# Resource recovery from used rubber tires

Takeshi Amari [a], Nickolas J. Themelis [b], Iddo K. Wernick [c],[*]

[a] *Mitsubishi Heavy Industries (Visiting Scholar, Columbia University, 9/97-9/98), Technical Headquarters, Yokohama R&D Center, 1-8-1, Sachiura, Kanazawa-ku, Yokohama 236-8515, Japan*
[b] *Columbia University, Earth Engineering Center, 500 West 120th St., New York, NY 10027, USA*
[c] *Columbia Earth Institute, 405 Low Library, New York, NY 10027, USA*

## Abstract

Including car, truck, bus, and airplane tires, 266 million tires were scrapped in the US in 1996 (Scrap Tire Management Council (STMC), 1997). More than three-quarters of these tires were used as fuel, recycled for material applications, or exported. The remainder accumulates in junkyards or landfills where they pose a fire hazard and provide a breeding ground for disease carrying rodents and insects. Using information on scrap tire composition and the current markets using them, we examine the technologies used to recover their value either for energy or as rubber. As the majority of scrap tires are used as fuel, we calculate their life cycle energy budget considering both the energy consumed for tire production and the energy recovered from their use as fuel. Based on our findings, we draw some preliminary conclusions on how to maximize value recovery from this ubiquitous artifact of industrial societies. © 1999 Elsevier Science Ltd. All rights reserved.

*Keywords:* Scrap tires; Tire derived fuel; Recycling; Life cycle energy accounting

## Composition of rubber tires

Globally, motor vehicles are the manufactured product of the highest value. They roll on rubber tires that wear out several times over the average vehicle's lifetime. Tires are made of vulcanized (i.e. cross-linked polymer chains) rubber and various reinforcing materials. The most commonly used rubber matrix is the co-polymer styrene-butadiene (SBR) or a blend of natural rubber and SBR. In addition to the rubber compound, tires contain:

Reinforcing fillers: Carbon black, used to strengthen the rubber and aid abrasion resistance.
Reinforcing fibers: Textile or steel fibers, usually in the form of a cord, used to provide the reinforcing strength or tensile component in tires. (The materials used for this purpose have progressed steadily from natural cotton through man-made rayon to a totally synthetic suite of nylons and polyesters. By the mid 1990's the use of steel tire cord increased substantially, occupying about 50% of the reinforcing fiber market (Corallo, 1995; Shemenski, 1994, p. 70)).
Extenders: Petroleum oils, used to control viscosity, reduce internal friction during processing, and improve low temperature flexibility in the vulcanized product. (By the mid 1990's, naphthenic oil captured more market share at the expense of aromatic oils, because the latter contain hazardous materials that require special handling.)

Table 1
Rubber compounding composition (Dodds et al., 1983)

| Component | Weight % |
| --- | --- |
| SBR | 62.1 |
| Carbon black | 31.0 |
| Extender oil | 1.9 |
| Zinc oxide | 1.9 |
| Stearic acid | 1.2 |
| Sulfur | 1.1 |
| Accelerator | 0.7 |
| Total | 99.9 |

* Corresponding author. Tel: +1-212-854-9462; fax: +1-212-854-6309.
*E-mail addresses:* takeshi_amari@d.ydmw.mhi.co.jp (T. Amari), njt1@columbia.edu (N.J. Themelis), iw4@columbia.edu (I.K. Wernick)

Vulcanizing agents: Organo–sulfur compounds, used as the catalyst for the vulcanization process; and Zinc oxide and stearic acid, used to activate the curing (cross-linking) system and to preserve cured properties.

A typical composition of synthetic rubber compound is shown in Table 1.

The amount of reinforcing steel or synthetic fibers used in rubber tires varies among manufacturers. For Western Europe, Guelorget et al. (1993) reports the following average composition of reinforcing fibers as a percentage of all material inputs.

Rayon: 2.8%
Nylon: 1.3%
Polyester: 0.1%
Steel: 13.1%

We use an average tire composition of 8% fabric (synthetic or steel), 3% steel wire and 89% rubber compound, as reported by Brown et al. (1996) for the life cycle energy analysis shown later.

## Combustion/pyrolysis of used rubber tires

### Tires as fuel

Tires can be used as fuel either in shredded form (Tire Derived Fuel (TDF)) or whole, depending on the type of combustion furnace. The Scrap Tire Management Council reports that over 57% of scrap tires in the US were used as fuel in 1996, Fig. 1 (STMC, 1997).

In considering the value of tires as fuel it is interesting to compare the typical composition of tires with that of coal, Table 2. The Babcock and Wilcox Company conducted tests with three types of shredded tires (Granger and Clark, 1991): 1.25 cm rubber "fuzz" and 5 cm rubber tire pieces with and without steel reinforcement. The results of the analysis show that, compared to coal, the tire samples had less moisture, significantly more combustible matter, and less fixed carbon. The heat content of the shredded tire samples tested was 10 to 16% higher than that of coal. The TDF ash sample contained 1.2 to 1.3% sulfur. This corresponds to approximately one-half of the sulfur content of US eastern coal and is about the same as low sulfur-western coals.

The ash residue from the TDF samples was 16%, 23%, and 9%, which compares to coal combustion, which yielded 11% ash. Charred steel, that can be recovered, accounts for the higher values for the TDF ash. The ash chemistry varies significantly between coal and TDF. Table 3 shows the principal constituents and their concentrations expressed as oxides, in the coal and TDF ash samples. Zinc oxide (ZnO), added during the rubber compounding process to control the rate of vulcanization, results in the high concentration of zinc which can be recovered from the ash. Generally, the ash residues from TDF contain a lower heavy metals content, making them less of a solid waste disposal burden than ash from standard coal combustion. Finally, using rubber tires as fuel results in lower NOx emissions when compared to many US coals (Ohio Air Quality Development Authority, 1991).

### Markets for tires as fuel

The largest use of TDF (29.8%) is for cement production in rotary, fuel-fired kilns, Fig. 2. In this oper-
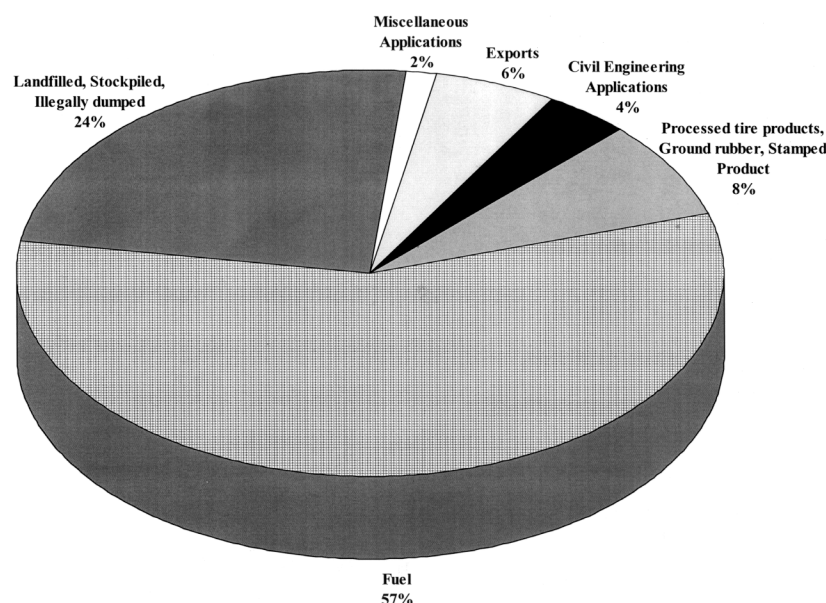


Fig. 1. Disposition of scrap tires, US 1996.

Table 2
Analysis of various tires, TDF, and coal

| | Energy Content (MJ/kg) | Components (wt%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Moisture | Ash | S | C | H | N | O | Volatiles |
| Tire Type[a] | | | | | | | | | |
| Fiberglass | 32.47 | 0.00 | 11.70 | 1.29 | 75.80 | 6.62 | 0.20 | 4.39 | |
| Steel-belted | 26.67 | 0.00 | 25.20[b] | 0.91 | 64.20 | 5.00 | 0.10 | 4.40 | |
| Nylon | 34.64 | 0.00 | 7.20 | 1.51 | 78.90 | 6.97 | <0.10 | 5.42 | |
| Polyester | 34.28 | 0.00 | 6.50 | 1.20 | 83.50 | 7.08 | <0.10 | 1.72 | |
| Kevlar-belted | 39.20 | 0.00 | 2.50 | 1.49 | 86.50 | 7.35 | <0.10 | 2.11 | |
| TDF Type**[c] | | | | | | | | | |
| Rubber "fuzz", 1.25 cm | 32.10 | 2.26 | 16.48 | 1.30 | 69.74 | 6.30 | 0.45 | 3.40 | 64.66 |
| Rubber, 5 cmw/metal | 31.05 | 0.75 | 23.19 | 1.33 | 67.00 | 5.81 | 0.25 | 1.64 | 54.23 |
| Rubber, 5 cm w/o metal | 32.58 | 1.02 | 8.74 | 1.23 | 72.15 | 6.74 | 0.36 | 9.67 | 67.31 |
| Unspecified coal** | 28.23 | 7.76 | 11.05 | 2.30 | 67.69 | 4.59 | 1.13 | 5.47 | 34.05 |

[a] Pope (1991).
[b] Includes steel.
[c] Granger and Clark (1991).

Table 3
Principal chemical elements in ash of coal and three rubber samples (Granger and Clark, 1991)

| Ash analysis (%) | Coal | Rubber 1.25 cm "fuzz" | Rubber 5 cm W/metal | Rubber 5 cm w/o metal |
|---|---|---|---|---|
| Silicon as $SiO_2$ | 47.98 | 18.21 | 5.16 | 22.00 |
| Aluminum as $Al_2O_3$ | 20.70 | 6.99 | 1.93 | 9.09 |
| Iron as $Fe_2O_3$ | 18.89 | 30.93 | 0.35 | 1.45 |
| Titanium as c | 0.82 | 6.01 | 0.14 | 2.57 |
| Calcium as CaO | 3.30 | 5.99 | 0.56 | 10.64 |
| Magnesium as MgO | 0.79 | 0.73 | 0.10 | 1.35 |
| Sodium as $Na_2O$ | 0.48 | 1.07 | 0.13 | 1.10 |
| Potassium as $K_2O$ | 2.06 | 0.55 | 0.14 | 0.92 |
| Sulfur as $SO_3$ | 4.33 | 8.35 | 0.99 | 15.38 |
| Phosphorus as $P_2O_5$ | 0.62 | 0.56 | 0.10 | 1.03 |
| Zinc as ZnO | 0.02 | 20.60 | 5.14 | 34.50 |
| Metal | | | 85.28 | |
| Total | 100.0 | 100.0 | 100.0 | 100.0 |
| $(CaO+MgO+Na_2O+K_2O+SO_3+P_2O_5+ZnO)/(SiO_2+Al_2O_3+TiO_2)$ | 0.37 | 1.26 | 11.98[a] | 0.46 |

[a] Assuming all metal content as $Fe_2O_3$.

ation, a mixture of finely ground calcareous (e.g., limestone), argillaceous (e.g., clay, shale) and siliceous (e.g., sand) materials is heated to 1500–1600°C to produce calcium silicate clinker which is later ground with gypsum to produce cement powder. Scrap tires serve as excellent fuel for the cement kiln, either whole or shredded. The very high temperatures and oxidizing atmosphere in the kiln provide for complete combustion of the tires, including the volatile matter produced during combustion. Additionally, the volatilized iron oxide resulting from combustion is useful for the cement product, reducing the costs of adding supplemental iron to the feed mix (Ohio Air Quality Development Authority, 1991).

The second largest users of TDF (23%) are pulp and paper mills. The primary use of TDF for pulp and paper mill boilers is to provide a heat source for drying and generating steam for electric power. TDF is also used for the calcination of limestone to lime (CaO), an ingredient in papermaking. Unlike cement, paper properties are affected adversely through exposure to TDF emissions, thus requiring a separate combustion chamber. Other users of TDF include electric utilities (19%), industrial boilers (13%), dedicated tire-to-energy facilities (10%), and waste-to-energy facilities (4%). More recently, copper smelters and iron cupola foundries have started using TDF (STMC, 1997).

Generally tires need to be reduced in size to accommodate furnace apertures. Besides size reduction, use of TDF at existing facilities may require some physical pro-
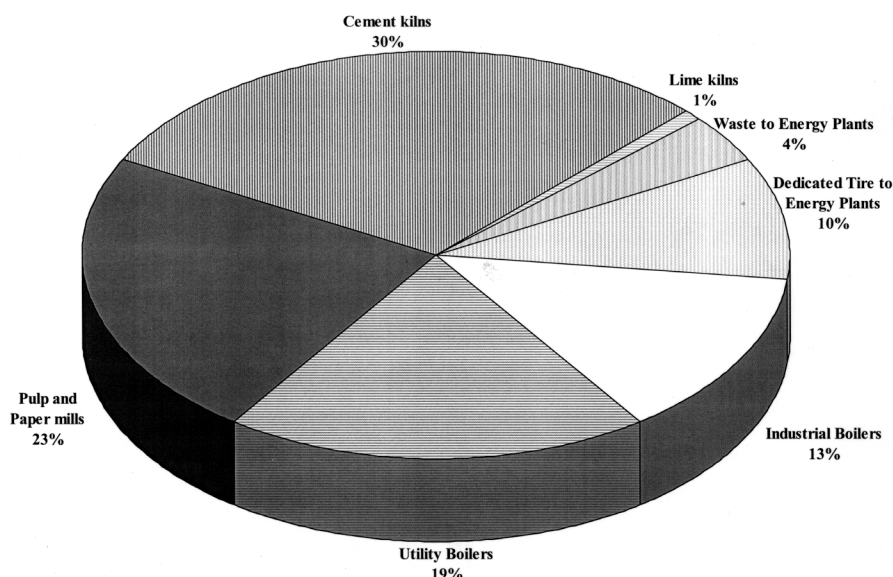
Fig. 2.   Markets for tire derived fuel, US 1996.

cessing, for each individual type of furnace. For example, the wire contained in tires may cause mechanical trouble in grate furnaces. To comply with air emission regulations, air pollution prevention equipment may also be necessary. Despite these requirements, converting scrap tires to fuel is fairly easy because of their high heating value, "clean" combustibility, and easy handling (e.g., transportation, storage).

*Pyrolysis*

Pyrolysis offers another route for high temperature resource recovery from tires. Pyrolysis involves the thermal decomposition of a substance into low molecular weight products under an inert atmosphere. Tire pyrolysis produces three principal products: gas, oil, and char. The gas and oil, which comprise about a half of the pyrolysis product by weight, have an energy content similar to conventional fuels. Char is a fine particulate composed of carbon black, ash, and other inorganic materials, such as zinc oxide, carbonates, and silicates. The economic feasibility of tire pyrolysis is strongly affected by the value of the solid char residue. Pyrolysis products have historically yielded poor returns as the prices obtained for products failed to justify process costs. An examination of current practice reveals that although more than 30 major pyrolysis projects have been proposed, patented or built over the past decade, none have been commercially successful. As of 1997 no tire pyrolysis plants were operating in the United States (STMC, 1997).

Looking to the future, Wojtowicz and Serio (1996) propose a scheme for processing scrap tires into higher value-added products (e.g., activated carbon and carbon black). In their process, char upgrading is implemented in a closed-loop activation step that yields an activated carbon and eliminates undesirable by-products and emissions. The process yields substantial quantities of oils in addition to the char which undergoes processing for value-added products.

## Recycling used rubber tires

In the US, approximately 30 to 33 million tires—over 10% of used tires—were retreaded in 1996 and returned to service, most commonly for commercial uses such as trucks, buses, and airplanes. Retreading offers the most resource efficient strategy for used tire recovery, saving both material and energy. Besides reuse, scrap tires can be recycled whole or size-reduced for civil engineering applications and agricultural uses and for composite materials. Whole tires are used for applications where their physical form, resilience to impact, and longevity are beneficial, for example in marine docks and as highway crash barriers. Ground rubber from tires can be added to other polymers (rubber or plastic) to extend or modify properties of thermoplastic polymeric materials.

*Markets for tires as material*

Though some markets for ground rubber have weakened in the last decade, several new applications have developed and several others have expanded. An estimated 12.5 million tires were used for size-reduced rubber applications in 1996, more than two-and-a-half times the 4.5 million used for ground rubber in 1994. Table 4 shows market demand for size-reduced rubber.

For composite applications, ground tire rubber is formed into a set shape and usually held together by an

Table 4
Market demand for size-reduced rubber (in million pounds) (STMC, 1997)

| Product/Application | 1995 | 1996 | 1998 (est.) |
| --- | --- | --- | --- |
| Pneumatic Tires | 33.5 | 48 | 140 |
| Friction Materials | 7.5 | 8 | 8.5 |
| Molded and Extruded Plastic/Rubber | 14 | 18 | 24 |
| Rubber/Plastic Bound Products | 105 | 134 | 160 |
| Athletic and Recreation | 16 | 24 | 50 |
| Asphalt Products | 102 | 168 | 200 |
| Total | 278 | 400 | 582.5 |

adhesive material (e.g., urethane or epoxy). Particulate rubber makes surfaces more resilient and less rigid, while allowing the surface material to maintain traction and shape. Ground rubber products can be used for applications including flooring materials, dock bumpers, patio decks, and railroad crossing blocks. Products molded and extruded from ground tire rubber include livestock mats and removable speed bumps. Ground rubber products are also used for athletic and recreational materials, such as running tracks and playground surfaces. Use of ground tire rubber as filler material in the tread and sidewall of new tires is generally limited to a maximum of 1.5% of the tire weight. However, tests performed jointly by Michelin and Ford, show that tire manufacturers can add up to 10% of recycled rubber to passenger tire compounds, without compromising tire performance (Phillips, 1997).

Size reduced tire rubber has demonstrated utility as a mixing ingredient with asphalt for highway construction. The use of rubber-modified asphalt in US federal highway construction suffered a setback in the mid 1990's. Section 1038(d) of the 1991 Intermodal Surface Transportation Efficiency Act required all states to begin using rubber-modified asphalt for a specified portion of their asphalt paving beginning in 1994, with the requirement increasing each year until 1997, when 20 percent of all federally aided asphalt paving would have had to contain a specified volume of rubber. The provision generated opposition from the asphalt paving community and from state highway administrators. Ultimately, the mandate was repealed as part of the Federal Highway Systems Act passed in late 1995. The reasons cited included lack of standard mix designs, continuing questions about the ability to recycle modified asphalt, and cost. For this "waste" material, as for so many others, the need for industry standards and better infrastructure present barriers to market penetration.

### Technologies to improve ground tire rubber properties

The stability of rubber as a compound results from the vulcanization process. This same stability inhibits recycling because the vulcanized rubber particle surfaces have difficulty binding to other materials. We discuss several technologies developed to overcome this barrier to expanding markets for ground rubber in material composites.

### Devulcanization

Devulcanization reverses the sulfur–carbon bonding that makes rubber stable. Traditional methods involve exposure to high temperatures and pressures for extended periods of time. Because of their energy intensity, environmental concerns, and limited economic success, these methods are rarely used today. Phillips (1997) reports that a Malaysian company, STI–K, produces devulcanized scrap tire rubber using a proprietary chemical agent mixed in an open mill. The STI–K process has received criticism from some industry groups and its eventual wide-scale use is difficult to predict. Tukachinsky et al. (1996) reports on another technology that uses ultrasonic energy to devulcanize tire rubber, but is not yet commercially available. We note that achieving commercially successful devulcanization technologies will not eliminate the problems associated with recycling. Today's tire market includes many types of tires that typically contain combinations of several types of polymers. Thus, even the materials resulting from an ideal devulcanization method contain a mix of polymers, that compare poorly to virgin polymers. This quality difference limits the market for high end uses, such as new tire manufacturing.

### Surface modification

Surface modification methods treat ground rubber to make it more reactive without breaking the bonds in the vulcanized material. Two basic approaches to surface modification technologies dominate: 1) Coating the rubber with a bonding agent to make it more chemically active in a new compound; and 2) Treating the rubber particles with a caustic gas to "activate" the surface, thus allowing the material to bond with other polymers, usually urethane.

One US company, Air Products and Chemicals, developed surface-modification technologies to treat plastic and elastomers over the 1980s and early 1990s. In their process, steel and fabric are removed from the tires, and the ground material is exposed to oxidative gas

mixtures containing small amounts of fluorine and at least one other reactive gas, such as oxygen or sulfur dioxide. The ensuing reactions form polar reactive groups, such as hydroxyl (OH) or carboxylic acid (CO2H) that increase the surface energy of the material, enabling it to bond chemically to new polymers. This process also creates numerous double bonds on the surface of the rubber, allowing new uses for unsaturated polymers, free radical polymers, and rubber formulations (US Department of Energy, 1992).Table 5 presents a summary of scrap tire utilization technologies.

## Life cycle energy budget for tire production

Having established that the majority of scrap tires are recovered for their energy value, we now calculate the energy input for rubber tire manufacture and compare it with the energy recovered from tire combustion. As noted earlier, the primary man-made materials used for making rubber tires are the styrene–butadiene co-polymer (SBR) and carbon black. Fabric and steel are used as reinforcing material. In our examinations of raw material and energy use, we assume the composition of rubber tires to be 89% SBR and carbon black, 8% fabric and 3% wire (Brown et al., 1996). The ratio SBR/carbon black was assumed to be 2 to 1 (Dodds et al., 1983). Other additives such as extender oil and sulfur were omitted in order to simplify the analysis. Under these assumptions, the material flows for production of 1000 kg of rubber tires are shown in Fig. 3. We use representative manufacturing methods to determine mass flow values and the energy required for processing.

### Energy flows for tire components

#### SBR

SBR is produced by the polymerization of styrene and butadiene. The styrene is derived mostly from the benzene product of crude oil, and the butadiene is obtained from ethylene, generally produced from natural gas. These feedstocks, benzene and ethylene, represent two

Table 5
Summary of scrap tire utilization technologies

| COMBUSTION/PYROLYSIS | | |
|---|---|---|
| Facility type | Combustion vessel | Specifications |
| Cement plant | Rotary Kiln | Shredded or whole tire. Can be co-fired with coal or coke. |
| Paper Mills, Electric utility, General Industry | Spreader Stoker | Size reduced[a] to 2.5–10 cm. Can be co-fired with coal or wood. |
| Electric utilities | Cyclone Boiler | Size reduced to 2.5×2.5 cm or less. Can be co-fired with coal. Requires de-wiring.[b] |
| Electric utilities | Pulverized Coal Boiler | Size reduced to 0.8–2.5 cm. Can be co-fired with coal. Tests with whole tires underway. |
| Electric utilities | Fluidized Bed Boiler | Size reduced to 5–25 cm. Can be co-fired with coal. Tolerates wire. |
| Dedicated-tire-to-energy facility | Stoker Boiler | Can use whole tires. Can be co-fired with coal, gas, and waste wood. |
| Tire Pyrolysis plant | Requires size reduction for high temperature processing in inert atmosphere to produce fuel and carbon materials. For cost information see (Wojtowicz and Serio 1996) | |
| MATERIAL RECYCLING | | |
| Application | Process Description | Specifications |
| Bound Rubber Products[c] | Formed into a set shape and held by adhesive | Product specific |
| Rubber Modified Asphalt | Blended with asphalt to modify asphalt properties | Product specific |
| Molded and Extruded Plastics/Rubber | Added to other polymers to extend or modify properties | Wire and fabric must be removed |
| New Tire Manufacturing | Used as filler in new tires | Product specific |
| TREATMENT TECHNOLOGIES | | |
| Technology | Process Description | |
| Devulcanization | Reverses sulfur–carbon bonding to enhance ability to chemically bond to other polymers. | |
| Surface Modification | Prepares rubber surface for bonding with polyurethane, latex and other polymers. For cost information see US Department of Energy (1992). | |

[a] Costs for size reduction to 5 cm~$20/ton

[b] Dewiring increases costs by 25–50%

[c] Incurs additional grinding costs beyond primary grading
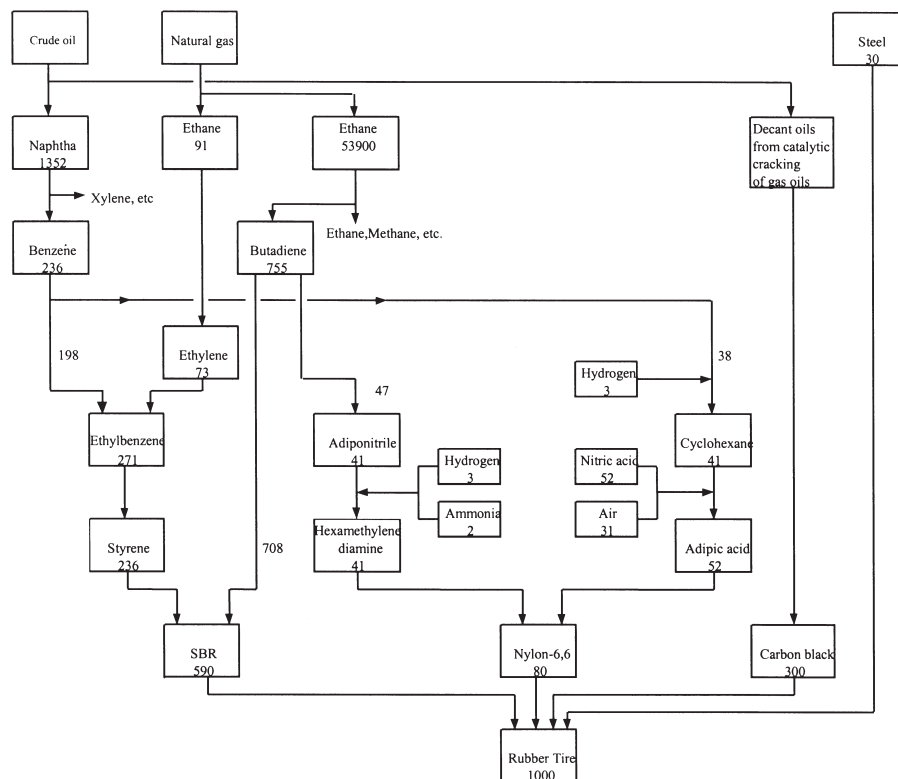
Fig. 3.   Material flows for rubber tire production (mass requirements (kg) are expressed on the basis of 1000 kg rubber tire produced).

of the most common basic petrochemical intermediates. The material requirements for producing SBR for 1000 kg of rubber tires include 236 kg of benzene, 73 kg of ethylene, and 755 kg of butadiene.

Benzene is produced from an aromatic complex that also yields toluene and xylene. The feedstock requirements for the aromatic complex depend on the available feedstocks and desired product. The most common feedstock for aromatics production is petroleum naphtha. Styrene is produced by dehydrogenation of ethylbenzene, a product of the alkylation of benzene. Using straight-run naphtha derived from Arabian light crude in a process designed to maximize the yield of benzene and para-xylene requires 1352 kg of naphtha to produce 236 kg of benzene. Operating conditions for maximizing the yield of benzene and para-xylene are reported by Meyers et al. (1996). Alkylation of the benzene is exothermic while the dehydrogenation of ethylbenzene is endothermic allowing for energy savings through proper integration of process energy flows. The reaction of benzene and ethylene takes place on acidic catalysts while the dehydrogenation of ethylbenzene to styrene takes place on an iron oxide–potassium oxide catalyst in the presence of steam. Brown et al. (1996) report the material and energy requirements.

Butadiene is produced as a by-product in the steam cracking of hydrocarbons to produce ethylene from ethane. The yield of butadiene from ethane is less than 2%

while the yield of ethylene is 80% (Lee et al., 1990). As a result of steam cracking, a mixture of olefins, aromatics, tar, and gases is formed. These products are cooled and separated into specific boiling range cuts of each carbon number stream. Separation and purification of butadiene is carried out principally by extractive distillation. The energy requirement of extractive distillation of butadiene from the C4 stream is provided by Coogler (1967). In the US, more than 70% of the ethylene capacity is based on light hydrocarbon feedstocks, such as ethane, ethane/propane mix, natural gas liquids (NGL), and liquefied petroleum gas (LPG). The present analysis assumes that the feedstock for ethylene is ethane and that the product yield is as reported by Lee et al. (1990).

The material and energy requirements for the polymerization methods used to produce SBR, emulsion polymerization and solution polymerization, are reported in Brown et al. (1996). Table 6 shows the energy consumption corresponding to the various stages of the flow sheet for SBR production. From the table it can be seen that, starting from naphtha and ethane as raw materials, the production of 1 kg of SBR requires 55.8 MJ of energy.

*Carbon black*

About 95% of US feedstock of carbon black derives from heavy distillates from catalytic cracking. The

Table 6
Energy consumption in production of 1 kg of SBR from naphtha and ethane

| Material | Process and feedstock | Material use (kg/kg of SBR production) | Electricity requirement (MJ/kg of product) | Electricity Usage (MJ) | Fuel requirement (MJ/kg of product) | Fuel Usage (MJ) | Conversion Ratio (% feedstock to material) | Total Energy Usage (MJ) |
|---|---|---|---|---|---|---|---|---|
| Benzene | Catalytic Reforming, Aromatics extraction for production of aromatics from naphtha and liquid–liquid extraction of BTX | 0.336 | 1.90 | 0.11 | 3.80E+01 | 2.23 | 17.4% | 2.34 |
| Ethylene | Steam Cracking for conversion of ethane to ethylene | 0.124 | 3.14 | 0.31 | 2.34E+01 | 2.32 | 80.0% | 2.63 |
| Styrene | Alkylation and Dehydrogenation for Styrene synthesis from benzene and ethylene | 0.4 | 0.30 | 0.11 | 3.84E+01 | 0.001 | 87.0% | 1.35E+01 |
| Butadiene | By product of Steam Cracking for conversion of ethane to ethylene | 1.2 | 1.79E+02 | 3.01 | 1.34E+03 | 2.24E+01 | 1.40% | 2.54E+01 |
| Butadiene | Extractive Distillation for separating and purifying Butadiene from C4 stream | | | | 2.49 | 2.99 | | 2.99 |
| SBR | Emulsion/Solution Polymerization from Styrene and Butadiene | | 0.86 | 0.86 | 8.07 | 8.07 | | 8.93 |
| Total usage for production of 1kg of SBR | | | | 4.40 | | 5.14E+01 | | 5.58E+01 |

energy utilized for producing oil-furnace carbon black is in the range of 93–160 MJ/kg (Kirk-Othmer, 1996).

*Fabric*

Various materials are used for reinforcing rubber tires. To simplify this analysis, we choose nylon-6,6 as the representative reinforcement fabric material. The energy utilization in the production of nylon-6,6 from hexamethylenediamine and adipic acid is 43.49 MJ/kg (Frederick and Moran, 1975; Weissermel and Arpe, 1997).

*Steel*

The production of bulk steel products starting from iron ore has been estimated at 31.1 MJ/kg and 8.7 MJ/kg starting from scrap (Chapman and Roberts, 1983, p. 138). Based on government data and industry reports, we estimate the proportion of steel production from scrap in the US as 56% (US Geological Survey, 1997). Therefore, we estimate the average consumption of energy for the production of steel at 18.5 MJ/kg. In the present study, it is also assumed that conversion of bulk steel to fine wire increases energy consumption by an additional 50%. Accordingly, the energy use per kilogram of steel wire was assumed to be 27.8 MJ/kg.

Table 7 summarizes the total energy use for producing 1 kg of reinforced rubber tire, totaling 87 MJ, contained in the feed materials, and used for the manufacturing process.

The above estimate does not include the energy required for size reduction of tire scrap. As shown in Table 5, the required size of TDF ranges from 0.6 cm to 25 cm, while some facilities accept whole tires. Though no direct data for energy use from size reduction of tire scrap exist, an approximate estimate can be based on tire shredding cost data from the US Environmental Protection Agency (1991). These data show that typical energy requirements for shredding 500–800 tires per hour down to 10–20 cm pieces equal about 99.4 kJ/kg, less than one half percent of that recoverable by TDF combustion.

Using a typical value for the recoverable energy value from tires as 32 MJ/kg from Table 2, we conclude that slightly more than 37% of the energy embedded in a new manufactured rubber tire is recoverable as energy. Therefore, from an energy point of view, it is preferable to recycle rubber as rubber (e.g. in rubber composites) than to use it as a fuel.

## Conclusions

The tire waste stream consists of a product that represents a century of manufacturing innovation. Al-

Table 7
Energy usage for the production of 1 kg of rubber tires

|  | Material usage (kg/kg of Tire production) | Energy usage (MJ/kg of product) | Total Energy Usage (MJ/kg) |
|---|---|---|---|
| 1. SBR | 0.59 | 55.79 | 32.92 |
| 2. Carbon Black | 0.30 | 126.50 | 37.95 |
| 3. Steel | 0.03 | 27.80 | 0.83 |
| 4. Fabric | 0.08 | 43.49 | 3.48 |
| 5. Manufacturing[a] | – | 11.70 | 11.70 |
| Total |  |  | 86.88 |

[a] Brown et al. (1996)

together, used tires annually represent about 23 petajoules (23E+15) of embedded energy from raw material and manufacturing. In terms of equivalent oil usage, this amounts to almost four million barrels of oil annually. As industrial civilization matures through its next stage, society and industry must endeavor to recover the maximum amount of value from this material resource.

Reusing tires (i.e., retreading) offers the best strategy for value recovery, requiring the least new material and energy to achieve the highest value-added use in the economy. For tires that are scrapped, our study shows that less than 40% of the energy embedded in tires is recoverable as fuel energy. Use of tires for some applications may not offset energy use for some materials (i.e., aggregates), but it does offset energy use when replacing polymers. As a fuel, tires are superior to coal in specific energy content and the environmental burden of residues. While the use of tires as fuel may not represent the optimal strategy for value recovery, the environmentally responsible combustion of tires for energy is preferable to the health and aesthetic problems resulting from their accumulation in landfills. More than half the tires scrapped in the US are used for fuel. Local regulations and the lack of adequate infrastructure for collection and transportation may hamper further market development for TDF in some regions.

The very performance properties sought in tire manufacture (e.g., strength and durability) frustrate attempts to recycle tires for use in other products. Using tire rubber for products typically requires that steel wire be removed, currently a costly process. The stability of the rubber compound itself necessitates treatment to make it compatible with other materials. Advances in de-wiring technologies and surface treatment technologies would help to reduce these barriers to economic recycling of rubber tires for products. More fundamental change may result from the design of tires to be both durable, and more easily recycled. Encouraging reuse and research and development of enabling technologies offer promise for wiser management of this solid waste stream and better conservation of natural resources.

## References

Brown, H.L., Hamel, B.B., 1996. Energy analysis of 108 industrial processes. The Fairmont Press, Inc, Lilburn (GA).

Chapman, P.F., Roberts, F., 1983. Metal Resources and Energy. Butterworth, Boston (MA).

Coogler, W.W. Jr., 1967. Butadiene from special distillation. Hydrocarbon Processing 46 (5), 166–168.

Corallo, G., 1995. Historical Review of Light-Duty Tire Carcass Reinforcement and The State of Current and Next Generation Technology. American Chemical Society, Rubber division, Philadelphia (PA).

Dodds, J., Domenico, W.F., Evans, D.R., 1983. Scrap tires: a resource and technology evaluation of tire pyrolysis and other selected alternative technologies. US Dept. of Energy Report No. EGG-2241, Washington, DC.

Frederick, A.L., Moran, M.K., 1975. Faith, Keyes, and Clark's Industrial Chemicals. 4th ed. Wiley, New York (NY).

Granger, J.E., Clark, G.A., 1991. Fuel characterization of coal/shredded tire blends. Proceedings of the Electric Power Research Institute (EPRI) Conference on Waste Tires as a Utility Fuel. EPRI, San Jose, CA.

Guelorget, Y., Julien, V., Weaver, P.M., 1993. A life cycle analysis of automobile tires in France. Working Paper (93/67/EPS), INSEAD, Fontainebleau, France.

Kirk-Othmer Encyclopedia of Chemical Technology, 1996. 4th ed. Vol. 4, p. 1051. Wiley, New York, NY.

Lee, A.K.K. et. al., 1990. Saudi ethylene plants move toward more feed flexibility. Oil and Gas Journal 88, 60–65.

Ohio Air Quality Development Authority, 1991. Air emissions associated with the combustion of scrap tires for energy recovery. Malcolm Pirnie, Inc., Columbus, OH.

Phillips, M., 1997. A higher purpose for scrap rubber. Recycling Today 35, 42–46.

Pope, K.M., 1991. Tires to energy in a fluidized bed combustion system. Proceedings of EPRI Conference on Waste Tires as a Utility Fuel. EPRI, San Jose, CA.

Meyers, R.A. et. al., 1996. Handbook of Petroleum Refining Processes. 2nd ed. 2.5-2.11. McGraw-Hill, New York (NY).

Shemenski, R.M., 1994. Wire J. Int. Cambridge University Press, Cambridge (MA).

Scrap Tire Management Council (STMC), 1997. Scrap Tire Use/Disposal Study 1996 Update. STMC, Washington, DC.

Tukachinsky, A., Schworm, D., Isayev, A.I., 1996. Devulcanization of waste tire rubber by powerful ultrasound. Rubber Chemistry and Technology 69, 92–103.

US Department of Energy, 1992. Surface-modification technology for scrap tire reuse. USDOE Office of Industrial Technologies, Washington, DC.

US Environmental Protection Agency, Office of Solid Waste, 1991. Markets for scrap tires. USEPA, Washington, DC.

US Geological Survey, 1997. Mineral commodity summaries. USGS, Reston, VA.

Weissermel, K., Arpe, H.J., 1997. Industrial Organic Chemistry. 3rd ed. VHC Publishers, Inc, New York (NY).

Wojtowicz, M.A., Serio, M.A., 1996. Pyrolysis of scrap tires: can it be profitable? Chemtech 26 (10), 48–53.