RECYCLING, PLASTICS

1. Introduction

In 2003, >236 million tons of municipal solid waste was generated in the United States, equivalent to 4.5 lb (2.04 kg) per person per day (1). Of this, 30% was recovered and recycled or composted, 14% was incinerated and the remaining 56% disposed of in landfills. Plastics accounted for 11.3% or 26.7 million tons [53.3 billion lb (24.17 kg)] of municipal solid waste.

Three different methods are used to divert materials from the waste stream. Source reduction reduces the amount that is thrown away through improved design, manufacture, or use of products and materials. Recycling involves separating materials from the waste stream and reprocessing them to make new products. Composting decomposes organic wastes producing a fertilizing material that can be spread on soil. Recycling and composting diverted 72 million tons of materials from landfills in 2003 or 30.5% (1). The recycling rate of plastic milk bottles in 2003 was 31.9% and that of plastic soft drink containers was 25.2% (1). In comparison, the recycling rate of aluminum cans was 43.9%.

Both economic factors and governmental regulations are driving recycling (2). Energy costs associated with recycling are almost always less than in manufacture of products from virgin materials. Plastics recycling takes only 10–15% of the energy needed to refine petroleum and manufacture virgin resins. Incineration of plastics is a less efficient means of saving energy. For example, 100 lb (45.4 kg) of high density polyethylene has a fuel value of 20×10^6 Btu (19 kJ). Recycling saves twice this, 40×10^6 Btu (38 kJ). Life cycle analysis has been used to determine the most economically and environmentally acceptable method of using recovered plastics: mechanical recycling of the plastic, depolymerization to produce monomers, or incineration to produce energy (3). The most acceptable technology depends on the type of polymer and local business and environmental conditions.

Both economic and environmental factors have led to government regulations designed to promote recycling. In some areas, the number of landfill sites is becoming limited. Although the number of landfills in the United States is declining, the remaining sites are large, modern facilities. Concerns about landfill disposal costs are becoming less of a factor in promoting North American recycling. However, the effect of plastic wastes on the environment is a growing concern.

2. Separation of Commingled Materials

Random mixing of plastics leads to a significant adverse effect on properties. For example, mixing a few percent polypropylene in polyethylene leads to a significant reduction in tensile strength due to the formation of two immiscible phases having little adhesion (4). Hence, different types of plastics must be separated from each other. Solid wastes, particularly from residential curbside collection programs, arrive at material recovery facilities (MRF) as a complex mixture. The MRFs are typically built to process 100–500 tons of waste per day (5).

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Unit operations are summarized in Fig. 1. The wastes are dumped on a tipping floor. There paper products are separated from metals and plastics. Metals and plastics, mostly containers, are pushed onto a conveyer belt. Two types of magnetic separators remove steel and aluminum from plastics and glass. Density differences or manual sorting are used to separate glass from plastics. The glass containers are hand sorted by color. The plastics are separated into individual polymer types by the MRF or in separate reclaiming facilities (5). Plastic bottles are classified into clear poly(ethylene terephthalate) (PET) soft drink bottles; green PET soft drink bottles; translucent high density polyethylene milk, water, and juice bottles; pigmented high density polyethylene detergent bottles, poly(vinyl chloride) (PVC) water bottles, and food containers, such as polypropylene ketchup bottles (5). Processing equipment capable of separating pigmented bottles from clear ones has been installed in some facilities (6).

When processing municipal solid wastes, an eddy current separation unit is often used to separate aluminum and other nonferrous metals from the waste stream. This is done after removal of the ferrous metals (see Fig. 1). The eddy current separator produces an electromagnetic field through which the waste passes. The nonferrous metals produce currents having a magnetic moment that is phased to repel the moment of the applied magnetic field. This repulsion causes the nonferrous metals to be thrown out of the process stream away from nonmetallic objects (7).

Another separation device that may be used is the mineral jig. This unit produces a loose vibrating bed of particles in a liquid medium. The vibrations segregate the solids into layers of density. The dense nonferrous metals, primarily lead, zinc, and copper are at the bottom while organics are at the top. The middle layer is primarily glass.

2.1. Separation of Impurities.   After separation of the plastics, a number of impurities may still be present. This include inks used to print information and label onto plastics, and labels, wood, and dirt accumulated during use and disposal of the plastic. Washing technology has been used to remove inks, labels, and encrusted dirt from plastics, particularly bottles (8). A number of technologies have been used to separate other materials from plastics. Froth flotation has been used to separate PVC from PET despite the similar densities of these polymers (9). In laboratory tests, froth flotation separated PVC, polycarbonate (PC), polyacetal, and poly(phenylene ether) (PPE) from each other. Wetting agents, such as lignosulfonates, tannic acid, and saponin were required to promote the separation (10). Plastics may be separated from mixed bulk materials based on particle size (11). To separate poly(vinyl butyral) (PVB) in window glass from impurities, the polymer is melted and allowed to flow into supercritical carbon dioxide (12). Another technique to remove impurities from melted polymers is filtration (13).

3. Plastics

In May 1992, the U.S. Food and Drug Administration (FDA) established the following guidelines to help assure the consumer safety of plastics recycling processes (14). Primary recycling is the recycling of plastics that are plant

scrap and have not been sold for consumer use. Secondary recycling is the physical cleaning and processing of postconsumer plastic products. Tertiary recycling is the chemical treatment of polymers resulting in depolymerization to produce monomers that are purified and then polymerized to produce new polymer. Using tertiary recycling, materials, such as fillers and fibers, can be physically removed from the monomer. The monomers can also be purified by distillation and other processes prior to polymerization to produce new polymer. The leading example of tertiary recycling is PET. Tertiary recycling also has been suggested for nylon from discarded carpets (15).

Residential collection programs indicate high collection rates for easily recognized types of containers (Table 1).

Sorted plastic packaging materials are shipped, usually in bales, to processing plants to be converted to polymer resins. The bales are broken and the bottles sorted to ensure that only one type of polymer is further processed. Processing consists of chopping and grinding the bottles into flakes. These flakes are washed. Processing steps, such as flotation are used to remove polymeric contaminants from the flakes (9,10). The flakes are melted and converted into pellets.

For high value food packaging applications, minimal migration of contaminants into food products is critical. Currently the FDA requirement is a maximum 0.5 parts per billion (ppb) of noncarcinogenic compounds by dietary exposure (16).

3.1. Poly(ethylene terephthalate).

Poly(ethylene terephthalate) is used extensively in food packaging applications (17). About 1003 million lb (454.95 kg) of postconsumer PET containers were recycled in 2004, a recycling rate of 21.4% (18). Cleaning of the recovered plastic comprises washing, rinsing, and drying.

Poly(vinyl chloride) is a common impurity in PET. Melting PET containing PVC will produce black spots due to charring of the PVC during processing to produce new bottles (19,20). Poly(vinyl chloride) and PET have very similar density values; both will sink to the bottom of the water bath during rinsing. Therefore, it is difficult to separate the two polymers after the bottles have been ground into small particles (19). However, froth flotation has been shown to be an effective means of separating these two polymers (9).

For food applications, improved cleaning of PET produced by secondary recycling is needed. Supercritical fluid extraction using carbon dioxide (14) and solvents, such as propylene glycol (21) have been proposed. High temperature and the use of vacuum to remove volatile impurities has also been suggested (22). Stripping of volatile components at temperatures >160°C for 3 min has been reported (23). Application of multilayer approach, the manufacture of a bottle with an inner layer of recycled PET sandwiched between surface layers of virgin PET, is used commercially for soft drink applications (24).

Originally, PET was used virtually exclusively to package soft drinks. As a result, the recycling stream was quite homogeneous consisting of unpigmented one- and two-liter bottles with a small percentage of green bottles (25). However, PET is now used to package a wide variety of beverages besides soft drinks including water, fruit juices, tea, and beer plus other products, such at peanut butter, ketchup, and edible oils. These products are often packaged in bottles colored with a wide range of pigments and in many sizes and shapes. In addition

various label adhesives and barrier resins are combined with the PET. These impurities, which make careful sorting of containers in the waste stream essential, can reduce yield of the sorting process and can reduce the quality of products made with recycled PET.

In the United States, PET from recycled bottles is primarily used in fiber applications (Table 2).

The second-largest market, new food and beverage containers, typically requires tertiary PET recycling processes to obtain FDA approval for use in food and beverage contact applications. Two PET tertiary recycling technologies have been used commercially: methanolysis (27) and glycolysis (28). Both cleave the ester linkages in the polymer to form monomers. In methanolysis, methanol is used to cleave the polymer ester linkages producing stoichiometric amounts of dimethyl terephthalate and ethylene glycol (27,29). The ethylene glycol is separated and purified by distillation. The dimethyl terephthalate is purified by crystallization and distillation. Both bis(hydroxyethylterephthalate) and oligomers are formed (28,29). These are recovered and purified by vacuum distillation and then polymerized in the presence of ethylene glycol to form PET.

Glycolysis is claimed to be somewhat less costly than methanolysis (30). Depolymerization is not taken completely to monomers (31). Rather, recovered PET is depolymerized to low molecular weight oligomers. Contaminants are removed using proprietary technology. The oligomers are then fed to a melt polymerization vessel in which PET is produced.

Hydrolysis yielding terephthalic acid and ethylene glycol is a third process (30). High temperatures and pressures are required for this currently noncommercial process. The purification of the terephthalic acid is costly and is the reason the hydrolysis process is no longer commercial. Recently, the use of ammonium hydroxide to promote PET polymerization has been described (32).

Suitability for food contact is a critical property in selling recycled PET. The FDA has issued letters of nonobjection to operators of methanolysis and glycolysis processes for recycling PET (33). Two-liter PET soda bottles containing recycled PET manufactured by glycolysis and methanolysis are widely available. The FDA has also issued a letter of nonobjection for a trilayer PET material having a middle layer sandwiched between two virgin layers of PET. Volatile materials associated with beverages and food can be removed efficiently from recovered PET by volatile stripping for three minutes at 160°C (34). However, if the air is recycled, volatile substances can be deposited as a film on the polymer particles.

3.2. Polyethylene.   About 24.8% of produced high density polyethylene (HDPE) is recycled in the United States, mainly milk and water jugs and liquid laundry detergent bottles (25). Cleaning of the recovered plastic comprises washing, rinsing, and drying (19). Removing labels is the worst problem in washing and drying stages. Detergents are often used to improve the efficiency of label removal. Metal-foil labels can introduce metals into the polymer. When metal-foil labels are heat sealed onto plastic, the only way to remove them is using an extrusion-melt filter. This leads to plugging of the filter screens causing more frequent changes and increasing production costs.

During the rinse cycle, polyethylene particles float to the surface of the water bath. The higher density PET and PVC particles sink to the bottom of the bath and can be separated from the polyethylene.

End uses for U.S. recycled HDPE bottles are summarized in Table 3.

Unpigmented HDPE is used for new bottles for nonfood applications, such as detergents, motor oil and household cleaners (25). Pigmented HDPE is used for pipe and garden products such as edging and flower pots. Use of both pigmented and unpigmented HDPE in residential decking boards and fence posts is growing (25,31). Other recycled HDPE uses include reusable container lids, truck bed liners, and pallets (31). Curbside residential recycling collection containers themselves often contain as much as 95% recycled HDPE (33). The U.S. Environmental Protection Agency (EPA) has recommended that the U.S. government purchase shipping pallets containing 25–100% recycled polyethylene (34). This represents a sizable market as the U.S. Postal Service alone uses >3 million polyethylene pallets. Another large potential market in the United States is plastic and concrete railroad ties (35). About $700 million is spent annually to replace 18–20 million of the 850 million wood and concrete ties currently in use. HDPE can also be shredded into small particles and blended with cement to create concrete (36). However, despite a low addition level (0–5% relative to cement), the HDPE had an adverse effect on cement compressive strength. An alkaline bleach treatment of the HDPE particles prior to blending reduced this adverse effect.

Blends of PET and HDPE have been suggested to exploit the availability of these clean recycled polymers. The blends could combine the inherent chemical resistance of HDPE with the processing characteristics of PET. Since the two polymers are mutually immiscible, ~5% compatibilizer must be added to the molten mixture (37). The properties of polymer blends containing 80–90% PET/20–10% HDPE have been reported (38). Use of 5–15% compatbilizer produces polymers more suitable for extrusion blow molding than pure PET.

Low density polyethylene has been pyrolyzed at 800°C to produce ethylene, propylene, and other light olefins in 75% yield (39).

3.3. Polypropylene. Polypropylene (PP) is used in packaging applications as films and in rigid containers. Battery cases could be considered another packaging application. Dead batteries are often collected at the point of sale of new batteries. In the United States, some states have laws mandating this. Lead, acid, and plastics, particularly PP from battery casings is recovered and recycled (37). PP is also recovered from bale wrap and other PP fabrics used for wrapping in the textile industry and from other containers (40).

Steps in polypropylene recycling include size reduction grinding, washing, rinsing, and drying to remove contaminants and produce PP flakes (40). After extrusion, molten polymer is filtered through screen packs. The polymer may be separated into different melt flow ranges to produce more uniform product grades.

3.4. Polystyrene. Polystyrene (PS) is widely used in many packaging applications. These include injection molded products such as beverage containers, dairy product containers, and packaging for personal care products (41). Extruded solid-sheet PS packaging products include salad boxes, dairy product containers, baked goods containers, and vending cups and lids. Extruded foam sheet PS packaging products include poultry and meat trays, produce trays,

hinged lid containers, egg cartons, and foam cups. Blow and foam molded PS packaging products include vitamin bottles, loose fill packaging, and cushion packaging.

Polystyrene items separated from the solid-waste stream are subjected to one or more of the following unit operations: densification (for PS foams), granulation to reduce particle size, washing, drying, extrusion, and pelletizing (41). The finished pellets have properties similar to the virgin resin. High density baling is used to increase the bulk density of polystyrene, often by a factor of two. Contaminants are more easily removed before this densification step than after. A demonstration plant chemically decomposes polystyrene to produce monomer (41). Polystyrene may be cracked at $130°C$ over sulfated zirconia to produce benzene (41). Dissolution of polystyrene in solvent, such as mixtures of propyl bromide and isopropyl alcohol, filtration to remove solid contaminants, and volatilization and recovery of the solvent to produce solid polystyrene for reuse has been described (42).

Granulated polystyrene foam has been used as an additive in lightweight cement or as a soil additive to retain moisture and minimize compaction (41). Specially designed cup shredding machines for use with vending machines dispensing drinks in PS cups have been commercialized (43). However, recovery rates for other PS packaging products is significantly less than for easily recognized PS foam consumer product packaging (41).

Polystyrene has a high heating value, 46,000 kJ/kg compared to heating oil, 44,000 kJ/kg (41). Thus, incineration for its energy value is another possible application for recovered polystyrene.

3.5. Other Plastics.   A relatively small amount of PVC goes into packaging applications and appears in municipal solid waste (20). The greatest concern with PVC is as a contaminant in other polymers being recycled, particularly PET. Applications for recycled PVC include as an inner-layer sandwiched between two virgin PVC layers in pipe and sheet for blister packaging and other packaging applications.

Polyurethane is pulverized to increase its bulk density, mixed with 30−80% of a thermoplastic molding material, gelled, and then granulated to give coated urethane foam particles 0.1−0.15 mm in size (44). The particle bulk density is three times that of the polyurethane, while the volume is 15% less. This material may be injection molded or extrusion molded into products (45). Other technologies for recycling polyurethanes have also been reported.

The recycling of engineering thermoplastics such as polyamides, acrylonitrile−butadiene−styrene (ABS), and polytetrafluoroethylene (PTFE) have been discussed (46). Property degradation as a result of use, recovery, and recycling is a concern.

3.6. Commingled Plastic Wastes.   Owing to the property deteriorations that usually occur on polymer mixing (4), commingled plastics are useful and economic only for low value applications in which echanical properties are not demanding. Such applications include park benches and parking barriers. Plastics in municipal solid-waste streams are often contaminated with paper, which is difficult to separate from the plastic materials. If the cellulose fibers have a sufficient length, 0.2−2 mm (47), they can improve the mechanical properties of the plastic. Usually, a reactive compatibilizer is required to improve the

compatibility of the polymer phases and promote bonding of the cellulose to the plastics (48). One example cited is the addition of 30% cellulose fiber to a 70:30 mixture of low-density polyethylene (LDPE) and high impact polystyrene. An addition level of 30% maleic anhydride grafted styrene–ethylene–butylene–styrene block copolymer was used as the compatibilizer. This additive level was too high to be economic. However, the compatibilizer level was not optimized.

The supply of commingled plastics is much greater than the demand (49). Therefore, a critical issue in recycling commingled plastic wastes is the identification and separation of the plastics that are present. Near-infrared (ir) (900–1700 nm) spectroscopy has been proposed to identify polyethylene, PET, PP, PS, and PVC (18). A spectrograph with an InGaAs-array detector has been developed to record spectra from postconsumer packaging materials located on conveyer belts (50). Atomic absorption spectroscopy can be used when one of the polymers has a different atomic compositions than other polymers in a mixture (49). An example is the separation of PVC from polymers not containing chlorine.

The economics of recycling PET are more favorable than recycling HDPE. To increase the recycling of HDPE, the separation of bottles made of these two plastics could be omitted and a mixture processed. Coarse, light-colored powders of the two polymers have been prepared by an experimental solid-state shear extrusion pulverization process (51). The powder has been successfully injection molded without pelletization.

Thermal degradation of mixtures of the common automotive plastics PP, ABS, PVC, and polyurethane can produce low molecular weight chemicals (52). Composition of the blend affected reaction rates. Sequential thermolysis and gasification of commingled plastics found in other waste streams to produce a syngas containing primarily carbon monoxide and hydrogen has been reported (53).

One alternative to identifying and separating different types of plastics is using commingled plastics directly. Since the composition and physical properties of commingled plastics can vary from day to day, applications are limited. One such product is a building material containing Portland cement as the binder, a filler (sand, gravel, or stone), and a plastic with a maximum particle size of 5–10 mm (54). The ratio of binder to aggregate is 1:4–8 while the binder + filler/plastic volume ratio is 3–9:1. Concrete made using this material performs, as well as standard concrete not containing plastic. In Germany, mixed plastics have been blended with pulverized fuel ash and the mixed used to manufacture fencing and posts (55).

Styrene block copolymers have been used as compatibilizers for mixed plastics to permit their processing for applications such as those outlined earlier (48,56).

Laboratory tests indicated that gamma radiation treatment and cross-linking using triallylcyanurate or acetylene produced a flexible recycled plastic from mixtures of polyethylene, polypropylene, general-purpose polystyrene, and high impact grade PS (57).

Another alternative to separating commingled plastics is advanced waste recycling. This is the high temperature–high pressure conversion of plastic wastes to form petrochemical process streams. Research is in progress to deter-

mine the conditions that will favor conversion of commingled plastic wastes to certain types of chemical feedstocks including synthesis gas (hydrogen + carbon monoxide), hydrogen, crude pyrolysis oil (containing benzene, toluene, and xylene), olefins, and oxygenates such as methanol, esters, and methyl formate (58). This technology has also been evaluated for producing fuels: medium Btu gas for boilers, and liquid fuels, such as diesel oil. None of these processes is currently economic.

Thermal cracking of commingled plastics can produce an excellent feed for steam crackers and catalytic crackers. During steam cracking, feed from commingled plastics produced higher yields of ethylene (34% vs. 28%), propylene (17% vs. 15%), and butylene (12% vs. 7%) than did the usual naphtha feed (59). During catalytic cracking, feed generated from plastics provided an 86% yield of naphtha grade product compared to a 62% yield from vacuum oil.

The Conrad recycling process utilizes an auger kiln to apply heat to plastics in the absence of oxygen (60). Feed preparation using the Conrad process requires minimal plastic particle size reduction, washing, and removal of non-plastic contaminants (57). Granulated plastics are introduced into a retort in the absence of oxygen using a rotary air lock. If the plastic particles are in their original form, they are introduced into the retort using a ram feeder. The plastics melt after entering the hot retort. An Auger keeps the molten mass moving. Thermally promoted carbon–carbon bond cleavage occurs. As depolymerization proceeds, volatile products are produced and swept out of the reactor. Interestingly, mixing polymers seems to improve thermal cracking of results. A 1:1 mixture of polypropylene and polyethylene cracked at a lower temperature than did polyethylene alone and provided a narrower mixture of products than either polymer did separately (58).

Results obtained for two mixed plastics are summarized in Table 4.

A balance exists between process temperature, plastics feed rate, and product yields (58). For example, lower temperatures increase wax formation due to incomplete depolymerization. Slower feed rates and increased residence times reduce wax formation and increase the yield of liquids. The data summarized in Table 4 illustrate that the addition of PET to a HDPE:PP:PS mixture changes the performance of the Conrad process. Compared to the reference HDPE:PP:PS mixture, increased amounts of solids are formed. These are 95% terephthalic acid and 5% mono- and bis(hydroxyethyl) esters. At higher temperatures, apparently enough water remains to promote decarboxylation. In contrast, the addition of LDPE or PS to the mixture had little effect on its behavior in the Conrad process.

3.7. Fiber-Reinforced Plastics and Composites. It is usually too expensive to separate fillers and fibers from recovered polymers. Hence, the recycled use of these polymers must tolerate the presence of fillers or fibers (49). Thermoset matrix composites are ground and used as filler for polymers. Remolding is usually by injection or compression molding (59). Fiber-reinforced plastics are recycled primarily from old automobiles and electrical equipment (casings and various plastic parts). Glass fiber-reinforced plastics have been made into sheet-molding compounds and bulk-molding compounds (60). However, the economical recycling of fiber-reinforced plastics remains a challenge. Dynamic mechanical thermal analysis is said to determine heat resistance,

impact resistance, and stiffness of glass-reinforced plastic before and after recycling (61). Thus, it could serve as a tool to determine the suitability of a glass-reinforced plastic for recycling.

3.8. Plastics in Electronics. Plastics constitute $\sim 17\%$ of the weight of electronics, primarily as the housing material (62). While more than 20 types of plastics are used in these products, high impact polystyrene accounts for more than half of the total plastic materials in recovered household electronics, in particular televisions. Engineering plastics, such as ABS and polycarbonate are also used. An increasing number of these products: old televisions, computers (keyboards, monitors, and central processing units), cellular phones, and household appliances, such as microwave ovens, are being discarded increasing the amount of plastics in waste streams. The problem of recycling end-of-life (EOL) electronics is of particular concern in Japan where the number of disused computers in 2005 is estimated at >80,000 while >95,000 television sets were processed for recycling in 2003 (63).

While in its infancy, these plastics are increasingly being sorted and reused in new electronic devices, construction and other applications. Separated engineering plastics have a higher value than other materials recovered from EOL electronics (Table 5).

Efficient collection appears to be the most significant hurdle to economical recycling of plastics from EOL electronics.

3.9. Recent Developments. A recent patent (65) describes the use of transition metal acetates as catalysts in aqueous solution to promote oxidation of polymer backbones to produce monomers or oxidized derivitives of monomers. Polymers processed using this method include PET, PVC, polyolefins, polycarbonates, and blends and copolymers of these materials. Supercritical carbon dioxide has been used to penetrate and plasticize polymers to aid in their conversion to monomers and oligomers (66). Among the polymers that may be processed in this fashion are PET, polycarbonates, Nylon polymers and polyurethane. Low value oils have been used in free-radical promoted pyrolisis and polyurethane to promote depolymerization (67).

4. Economics and Statistics

Costs of various waste disposal methods are summarized in Table 6.

Polymer recycling process costs for various operations are summarized in Table 7.

Total postconsumer plastic bottle recycling, largely PET and HPDE bottles, increased to 1667 million lb (756.13 kg) in 2003 (25) or 21.8% of the bottles produced (Table 8). The favorable economics of PET recycling have been attributed in part to forward integrated PET recyclers consuming their own product to make bottle resin (19).

Despite an increase in the number of pounds of PET recycled (to 1003 million lb (454.95 kg) in 2004), the PET recycling rate in 2004, 21.6%, was less than in 1995 (26). Between 1995 and 2004, the PET recycling rate decreased continuously. At the end of 2004, there were 14 U.S. plants producing clean PET flake from postconsumer bottles with a total capacity of 937 million lb (425.01 kg). Five

of these plants have letters of nonobjection from the FDA allowing them to use their recycled PET in direct contact with foods and beverages (26). In Canada there were three plants with a total capacity of 150 million lb (68.03 kg).

Capacity utilization by firms processing postconsumer PET bottles was ~84.4% in 2004 (26) while that for firms processing HDPE bottles was 68% (25). Bottles for products used outside the kitchen or consumed while traveling typically are not recycled due to lack of consumer awareness and low convenience. The American Plastics Council has concluded that increases in plastics recycling rates are becoming harder to achieve because some consumers are becoming increasingly apathetic about participating in curbside and drop-off recycling programs.

In Japan, 112,485 metric tons of PET were recycled into new products, primarily into clothing, carpets and sheet products, such as egg cartons in 2002 (63).

Some U.S. recycling sorting facilities are selling postconsumer PET and HDPE bottles to other countries, particularly China, for recycling (25). In 2004, 372 million lb (168.73 kg) of PET bottles (38% of the total recovered for recycling) was exported for recycling in other countries (26). In 2003, 100 million lb (45.35 kg) of HDPE bottles (12.1% of the total recovered) were exported for recycling in other countries (25).

With the exception of vehicle battery casings, few of the products in which polypropylene is used can be recovered and recycled in commercial qualities (38).

Recycling of many other plastics remains uneconomical (5). This is reflected in a number of companies closing plastics recycling operations in the mid-1990s (69).

The costs of separating and recycling commingled plastics is ~ 10 times more expensive than recycling easily separated homogeneous products such as PET and HDPE (70). For commingled plastics, gasification comes closest to competing with low cost landfilling (52).

Price swings, particularly in the PET and HDPE markets have contributed to a retrenchment in the U.S. plastics recycling industry in 1995−1997 (71). In 1994 in the United States, recycled PET, HDPE, LDPE, and PS had a 16−46% cost advantage (72). This cost advantage largely disappeared by 1996. Lower chemical feedstock prices made it more difficult for recycled plastics to compete with virgin resins in the absence of legislation mandating plastics recycling. However, increased feedstock costs since 2004 appear to be restoring the cost advantages of recycling plastics and a number of large municipalities including New York City have reinstituted plastics colleciton programs.

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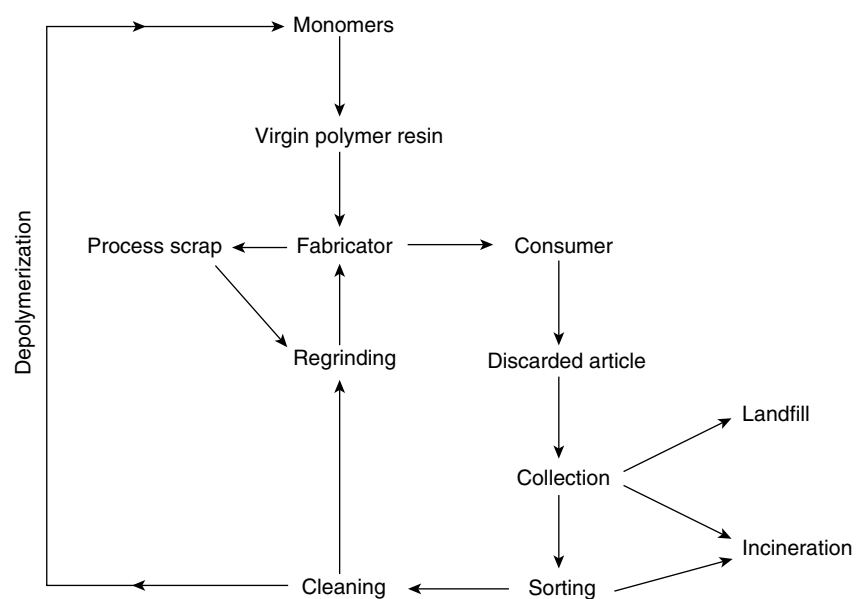
JOHN K. BORCHARDT
Southhaven Communications

Fig. 1.   Process steps in recycling.

Table 1. **Residential Recovery Rate by Package Type**[a]

Package type	% Recovery
beverage bottles	65
liquid detergent bottles	50
other rigid containers	10
packaging film	5
average of all plastics	30

[a]See Ref. 5.

Table 2. **U.S. Recycled PET Bottle End Use, 2004**[a]

End use	%[b]
fiber	54.5
food, beverage containers	14.3
strapping materials	13.2
nonfood containers	7.2
film, sheet	6.6
engineered resin	1.4

[a]See Ref. 26.
[b]Other end uses total ∼2.7%.

Table 3. **U.S. Recycled HDPE Bottle End Use, 2002**[a]

End use	%[b]
nonfood bottles	43
pipe	20
lawn, garden	15
film, sheet	8
lumber	8
pallets, crates, buckets	3
Automotive	2

[a]See Ref. 25.
[b]Other end uses total ~1%.

Table 4. **Gas Chromatographic Analysis of the Results of Cracking Polymer Mixtures Using a Conrad Unit**[a]

Analysis	60:20:20 HDPE:PP:PS	20:48:16:16 PET:HDPE:PP:PS
liquid yield (weight %)	73	55
gas yield (weight %)	27	38
solids yield (weight %)		7
Partial Oil Analysis (weight %)		
Aliphatics, carbon number		
≤ 10	9.4	21.3
11–15	16.6	17.6
16–20	9.9	9.9
21–25	3.5	4.7
26–30	1.7	2.2
31–40+	1.5	2.2
Aromatics		
benzene	2.3	1.4
toluene	11.0	3.8
ethylbenzene	5.7	2.6
xylenes		1.1
other alkyl benzenes		8.4
styrene	17.0	8.2
naphthalenes		3.7
unidentified		12.3

[a]See Ref. 58.
[b]Oven temperature = 649°C (1200°F). Auger temperature = 527°C (980°F) for the HDPE:PP:PS mixture, 479°C (895°F) for the PET:HDPE:PP:PS mixture.

Table 5. **Average Revenue from Materials Recovered from EOL Electronics (64)**

Material	U.S. $/lb
separated engineering plastics	$0.29
mixed plastics	$0.02
glass	$0.05
mixed metal	$0.10
ferrous metal	$0.0

Table 6. **Estimated U.S. Processing Costs of Waste Disposal Method**[a]

Method	Cost estimate
landfilling	$30/ton[b]
incineration for energy recovery	$100/ton
recycling of PET and HDPE bottles	$100−150/ton

[a]See Ref. 68.
[b]Cost varies with the location of the landfill.

Table 7. **Approximate Polymer Recycling Costs**[a]

Process step	Costs	
	$/lb	% of total cost, %
collection	0.10	27
sorting	0.12	32
subtotal cost	0.22	59
grinding/cleaning	0.15	41
Total	*0.37*	*100%*

[a]See Ref. 5.

Table 8. **Postconsumer Plastic Bottles Recycled in the United States in 2003**[a]

Plastic bottle type	Plastic recycled, millions of tons	Recycling rate
PET soft drink	531.8	30.2
PET custom	306.1	12.1
total PET bottles	837.9	19.5
HDPE (unpigmented)	420.4	27.3
HDPE (pigmented)	402.8	22.6
total HDPE bottles	823.2	24.8
PVC	0.2	0.2
LDPE/LLDPE	0.3	0.5
PP	5.7	3.4
PS	not determined	not determined
total bottles	*1667.4*	*21.0*

[a]See Ref. 25.