—d3˜H—d	1.81%
Isobutylene	C—d4˜H—d	4.26%
Trans-butene	C—d4˜H—d	0.40%
Cis-butene	C—d4˜H—d	0.29%
Butane	—d4˜H—d1	0.66%
Isobutane	—d4˜H—d1	0.23%
1,3 Butadiene		0.33%
Total (a)		100.07%

(a) Source reports Total as 100.07%; column

Source: [4-8]

Appendix Table E-1. Selected Properties of Commercial Carbon Blacks

Symbol	**Mean Particle Diameter angstroms**	**Surface Area m—u2˜/g**	**Volatile Matter (a) %**	**Symbol**	**Mean Particle Diameter angstroms**	**Surface Area m—u2˜/g**	**Volatile Matter (a) %**
Carbon Blacks for the Rubber Industry				Carbon Blacks for Inks, Paints, and Plastics (b)			
SAF	180 - 190	150 - 170	1.5 - 2%	HHC	100 - 130	1000 - 1700	9 - 16%
ISAF	200 - 220	115 - 140	1 - 2%	MCC	140 - 200	190 - 700	5 - 12%
MPC	240	120	6.0%	MCF	240 - 270	80 - 120	1 - 2%
EPC	270	110	5.0%	LCC	250 - 270	140 - 180	5 - 6%
HAF	250 - 290	75 - 85	1 - 2%	LCF	290 - 700	28 - 85	0.5 - 2%
FF	330	70	1.0%	MFF	270	110	1.4%
FEF	360	55	2.0%	LFC	250 - 260	500	12 - 13%
HMF	540	40	1.0%	LFF	220	155	4.0%
APF	600	35	0.6%	CF	190	200	2.0%
GPF	600	30	0.5%				
SRF	700	28	0.5%				
FT	1500	14	0.5%				
MT	5000	6	0.5%				

(a) ASTM D 1620
(b) Selected terminology: LCF = low-color furnace
HCC = high-color channel MFF = medium-flow furnace
MCC = mediium-color channel LFC = long-flow channel
MCF = medium-color furnace LFF = long-flow furnace
LCC = low-color channel CF = conductive furnace

Source: [6-5, 6-14]

Appendix Table E-2. Summary of Types and Applications of Special Carbon Blacks

Type	Surface Area m—u2˜/g	DBP mL/100g	Volatile Matter %	Selected Uses
high color	230 - 560	50 -120	2 - 10%	enamels, lacquers, and plastics
medium color	200 - 220	70 - 120	1 - 1.5%	color, and weather and UV protection
medium color, long flow	138	55 - 60	5%	inks, excellent flow, low viscosity
medium color, medium flow	96	70	2.5%	inks and paints
regular color	80 - 140	60 - 114	1 - 1.5%	for general color and UV protection
	46	60	1 %	blue tone in inks
	45 - 85	73 - 100	1 %	standard and offset news inks
low color	25 - 42	64 - 120	1 %	one-time carbon paper, ink, cement
thermal balcks	7 - 15	30 - 35	0.5 - 1%	tinting - blue tone, utility uses
lamp blacks	20 - 95	100 - 160	0.4 - 9%	paints for tinting - blue tone
conductive blacks	254	180	2.0%	conductivity and antistatic
acetylene	65	250	0.3%	conductive, antistatic; tire curing

Source: [6-5]

Appendix Table F-1. Summary of Potential Waters and Management Options - All Tire PGL Projects

Company	Potential Waste	Waste Reneration Rate lb/ton tires	lb/ton char	lb/ton oil	lb/ton gas	Management Option
AEA Beven	Char	800		3,828	3,493	Sell as coal substitute
	Scrap Steel	300	755	1,437	1,311	Sell
	Process Wastewater	30	75	143	131	
American	Char	550		1,100		Sell as fuel, landfill
Ecological	Scrap Steel	550	2,033	1,100		
Tech.	Fiber					Landfill
	Process Wastewater	8	30	16		Off-site treatment
American	Char	610		1,525	4,067	Sell as carbon filler or carbon black
Tire	Scrap Steel	200	656	500	1,333	Sell, landfill
Reclamation	Ash	90	295	225	600	
	Cooling Tower Blowdown	2,390	7,836	5,975	15,933	Off-site treatment
BBC Engineering						
	Char	700		1,337	4,142	
	Scrap Steel	130	372	249	769	
	H2S					
Champion	Carbon Black	600		1,417	10,256	Sell
	Scrap Steel	265	883	626	4,530	
	Ash					Sell as fertilizer supplement, landfill
Cheyenne	Char	540		2,160	1,421	Sell
	Scrap Steel	180	667	720	474	
	Ash	20	74	80	53	Landfill
Conrad	Char	740		1,850	3,289	
	Scrap Steel	56	151	140	249	
ECO2	Carbon Black	450		864	9,584	Sell
	Other	160	790	318	3,917	
	Scrap Steel	140	650	271	3,084	Sell
	Fiber	50	230	97		
Heartland	Char					Sell for use in asphalt & roofing
	Scrap Steel					Sell
	Fiber					
	Ash					
Hamburg,	Char	700		3,000	4,167	Recycle as fill
U of	Scrap steel	250	792	1,167	1,584	
	Process Wastewater	150	459	667	917	
Premium	Char	500				
	Fiber					Landfill
Pyrovac	Char	500		909	8,333	
	Scrap Steel	180	720	327	3,000	
	Fiber	100	400	182	1,667	
	Discharged Cooling Water					Cool and discharge
Recycling	Char	75 % by vol.				Sell
Indus.	Scrap Steel	100				Bale & recycle
of MO	Fiber					Bale & recycle
RMAC	Char					Sell as fuel, use as process fuel
	Scrap steel					Landfill
	Process Wastewater					Treat
Seco/	Char	800		2,000	7,477	Sell as pigment & rubber filler
Warwick	Scrap Steel	80	200	200	748	Sell
	Discharged Cooling Water					
Texaco	Ash					
	Hyroden, Ammonia, & Methanol					
	Sulfur					
	Scrap Steel					
Worthing	Char	700		1,556	3,500	Sell as coal substitute
	Scrap Steel					Sell
	Discharged Cooling Water					

Source: Survey information.