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Review

A ten year review of plastics recycling

S. Garry Howell

Risk Reduction Engineering Laboratory, U.S. Environmental Protection Agency, 26 Martin Luther King Drive, Cincinnati, Ohio 45268 (USA)

Abstract

A short history of the practice of plastics recycling as practiced in the United States and Europe for the past ten years indicates that much progress has been made in educating the public sector about the environmental damage done by the indiscriminating disposal of plastic items and potential opportunities to recycle them. Recent legislation has made the collection of some discarded plastic articles more efficient, and has provided economic incentives to recover and reuse waste plastics. A discussion of the methods of collecting, separating, cleaning, and fabrication of plastic wastes into useful items leads to the conclusion that much work is yet to be done to develop more efficient ways to perform these tasks. In addition, improvements in blending the disparate plastic materials in wastes could lead to the production of better products made from recycled materials. The public must be made aware of the fact that consumer products made of recycled plastics are often as good as those made of virgin material. And that the resulting environmental benefits as well as energy savings are for the common good.

Introduction

This review will discuss the following aspects of plastics recycling:

- Types of plastics (thermoplastic and thermosetting);
- Resin manufacture (polyethylene, polypropylene, poly(vinylchloride), poly(ethyleneterephthalate), polystyrene;
- Sources of plastic waste;
- Collection/recovery;
- Separation technologies;
- Product finishing; and
- Applications for recycled plastics.

Considering the enormous quantities of plastic material produced in the United States, as shown in Fig. 1, it is little wonder that discarded plastics have become a significant portion of municipal waste streams. Figure 2 shows the composition of municipal waste in the United States; the quantities given are percent by weight, for while plastics constitute only 6.5% (the General Accounting Office estimates 7.2%) by weight, the inherent low densities of the resins and low bulk densities of plastic products such as bottles are estimated

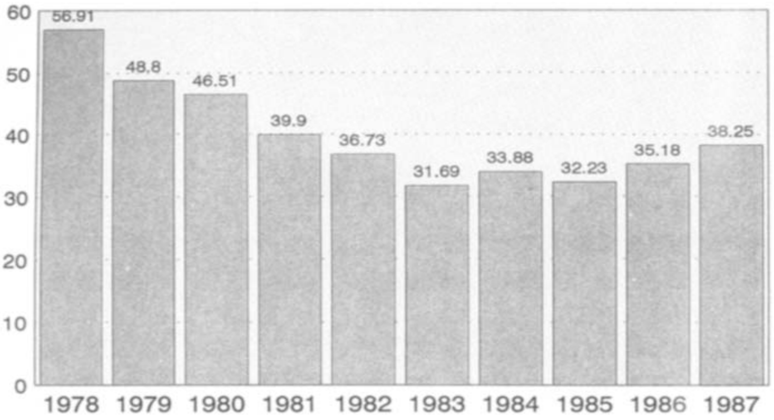


Fig. 1. U.S. plastics production in billions of pounds (source: Modern Plastics).

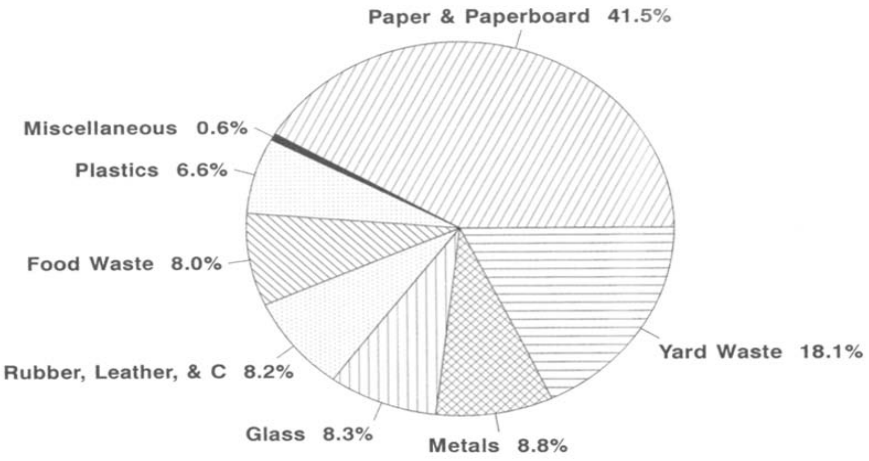


Fig. 2. Composition of municipal waste by weight percentage (source: U.S. EPA).

to compose 12 to 20% of the volume of landfilled waste [1]. A large part of the waste is discarded packaging of one type or another. The low price of plastic shrink wrap, blister packs, bottles, *ad infinitum*, has resulted in a "throwaway mentality"; we discard items which appear to have an almost infinite life if landfilled, and sometimes present a hazard to marine life. Incineration is an option for most plastics, (if the offgases are scrubbed) which, with the exception of some of the halocarbons, have a high fuel value; but incineration recovers only a part of the energy content of the materials, since the energy consumed in resin manufacture is wasted. Modern plastic materials are almost universally derived from petroleum and natural gas. Recovering and recycling plastics means that in addition to the hydrocarbon content saved, a large part of the energy expended in production is saved also.

A common perception is that plastics are a relatively recent invention. In reality, the first synthetic plastic, cellulose nitrate (celluloid), was developed over 120 years ago (1869), and phenol-formaldehydes (Bakelite) over 80 years ago, in 1909. The volumes of these and subsequently developed plastic materials such cellulose acetate and poly(vinyl chloride) (PVC) were relatively small, and since they were made into semidurable items such as electrical equipment or insulation, motion picture film, billiard balls, etc.; they were not considered a nuisance when discarded. The "Plastics Age" might be considered as beginning in the late 1940's when the high volume production of low density polyethylene (LDPE) began. The rapid growth of the industry is illustrated in Fig. 1, which includes all plastics, thermosetting (once formed or molded, they cannot be reshaped by heat) and thermoplastics, which can, within reason, be recycled by remelting, and reshaped into different objects. Production volumes of the more common thermoplastics is shown in Fig. 3, along with the amounts of the four major types recycled in 1988.

This review will be primarily concerned with thermoplastics, particularly those most often fabricated into disposable items which have a very short usable life and are discarded shortly after purchase. The sources of wastes, means of recovery from waste streams, technologies for converting the waste material, and uses and markets for the recycled plastics will be discussed.

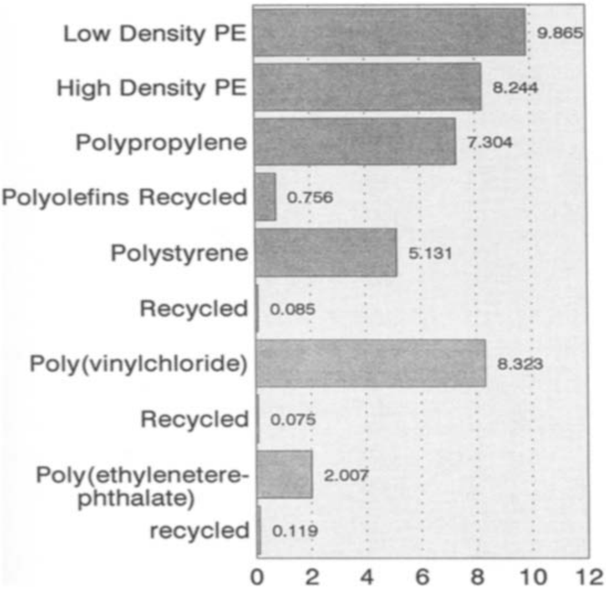


Fig. 3. Production of more common plastics vs. volume recycled in 1988 (source: Modern Plastics).

Types of thermoplastics

Thermoplastics are generally divided into two groups, the first, often called *commodity plastics*, would include the polyethylenes (PE), polypropylene (PP), poly(vinyl chloride) (PVC), polystyrene (PS), their copolymers, and poly(ethylene terephthalate) which is variously known as PET, PETE, or polyester. These products are low priced and produced in huge quantities; prices range from $0.50 to $0.70 per pound ($1.05–$1.50/kg). The combination of low price and physical properties explains their widespread use in disposable packaging, in one time use agricultural and architectural coverings, and in some engineering applications where their physical properties are acceptable.

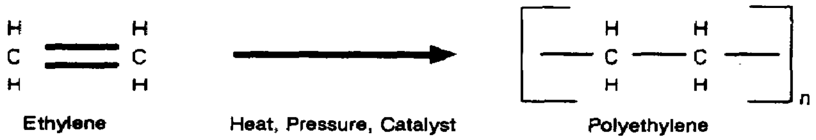
The second group is called *engineering plastics*; characterized by higher strength, resistance to heat, and impact resistance, they have become widely used to replace metals in many automotive, appliance, aerospace, and industrial products. Prices of these range from $0.85 to more than $10.00 per pound ($1.80–$21.00/kg). Their applications to more durable goods and lower production volumes result in less of a pollution problem and will not be discussed at length in this review. An exception is PET, which has excellent clarity, mechanical properties, and heat resistance. It could be said to straddle the line between commodity and engineering plastics, as it is the plastic used in the ubiquitous clear plastic soft drink bottles, some hot filled food products, and in many mechanical applications as well. It can also be made into fiber (Dacron, Kodel, etc.) and films (Mylar, Cronar).

Resin manufacture

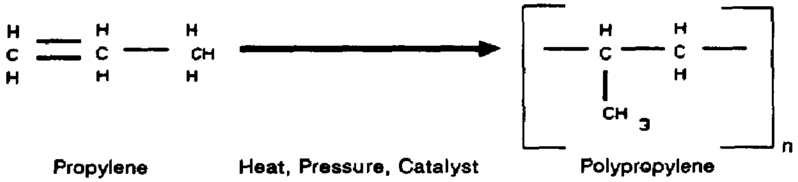
The great majority of modern synthetic plastics are derived from petroleum or natural gas. Polyethylenes and polypropylene belong to a class called polyolefins, since their starting materials (monomers) are olefins made by thermally cracking the larger hydrocarbon molecules in natural gas liquids or petroleum fractions. Poly(vinyl chloride) (PVC) might also be described as an olefinic material, since it differs from polyethylene only by having every second hydrogen on the chain replaced by an atom of chlorine. Generalized structures of the polyolefins and PVC are shown below.

The polyethylenes can be thermally cracked or depolymerized back to lower molecular weight polymers, or even, under severe conditions, to oily materials or to carbon and hydrogen. This process has been proposed as a method of recycling, but will not be discussed here. PVC can also be thermally cracked, with the evolution of hydrogen chloride gas (HCl), which is poisonous and corrosive. In common with other organic polymers, they can also be depolymerized or otherwise affected by the ultraviolet portion of sunlight and oxygen in the air. This is a slow process, and is made even slower by special inhibitors (antioxidants and ultraviolet stabilizers) added before fabrication into the final product. Without these inhibitors many uses for plastics (such as telephone cable jacketing exposed to sunlight and heat) would be of limited usefulness.

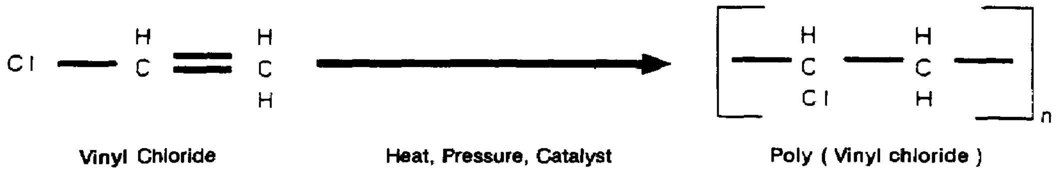
POLYETHYLENE



POLYPROPYLENE



POLY (VINYL CHORIDE)



Low density polyethylene (LDPE) is produced by contacting ethylene monomer and an organic peroxide catalyst (or more properly, initiator) at pressures of 15,000 to 50,000 psi and (1030–3400 bar) temperatures of 300 to 575 °F (150–300 °C).

High density polyethylene is catalyzed by heterogeneous catalysts which are organometals such as triethyl aluminum combined with titanium tetrachloride at 180–250 °F (80–120 °C) and 150–200 psi (10–14 bar).

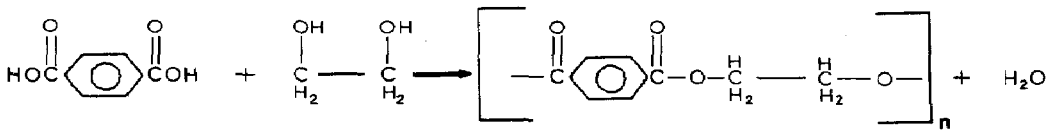
Polypropylene is polymerized with Ziegler–Natta type catalysts similar to those used for high density polyethylene but at lower temperatures and pressures.

Poly(vinyl chloride) polymerizations are carried out with peroxides, persulfates, or redox catalysts at relatively low temperatures and pressures. The type of catalyst and method of polymerization vary according to the intended end use for the product.

Poly(ethylene terephthalate)

Poly(ethylene terephthalate) (PET) is also a petroleum derived product, a copolymer of terephthalic acid, (which is made by oxidizing *p*-xylene), and ethylene glycol, or other glycols such as diethylene glycol or cyclohexane diethanol. A simplified reaction sequence showing the direct esterification reaction (there are actually three different processes, all arriving at the same end product) is shown here:

POLY (ETHYLENE TEREPHTHALATE)



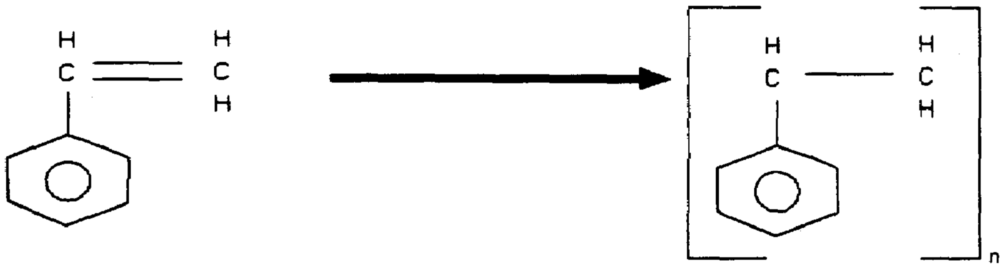
Terephthalic acid Ethylene glycol Poly (Ethylene terephthalate)

The fibers Dacron, Kodel, etc. made from PET are chemically identical to the resin made into bottles. Some attempts to incorporate them into the recycling chain have been made in Europe, but little has been done in the United States.

Polystyrene

General purpose polystyrene is a clear, somewhat brittle resin. Most disposable polystyrene items are of resins made by the following reaction sequence:

POLYSTYRENE



Styrene Heat, Pressure, Catalyst Polystyrene

The catalyst used in the process is a peroxide such as benzoyl peroxide.

The familiar foamed beverage cups, insulated containers, and home insulation are chemically identical to the clear drinking cups used on airlines. The foamed materials are made by incorporating a hydrocarbon such as n-pentane during the polymerization process.

Sources of plastics waste

Domestic

As indicated in Fig. 2, in 1984 the percentage of plastics in municipal trash was about 7.2% by weight, or about 9 million tons — almost double that present in 1976. By volume, the plastics waste amounts to between 12 and 20%, according to reliable sources [1]. No assay of the volumes of individual polymers

(PET, PE, PVC, etc.) appears to be entirely accurate, but it seems fair to assume that overall, the ratios of the plastics made into disposable items such as bottles, packaging films and containers, etc. would approximate the ratios of resins sold for these purposes. In 1988, over 16 billion pounds of plastics were used in packaging. This excludes the 935 million pounds of poly(ethylene terephthalate) sold for soft drink and speciality bottles [2].

Agricultural

The main uses of plastics in agriculture are in mulch films, feed bags, fertilizer bags, and in temporary tarpaulin-like uses such as covers for hay, silage, etc. A growing use is temporary covering for fields that are being fumigated. This film and the various bags would appear to be prime candidates for recycling, as they are reasonably clean and easily accumulated. Mulch and covering film are usually discarded after they have begun to deteriorate, generally as the result of being exposed to sunlight. Reprocessed resins produced with a high proportion of these films will have poor physical properties.

Industrial

Industrial and construction use of disposable plastics is difficult to quantify, as some plastic film is used for temporary enclosures, then left in place as a vapor barrier, while some is removed and discarded. Polystyrene foam is likewise widely used as insulation, with an almost indefinite lifetime, but many industrial products are shipped with foamed "popcorn" or molded packing, almost all of which is discarded. The low densities of these foams (1–2 lbs/ft^3 or about 1 kg/m^3 vs. soil at 70 times as dense) make them especially undesirable in landfills, while at the same time making hauling costs to recyclers prohibitively high. Much machinery, lumber, plywood, and bagged goods such as cement and mortar are shipped with polyethylene film covers. The majority of this could be easily recycled. Shrink wrapped cases are replacing corrugated paper cartons in many grocery items. Groceries should be prime candidates to initiate recycling programs, since they could serve as collection centers as well as being generators themselves.

"Fast food" containers

Foamed polystyrene is widely used in food packaging (meat and produce trays) at the retail grocery level, but the largest part of this 725 million lb/y market is in "fast food" containers. The volume of waste generated from this 725 million pounds is tremendous, for the density of the foamed material is only 2 to 3 pounds per cubic foot (~ 1.5 kg/m^3), which would indicate an uncompressed bulk of 13 to 20 million cubic yards (about 20×10^6 m^3) occupying space in our landfills!

A consortium of chemical and oil companies in the U.S. has announced the formation of National Polystyrene Recycling Company to build five regional plants to recycle polystyrene [3]. The five plants, said to cost $14 million, plan to collect the used material from restaurants, hospitals, schools, and other big users in 30 states. The consortium is only planning to recycle only 25% of the scrap available; there is obviously room for others to enter the market, though finding large, easy to collect volumes of scrap may be difficult.

Military

No reliable estimate of the amounts of recyclable plastics used by domestic military installations is presently available. Contact is now being made with the U.S. Department of Defense to quantify their usage of plastics. Because of the concentration of these facilities, recycling should be easier than for domestic waste.

Automobile wrecking

The amount of plastics used in automobile manufacturing has been growing at approximately a 9% rate over the past ten years. Even in 1979 (the approximate date of production of cars now being scrapped) the amount of plastics used in automobiles was 787,000 tons [4]. It would thus appear that a large part of the thermoplastic portion could be recovered. The recent introduction of thermosetting polyester skins on some large volume vans, has generated more interest in recovering these and other thermosetting materials. One large automobile manufacturer has concentrated on pyrolysis of glass reinforced panels, which results in the production of a mixture of combustible gases, oily material, calcium carbonate, glass fibers, and carbon char. The gases are burned in the pyrolysis furnace and supply all the heat needed for the process, leaving the oil for other fuel uses. An investigation of plastics recycling from automobile recyclers was done in 1975 by the U.S. Bureau of Mines [5], but only a crude sink/float technique was used to separate the plastics fraction, and little interest was generated since good homogeneous materials could not be produced. Interest is growing in identifying the various plastics components in automobiles with a molded or stamped-in label so that salvagers could more easily segregate the types as they strip the vehicle prior to crushing and grinding. An evaluation of an innovative process to separate the various kinds of resins from finely ground waste, such as from automobile grindings, is planned as a joint project between the U.S. Environmental Protection Agency (EPA) and a large plastic producer.

Wire and cable

A large source of recyclable plastic should be the electrical and telephone cables from demolished buildings. Until recently, these were burned to recover the copper or aluminum; now that strict emissions controls are required on these incinerators, physical separation of the plastic insulation would appear to be a viable option. One site where wire and cable was processed to recover the metal conductors is reputed to have over 100,000 tons of mixed plastic "fluff" in a pile covering over 7 acres (2.8 ha). The amount of plastic recoverable from wire and cable is not known, but 433 million lbs of PVC, 386 million lbs of LDPE, and 125 million lbs of HDPE were sold for insulation in 1988.

Collection/recovery

Segregation and collection of waste plastics from agricultural operations, military installations and naval vessels, and industrial, and construction sites should not be difficult if it were economically attractive to the generators. These operations typically generate relatively large quantities of discarded plastics in small areas, so segregation would appear to be entirely feasible.

Domestic waste

A successful plastics recycling operation must have a dependable source of waste which is not overly contaminated with wet garbage, which makes sorting and washing difficult. The recycling plant should not be too far from the collection points, since the cost of hauling the bulky materials such as empty bottles or polystyrene foam would greatly increase operating costs. An efficient collection system is therefore mandatory, and should operate over a large enough area (preferably urban) to supply an adequate amount of feedstock. Thus the collection of reprocessible plastics from urban waste has proven to be the most difficult and costly aspect of polymer recycling.

In the United States, early attempts to hand sort municipal garbage in bulk by spreading it over a moving conveyer belt proved to be unsuccessful, mainly due to the difficulty of finding employees willing to perform the sorting for low wages. The present trend is for states and municipalities to enact legislation requiring homeowners, and in some instances businesses, to presort trash. Under this curbside collection system, separate containers are furnished for wet garbage, newspapers, glass, metals, and plastics. Several states, Michigan among them, have enacted "bottle laws" which require purchasers to pay a deposit on all beverage containers, whether or not they were meant to be returnable. This has resulted in greatly increased recycling of PET bottles, but other types of containers such as PE milk and detergent containers, bags, film, etc. have been relatively unaffected although these items constitute about 80% of all plastics trash. The City of Cincinnati, OH, recently started a voluntary recycling system, and has found that 65% of households are participating; they had only predicted 35%. It is apparent that the public is aware of the need to recycle. In Cincinnati, the only plastics that the recycler, BFI, will take are PET bottles, which are easily identifiable, being clear, usually with an opaque base cemented to them, and polyethylene milk bottles which are mostly translucent white. In mixed wastes, these would be worth the extra effort to separate, as they can be easily hand sorted from a conveyer belt. In Europe, PVC bottles are widely used for wine and edible oils, and some attempts have been made to separate them for recycling. The PVC bottles are usually clear, and differentiating them from PET might be difficult for an untrained person. The Center for Plastics Recycling Research at Rutgers University Piscataway, NJ has been using X-ray fluorescence for identifying chlorine containing polymers.

As mentioned previously, a special case which is well worth mentioning is that of the foamed polystyrene fast food trays and cups which have become a litter problem, as well as occupying a disproportionate amount of landfill volume. Resin producers have formed at least two joint ventures to recycle these discards into usable products [6].

In contrast to American practice, the separation and collection of recyclables in Europe is much more efficient and has a long history. *Kunststoffe* (German for plastics), a technical magazine which covers the production, testing, and fabrication of plastics, devoted a large part of its May, 1978 issue to plastics recycling [7]. Since *Kunststoffe* is aimed primarily at the production and fabrication of plastics, the means used to collect and separate plastics are not covered in detail. The articles covered in this issue discussed other aspects which will be covered later in this review.

Separation technologies

Municipal waste

Municipal waste from which the "wet garbage" has been separated is the feed to several recycling operations in European countries. A flow chart of a Dutch process which has been operating for a year in 1978, is shown in Fig. 4 [8]. The TNO system operates at 15–20 tons (33,000–44,000 lbs) per hour, and is designed to recover metals, plastics, and papers from a mixed waste stream using a number of different operations. Figure 5 is a Sankey diagram of the TNO process, indicating the percent recovery of the various input materials. It is apparent from the flow chart that resorting to mechanical means to separate the various fractions is very difficult; one can count fourteen major pieces of capital equipment, exclusive of the conveyers, etc. required to carry material from one operation to the next. The final product is merely called "bales of plastic", apparently a mixture of all the overhead from the zigzag air classifier.

A process developed by SINTEF in Norway [9] is shown in Fig. 6. Note the similarities to the TNO process as far as the types of equipment employed in the first stages. Both preshred or grind the refuse, use trommels to screen it, then zigzag air classifiers to separate the light from the heavy fractions. The SINTEF process takes the overhead from the air classifier and passes it to a simple wash tank holding 250 liters (66 gal) of water where if is washed and separated into sink/float fractions. In reality, this separation is relatively easy;

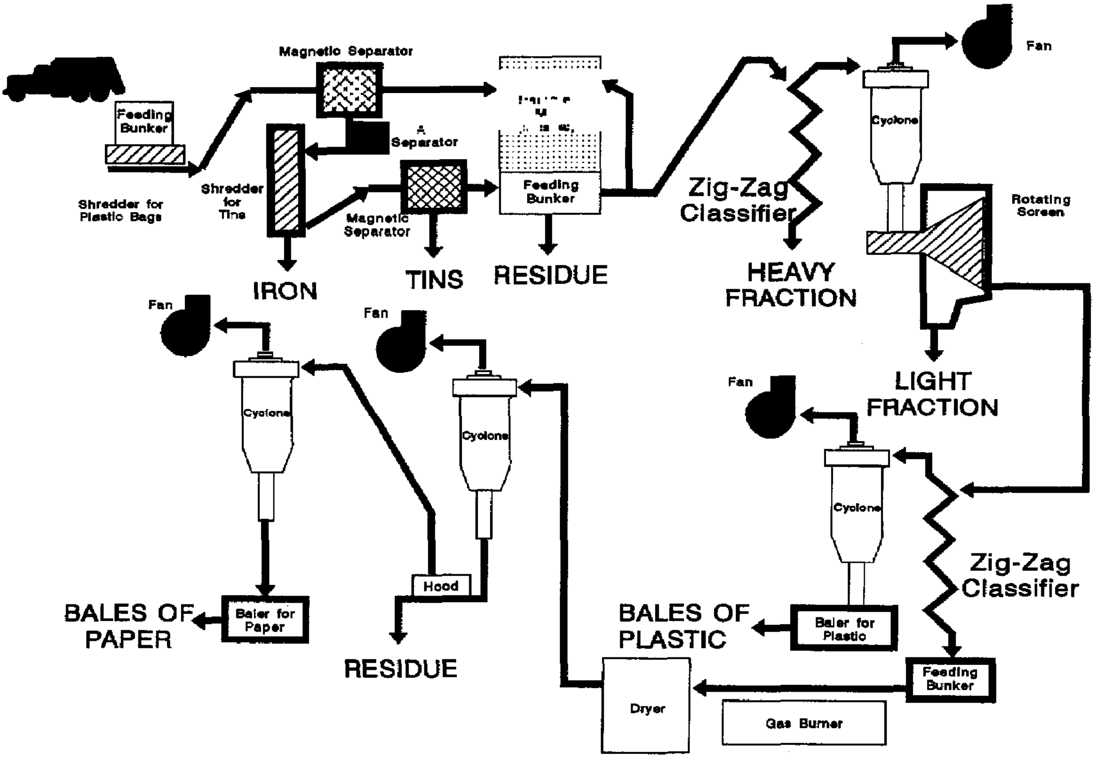


Fig. 4. The TNO/ESMIL waste sorting process (source: NATO/CCMS report 123 [8]).

after the ground particles of plastic are freed of dirt, oil, grease and adhering paper, the polyolefins (density <1 ton/m^3) will float, while the PVC, other plastics, and wet paper, etc. whose densities are greater than that of water, will sink. While the polyolefins all have a density ratio less than one (relative to water), and will be separated as a mixture of HDPE, LDPE and PP, using the mixture to make a product even as prosaic as a garbage bag is difficult. This problem will be covered in a later section.

Even if plastic waste has been presorted at the curb, some final classification is usually done to segregate the more valuable plastics (HDPE, PET, and PVC) from the main stream. One such system is described in a paper recently presented at Recyclingplas IV [10]. The AKW plastics recycling plant which has been operational in Blumenrod, West Germany since July 1988, is said to have its entire output sold. The Blumenrod plant, in the Coburg district, collects waste from a population center of about 280,000 people. Three collection systems are employed in the district. One, (Fig. 7-1) has a number of larger receptacles located in heavily used areas such as near parks, city centers, etc. The receptacles are marked for glass and for paper, with the non-recyclable material segregated. Further separation must be done in a "Material Recovery

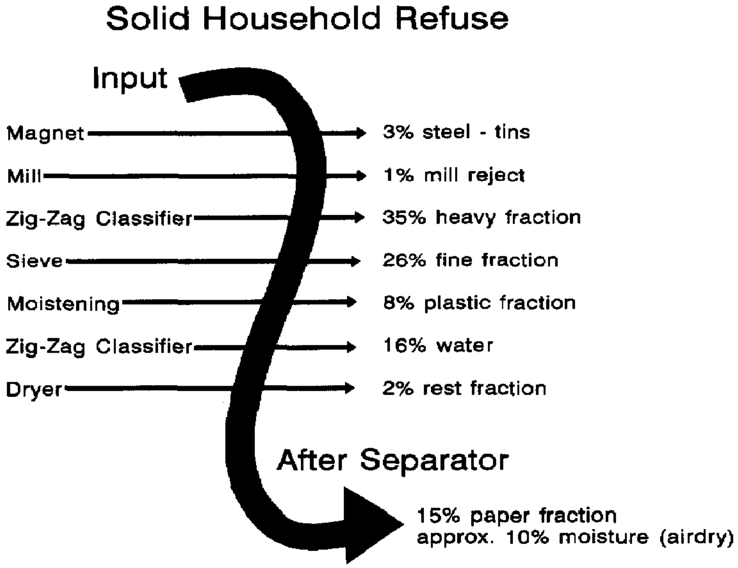


Fig. 5. Sankey diagram of TNO/ESMIL waste sorting process of Fig. 4 based on weight percentages (source: NATO/CCMS report 123 [8]).

Facility" (MRF). The amount of material collected from these points, while appreciable, is not nearly enough to justify the construction of a recycling facility, so a second system of curbside collection is also practiced (Fig. 7-2). Here the recyclables are all placed in a single bin which is taken to the MRF. This system, which is presently used in several U.S. cities and proposed for others, requires the householder to separate the waste paper, metal, and plastic into a "green bin", which greatly facilitates the sorting at the recovery facility. This system does not require the householder to make the decision as to what constitutes the most desirable recyclables, but does greatly decrease the amount of final sorting required. The third, and preferred system, requires some education of the householder, as a three bin system is in place, is shown at the bottom of Fig. 7. In all three cases a final hand sorting is performed at the recycling plant.

Diagrams of some of the early recycling operations indicate that little or no presorting was done. Even if the sink/float separation mentioned in the previous paragraph were used on a granular waste plastic stream containing say, polyethylenes, polypropylene, foamed polystyrene, solid polystyrene, PVC, and PET, the polyethylenes and polypropylene (polyolefins) plus a large portion of the foamed polystyrene would float. Attempts to fabricate useful items from this mixture would probably be futile, since the polyolefins and polystyrene are incompatible. The bottoms would have a mixture of all the other plastics plus some dirt and trash; attempts to fabricate useable products from them would also yield articles of both poor strength and appearance.

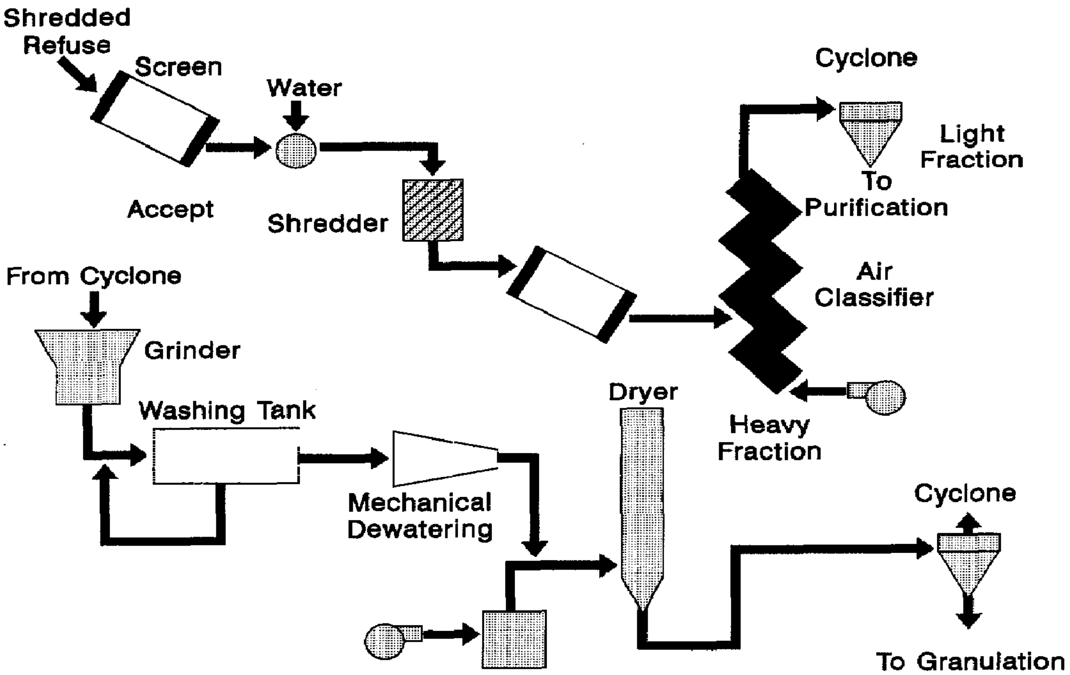


Fig. 6. Process for mechanically separating plastics from domestic waste (SINTEF process, source: NATO/CCMS report 123 [8]).

It is apparent that an efficient recovery operation must segregate the various types of plastics either by hand sorting before grinding, or by some mechanical means. Figure 8 is a pictorial presentation of the AKW sorting plant where mixed waste is hand sorted on moving conveyers before grinding. Although some attempt has apparently been made to presort at the collection points, metals, cardboard, paper, wood, and plastics are hand sorted again. In this illustration, only two classes of plastics are defined, rigid and film, although the text of Ref. [10] uses the terms plastic film and plastic bottle material. Since $>99\%$ of plastic films are polyolefin, no problem would likely result from compounding them into items for resale if an intensive mixer were used. Figure 8 does not indicate it, but the plastic bottles should be further separated into three or possibly four groups, LDPE, HDPE, PET, and PVC, since not only are the three major types incompatible, but they represent products of higher economic value if they are recovered in a relatively pure form.

Mechanical separation/classification

Zig-zag or cyclone air separators used in the earlier European processes are not very efficient for classifying particles of low density with high surface to volume ratios such as granulated plastics. This, coupled with the small density

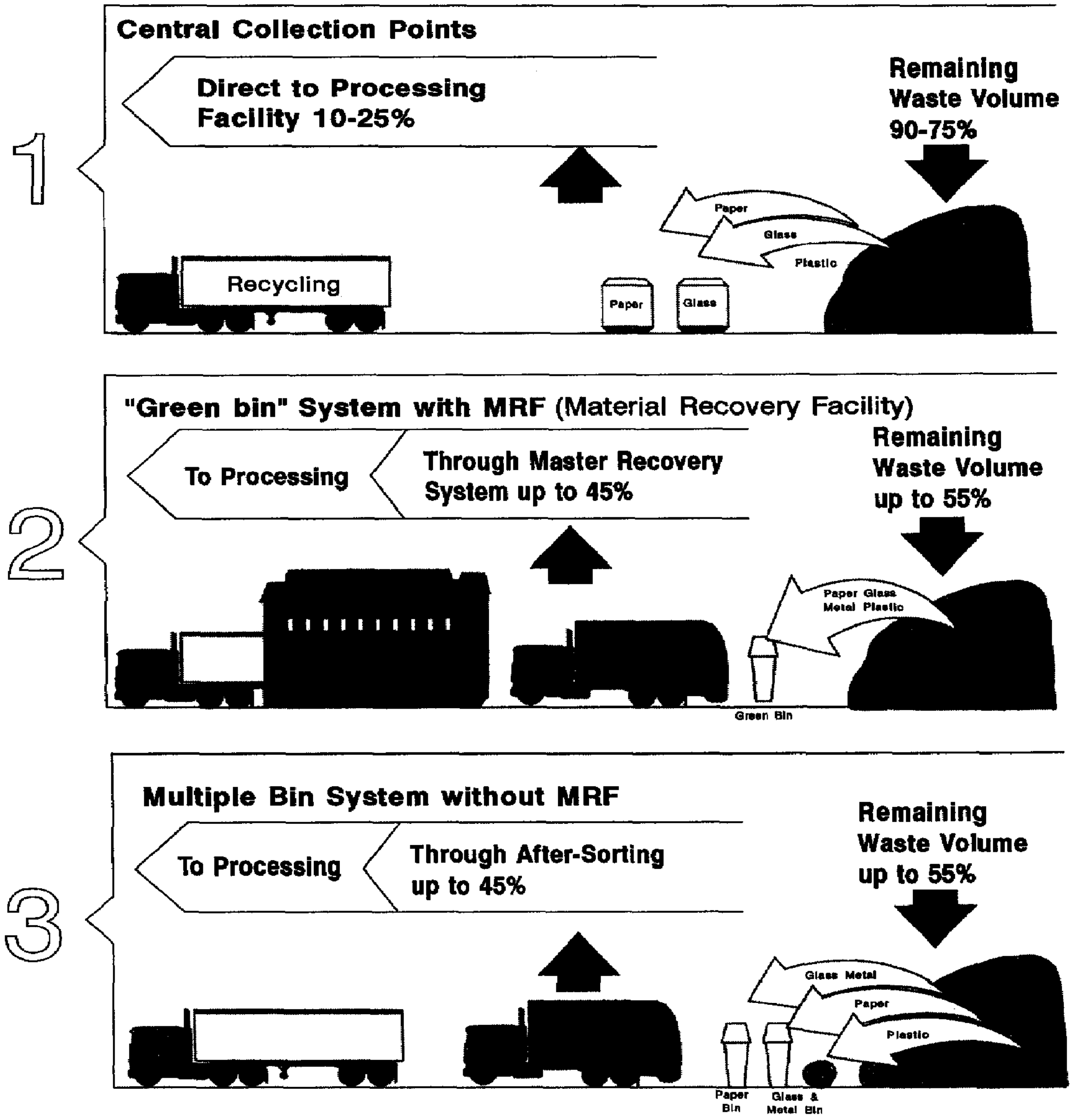


Fig. 7. The AKW post-consumer waste collection systems (consumer presorted) (source: AKW Apparate und Verfahren GmbH [18]).

differences between the several types of plastics (approximately 0.9 to 1.5 g/ml) yield and overhead product that is a mixture of the feed material. The AKW process uses hydroclones, which are cyclones operating with liquids as the conveying media, as shown in Fig. 9. The hydroclones complete the washing, and separate the solids into a heavy fraction which in their operation is primarily PVC and PS (polystyrene), and a light fraction composed of the

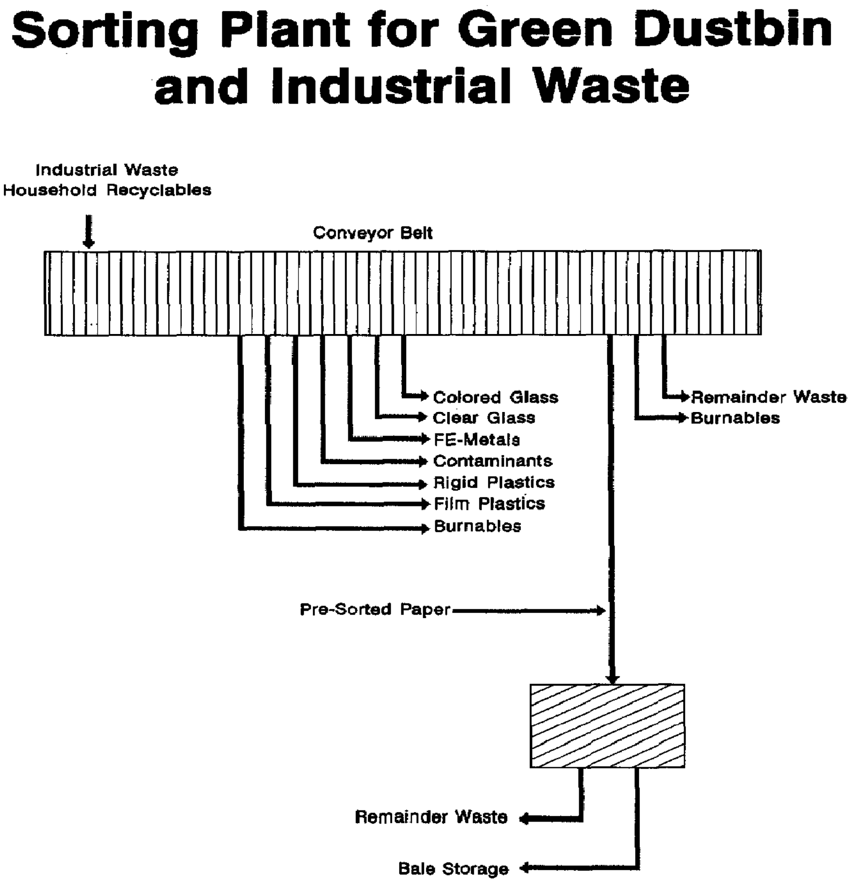


Fig. 8. Sorting plant for green dustbin and industrial waste (source: AKW Apparate und Verfahren GmbH [18]).

polyolefins (low and high density PE and PP). These fractions are then dewatered in a centrifuge and dried, both operations being carried out in conventional commercially available equipment. An overall view of the AKW MRF is shown in Fig. 8.

After separation or sorting, the plastic fractions are finely ground or shredded (in the earlier TNO and SINTEF processes the total stream was ground then separated in an air classifier) this would appear to be a relatively straightforward operation, but in practice can be very difficult. Most plastics are tough, and tend to tear rather than break cleanly. Also, when grinding a waste stream, there are pieces varying in size from one inch (25.4 mm) to pieces several yards or meters long; thicknesses may be as little as 0.001 in. (0.0254 mm) or up to 0.5 in. (12.7 mm). This variability required grinding equipment with extremely close tolerances, and the presence of dirt, grit, or other contaminants causes these to change quickly. Grinding also results in heat buildup which can change

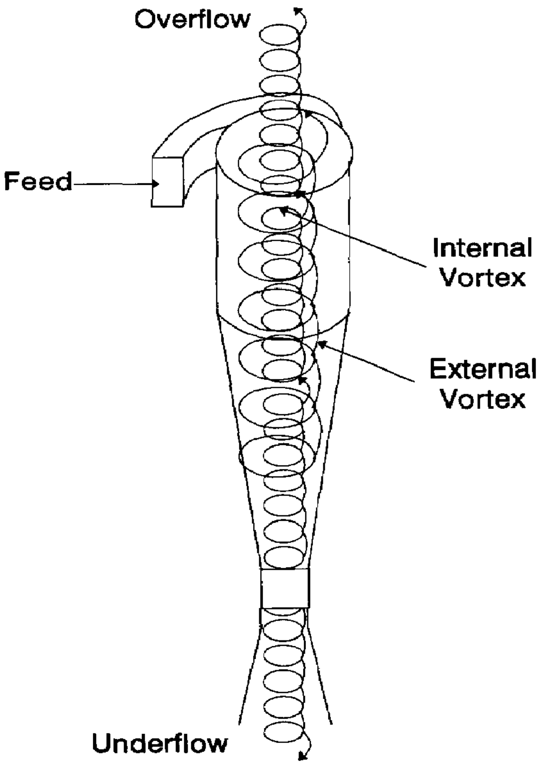


Fig. 9. Schematic of a hydrocyclone (source: AKW Apparate und Verfahren GmbH [18].).

knife clearances, and make the plastic more resilient and harder to cut cleanly. Some grinders operate with a gas stream flowing through the grinding chamber (some specialized operations use liquid nitrogen) which serves the dual purpose of cooling and conveying the material. The AKW system grinds the waste under water, which cools more efficiently than air and aids in washing the plastic particles.

PET Bottles

Of particular interest to most American recyclers are PET bottles, as they are easily identifiable, being clear or lightly tinted, usually with an opaque base cemented to them. The most valuable recyclable plastic in municipal waste is the ubiquitous PET soft drink bottle. In 1979, 1.5 billion of these containers were produced, consuming about 150 million lbs of resin [11]. Now PET is used in many other types of containers, from salad oil to peanut butter; the 1991 usage was 945 million lbs. These bottles are easily identified in waste (and often as roadside litter), and the recycled resin has a high resale value. These facts have resulted in PET becoming the most profitable of plastics recycling efforts, aided by mandatory recycling laws such as the one in Michigan and eight other states. Another incentive is offered by machines which return cash for each bottle inserted; the machines grind the bottles for periodic collection by the recycler.

Most PET bottles have two piece bodies, the clear or slightly tinted bottle proper, and a base molded of high density polyethylene. The caps and seal rings are sometimes aluminum, but more often HDPE; both types usually have an ethylene–vinyl acetate gasket or liner. Earlier bottles had a glued on paper label, which are now being superseded by shrunk on polyethylene film labels. Several recyclers have been in operation since 1980. Most of them grind the bottles, air separate the paper and fines, then use a sink/float process in water to separate the PE base from the PET and aluminum. The Center for Plastics Recycling Research (CPRR), has a pilot plant in Piscataway, NJ which uses an electrostatic separator to remove aluminum after the above separation steps [12]. At a nominal cost CPRR is offering the process for license.

HDPE/PVC Bottles

Milk bottles of HDPE are mostly translucent white; other polyethylene bottles are often brightly colored, but a sorter with little training can differentiate between HDPE and LDPE by the feel (LDPE is noticeably softer than HDPE). Both of these are worth the extra effort to separate, as they can be easily hand sorted from a conveyer belt. In Europe, PVC bottles are widely used for wine and edible oils, and some attempts have been made to separate them for recycling. The PVC bottles are usually clear, and differentiating them from PET might be difficult. The Center for Plastics Recycling Research has developed an X-ray fluorescence detector which may be used to identify PVC items.

Product finishing

Although some plastics fabricators have equipment capable of extruding or molding articles from the fluffy granulates, the majority are used to handling pelletized resins. It is therefore preferable to pass the dried granulate to an extruder to melt blend or homogenize and melt filter the mixed plastics and to form small pellets which are much more easily fed to the final fabrication step. Plastics extruders are deceptively simple in appearance and operation, consisting of a heated cylinder enclosing a long auger like screw. The screw is specially configured for each type of plastic, and sometimes has special mixing flights, interruptions for the removal of volatiles from the plastic melt, etc. The design of extruders and their ancillary equipment is a complex mixture of art and science, and they must be chosen with great care.

Extruders used to blend and pelletize the granulate are usually fitted with a "crammer feeder", which is an auger to force the fluffy granulate into the feed section of the extruder proper. As the mixed plastic particles are forced through the heated cylinder, they are heated both by conducted heat from the cylinder, and by friction as they are compressed by decreasing the depth of the screw flights. The frictional heat is of such magnitude that most extruders only use external heat for startup; while running they must be cooled by air or water on the external barrel surface, and water into the center of the screw. Feedstocks such as the granulated mixed plastics wastes often have some water or other volatiles in them despite the predrying step, and may require devolatilization in the extruder. This is accomplished by decompressing the melt near the middle of the barrel length, where a vacuum is applied. The melt is then further homogenized, passed through a fine screen, and exits the extruder through a multi holed die, where it is cooled, solidified, and chopped into pellets. Alternatively the melt is extruded as a sheet about 1/8″ (3 mm) thick, and passed through a "stair step" dicer, which cuts the sheet into uniform cubes.

Much emphasis has been placed on homogenizing the molten plastic at this stage of the operation. Non-crystalline polymers of similar chemical structures can often be easily melt blended and molded or extruded into useful products of reasonably high quality. PET is an excellent example; it is routinely recycled into molded products, "Fiberfill", geotextiles, or carpet fibers. Mixtures of crystalline polymers such as the polyolefins are much more difficult to homogenize, since each of the three components has a different melting point (low density polyethylene 110°C, high density 120°C, and polypropylene 140°C). When such a mixture is melted by merely raising the temperature without intensive mixing, the crystallites or spherulites of each species are not broken up, with the result that a thin film or fiber will have small particles (gels) of other polyolefins, or dissimilar polymers such as PVC, oxidized materials, etc. visible to the naked eye. Such impurities sometimes act as stress risers, weakening the product, and at the least are unsightly. It is therefore extremely important that a good homogenous blend of any recycled product be made at the recycling plant. Many good homogenizing extruders are commercially available, and while not able to make virgin quality product from scrap, will still make good recycled material.

To this point, only regrinding and pelletizing in preparation for reprocessing has been considered. Another possibility for recycle exists, which is to depolymerize the resins back to their monomers and either remake them into polymers, or find other uses for the molecular fragments [13–15] some of which may not be polymerizable. Polyolefins may be thermally depolymerized or "cracked", yielding a mixture of liquid and gaseous products. The latter will usually consist of the original monomer (ethylene, propylene, etc.); but most of the mixture will be composed of many higher olefins unless extremely severe conditions are used. Halogen containing polymers such as PVC will evolve hydrogen chloride or fluoride (HCl or HF) when heated, become brittle, discolored, and finally insoluble. Polyesters such as PET are easily depolymerized by hydrolysis in glycols or even water at high temperatures and appropriate pressures. Eastman Chemical Products Inc. has demonstrated that they may be depolymerized in propylene glycol [16], then reacted with acids such as maleic to produce a thermoset polyester resin. Goodyear and DuPont are also doing research on utilizing the depolymerization approach.

Applications for recycled plastics

High density polyethylene

Pending development of better means of sorting the various types of plastic materials into relatively pure fractions, it appears that at the present only two types could be considered for making into high quality objects, PET and HDPE. High density polyethylene (HDPE), from such objects as discarded milk containers, can be easily distinguished from other components of a waste stream, or sorted at the curb. After the bottles are reground and cleaned they may be recompounded into pellets for remolding or extrusion. The cost of such recompounded material is 25–35% less than virgin resin, and if strict quality control is performed by the recompounder, physical properties may be in the same range as the virgin polymer. It would seem that several non appearance automotive items could be made from reprocessed material, such as windshield washer fluid containers, fender and trunk liners, etc. Procter and Gamble has pioneered among consumer goods companies in the development of recycled plastics packaging. Recycled HDPE is used to make test quantities of one gallon jugs for Cheer® detergent. These containers are made in a three layer extrusion; virgin resin is used for the outer appearance layer, reclaim for the center, and again a layer of virgin for the inside in contact with the product.

Poly(ethylene terephthalate)

PET is already being recovered in such purity that it is suitable for some fiber uses such as pillow or cushion fillers. Proctor and Gamble has tested clear PET bottles made from recycled resin for Spic and Span® Pine cleaner. There are a number of automotive or industrial parts which could be made of reprocessed PET, either clear (radiator overflow tanks) glass filled (filler caps, terminal blocks) or compounded with other resins such as low density polyethylene (LDPE) which improves processibility, lowers moisture absorption, and also elevates some mechanical properties. (LDPE/PET blends have lower moisture absorption than PET alone).

Polypropylene

Most lead-acid automobile batteries are contained in polypropylene (PP) cases. Cases from batteries being reclaimed for their metal value are ground to 1/8″ pieces, washed, mixed with a foaming agent, and extruded into "I" beams for bed rails [17]. To quote from this article in *Modern Plastics* "One rather curious factor emanating from this reclamation project is a morphological change in the scrap PP which is thought to stem from the residual lead and sulfur imparted by the battery environment. The precise nature of the chemistry has not been determined, but the result is definite improvements in such properties as impact strength, flexural modulus, and heat deflection." The above phenomena might also be related to results reported by Zamorsky and Muras [20] when PP was repeatedly extruded and the melt viscosity only decreased by 4.4%, while the carbonyl index during weathering was relatively unchanged.

Assuming that the reclamation process is efficient enough to separate plastics from the other constituents in a waste stream, and that further, these are separated by some mechanical method which yields two streams, one having a relative density of less than 1.0, the other above 1.0, a number of marketable items could be produced. A few such items and sources of raw materials are shown in Table 1.

TABLE 1

Products made from recycled plastics

Product	Starting materials	Reference
Structural concrete (walls, etc.)	Foamed polystyrene (PS) + portland cement.	[8]
Dunnage (loose or molded)	Reground foamed PS food trays, refoamed, molded.	[8]
Drainage pipe	Foamed PS food trays, iron oxide, nucleator for azo foaming agent. PVC blister packs, bottles, circuit board holders + virgin PVC.	[12]
Bed rails	Recycled lead-acid battery cases, 0.5% foaming agent.	[17]
Fence posts or floors for farm buildings	Polyolefin waste (min 50%), up to 20% PVC, 20% paper + foaming agent.	[13]
Floor mats, wheel chocks, pads, truck bed liners, drainage pipe, telephone conduit	Copper contaminated wire and cable scrap.	[14]
Composite board	Plastics auto scrap, sawdust, (or chopped glass) 5% MDI-isocyanate binder.	[15]
Polyester polyols (raw materials for polurethane foams)	PET bottle scrap or polyester fiber from discarded clothing, chemically digested.	[16]
Garbage bags	polyolefin waste from household and industrial sources.	[18]
Greenhouse film	Clean reclaim film blended with linear low density PE.	[19]

Problems

The example of the reclaimed PP given above is unusual, for reclaimed materials usually have physical properties inferior to virgin resin. Nearly all molders of products such as battery cases will use resins of about the same molecular weight and molecular structure. When recompounded, these polymers will retain essentially the same structure, so they will be physically compatible, and retain most of their original properties. Clear plastic materials picked from domestic trash on the other hand, will appear to be uniform, but in reality the many manufactured items will be made from a variety of resins having vastly different molecular weights, copolymers (such as ethylene–vinyl acetate), pigments, and other additives. Some may even be multilayered composites of such disparate resins as polyvinylidene chloride (Saran®) and polypropylene. Despite thorough washing in systems such as the AKW process mentioned above, some of the products may have been used to package motor oil, vegetable shortening, or other products which absorb into the polymeric matrix and change its properties. This sensitivity to contamination is much more evident in crystalline polymers, a class which includes the polyolefins (polyethylene, polypropylene, etc.).

Conclusions

The continued buildup of plastic wastes in landfills has become a major source of concern for many sectors of society. Plastics manufacturers and their trade organizations have begun to realize that they must help diminish the problem, and turn their considerable technical skills to this end. In particular, research and development on means of separating the various types of plastics must be done. An educational campaign might be needed to make consumers aware that recycled plastics can serve as well in many applications as virgin materials. Cooperation between the organizations involved with plastics production, academia, and EPA has been excellent. Working together, the amount of plastics recycled should be greatly increased, with the results of pollution prevention, energy savings, and the creation of jobs through new businesses built around plastics recycling.

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