An Overview of Recycling Plastics from Durable Goods: Challenges and Opportunities

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Introduction

The recycling of plastics from packaging, particularly bottles, has grown significantly during the last ten years for most industrial countries. While the recycling industry has experienced significant market challenges due to price fluctuations, the recovery of polyethylene terepthalate (PET) and high-density polyethylene (HDPE) is still being carried out in numerous large scale operations throughout the world. The growth of bottle recycling has been facilitated by the development of processing technologies that increase product purities and reduce operational costs.

The recovery of plastics from other streams, such as durable goods is growing in interest. This stream includes items like: automobiles, appliances, computer and business equipment, electrical goods, and even sporting equipment. This interest is being driven by a number of factors such as actual and proposed take-back and producer responsibility legislation on end-of-life products, as well as green marketing initiatives by a number of durable goods manufacturers. Metals and even reusable components are frequently recovered from these streams of end-of-life equipment, but the plastics are not being recovered at similar levels. This is due to the fact that the plastics used in these goods are newer engineering materials and represent greater recovery challenges—both technically and economically.

Many end-users and plastic recyclers recognize that the plastics used in durable goods are often more valuable than those found in packaging. The recovery of these plastics, however, is complicated by a number of unique challenges, such as: a much wider range of different and incompatible plastics; a less developed collection infrastructure; more varied end products; lower overall volumes of these materials, particularly on an individual grade basis; and a much wider range of attached foreign materials such as metal, rubber, foams, fabrics, etc.

This paper prepared for IdentiPlast II[*] will first review the unique challenges associated to this part of the recycling business, then discuss approaches to address these challenges. It will provide an overview of the general approach used to recover plastics from durable good streams. Much of the work on recycling plastics from durable goods has been sponsored by the American Plastics Council (APC).

Specifically, the paper will briefly review the main steps associated to the recovery of plastics from end-of-life durable goods shown as a recycling loop in Figure 1: 1) Identification and Sorting, 2) Size Reduction and Liberation, 3) Separation of Non-plastic Materials, 4) Separation of Mixed Plastics, and 5) Upgrading. It will touch on some of the major advances in these areas, and set the stage for the more detailed discussions that will follow from other presenters.

Discussion

As with other types of materials such as metals and glasses, different types of post-use plastics must be separated from foreign materials and from one another to achieve good performance and acceptable market values. Most plastics are not highly compatible with one another, and while some commingled applications have been demonstrated, particularly with compatibilization technology, they typically capture much lower values than virgin plastic.

In summary, the primary reasons for segregating plastics by type are:

- Most foreign material contaminants decrease the performance of the host material, and most plastics are not uniformly compatible.
- The properties will be consistent and understood. Even if compatible blends are produced, it would be difficult to ensure consistent composition of a blend made from a mixed recycle stream. Markets for other than generic resins are difficult to define.
- The maximum formulation and upgrading flexibility is available to materials in a pure state.

Some method to sort plastics by type is required because there are many different types of plastics used in plastic products (particularly in the durables area) and the pre-labeling of plastics to assist with identification does not facilitate the sorting in a factory environment.

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[*] IdentiPlast II, April 26-28, 1999, Brussels, Belgium, sponsored by APME, APC, PWMI, and EuPC is the second international conference on plastics recycling technology. IdentiPlast I, held October 1997, focused on plastics identification and sorting technology. IdentiPlast II focuses on plastics separation technology.

Furthermore, part labeling will not impact most end-of-life durables streams for many years, reflecting the long life-cycle of many of these products. . One approach is to first identify the plastic and then effect some type of mechanically assisted sorting based on that identification. Another common approach is to depend on some type of intrinsic material property, such as density, to effect the sorting during the recycling operation. Both approaches will be discussed in the following sections.

Identification and Sorting Technology

In general, this approach refers to a fast and accurate identification of the primary plastic contained in a particular item followed by some type of manual or automated sorting of that item based on the identification. This area was the subject of the first IdentiPlast Conference, held in Brussels in October 1997, therefore only a general overview will be provided. The reader is referred to the proceedings from that conference and to an APME (Association of Plastics Manufacturers in Europe) summary paper for more detailed information (reference 1).

In the area of rigid plastics packaging, high speed automated plastic bottle sorting technology has come a long way since it was first envisioned many years ago as a way to meet demanding quality requirements. Bottles can now be identified and sorted at rates of over one ton per hour in some cases. In the most typical approaches, the system scans each bottle multiple times, and sometimes with multiple types of radiation (visible light, infrared light, X-ray) as it passes on a rapidly moving conveyor belt. The multiple scans ensure that the plastic has been measured independently from the labels or other non-plastic items, while the multiple types of radiation are used to pinpoint the plastic’s chemical make-up. This type of approach requires an identification speed of hundreds of measurements per second. This performance is a significant improvement from the many minutes of time required for the quickest laboratory methods just a few years ago, and would not have been possible without significant research effort.

There are over 250 automated bottle-sorting lines in commercial operation today. Advanced systems can identify all of the commercially used packaging resins and can sort by color. Other systems are in place which sort flakes by color and resin type (PVC and PET only today) at rates of over two tons per hour. Reviews of some of these bottle-sorting technologies can be found in references 2 through 7.

While the recycling of plastics from bottles is widely practiced commercially, the recycling of plastics from durable goods such as automobiles, computer and electronic equipment, appliances, building and construction and even sporting goods, is a more recent interest as the recovery of these products becomes more commonplace (8-11).

As with plastics from packaging, the plastics used in durable goods must be sorted according to type. Unfortunately, the automated bottle sorting technologies that were mentioned earlier are not applicable to most of the plastics found in end-of-life durable products for a variety of reasons:

- Durable parts come in a much wider variety of shapes and sizes compared to bottles.
- The average wall thickness of items is much greater in durable goods.
- The parts from durable products are often opaque and often contain carbon black.
- Coatings are used much more frequently for both decorative and functional reasons on plastics from durable goods.
- There are a much greater variety of plastic types found in durable products to meet the correspondingly wide variety of performance requirements.

The wide variety of shapes and sizes implies that the parts from durable goods will be difficult to “singulate” on a traditional conveying system. It also makes probing with a remote sensing device more difficult because the orientation of the surface and the distance to the surface with respect to the probe may change significantly with each part.

The thicker walls and part opaqueness, make energy transmission through the part much more difficult. Carbon black, in particular, absorbs much of the radiation from traditional spectroscopic identification techniques, making it difficult to obtain information from the underlying host polymer. Some bottle sorting techniques also rely on the simple fact that the degree of light transmission through a sample provides information regarding polymer type. Light transmission is not possible through most plastic parts from durable goods. Coatings, particular metallic ones, also interfere with most types of analysis techniques.

Finally, a large variety of plastic types, fillers, reinforcements and additive combinations are found in durable goods to meet the wide variety of aesthetic and performance needs in modern durable products. This means that the identification and sorting system must be capable of accommodating a much wider variety of materials than those developed for bottles, which typically focus on just three to five materials.

Beyond the differences in technical challenges, there are several factors associated with durable goods that make a slower and possibly more manual approach feasible, at least as an interim technique:

- Durable parts are more likely to be handled manually at some point in the recovery process (disassembly).
- In many cases, the value of the plastic used in a durable product is greater than that used in packaging.
- The average plastic part from a durable product weighs considerably more than an individual plastic bottle.

- Bottles are collected at curbside and are found in high piece volumes of similar parts, whereas most durable parts are collected by numerous different recycling infrastructures and occur in a much lower number of individual pieces, particularly of similar parts.

All of these factors suggest that a slower identification technique could be economically feasible for plastics coming from durable products. The parts are already frequently being handled manually in existing dismantling infrastructures, so a manual device could be easily incorporated into the process. Furthermore, each identification and sorting event, on the average, will result in greater value for durable parts than bottles because the amount of plastic being sorted is larger, and, in many cases, the value of the plastic itself is greater. Finally, it may prove difficult to collect large numbers of individual plastic parts from durable goods in one location, making a justification for potentially expensive and complicated automated technologies more difficult.

The identification and sorting considerations just discussed and their implications are summarized in Table 1. As described above, the implications suggest that a manual approach might be economically and technically feasible for some of the plastics coming from specific durable products. It was also clear that an automated approach would take much longer to develop. For these reasons, both manual and automated approaches have been pursued independently and concurrently by different companies and research organizations. Three types of manual equipment are being developed worldwide: hand-held, portable and bench. As might be expected, truly hand-held devices might not be able to identify the full spectrum of polymers, but could be very useful in niche applications. Bench top units are typically modified laboratory instruments that have been adapted to facilitate rapid plastics identification. Portable units attempt to bridge the gap between truly hand-held and bench-top units, much like laptop computers do between the personal digital assistants (PDAs) and desktop computers. The most desired device characteristics are summarized below:

- Accurate identification (less than 1% error rate)
- The ability to identify a wide variety of plastics in any color
- Fast response times (less than five seconds)
- Portable and rugged enough to be used in a recycling environment
- Economical enough for widespread use by recyclers
- Easy to use by non-professionals

Before 1994, no commercial devices existed that met the desired instrument characteristics. In fact, many minutes were required for an experienced spectroscopist to identify the type of plastic from which a sample was made, and the sample preparation was usually somewhat tedious and destructive.

The biggest single challenge in both developing and evaluating technologies to meet these goals is the wide variety of plastics used in durable products. Even within a specific plastic family, such as ABS, the number of formulation varieties available may be well over 100. This high degree of material tailorability has been one of the primary reasons for the dramatic increase in the use of plastics in durable products. Numerous additives can be used to achieve certain properties and the pigments used in polymers can also vary significantly, particularly between different application areas. Finally, many of the plastics from end-of-life durable products were formulated ten or more years ago and the materials have continuously changed and improved. The American Plastics Council and MBA Polymers, Inc., in particular, developed an extensive calibration and testing library containing some of the most commonly used plastics based on market data and feedback from end-users. This library has been used to help develop, evaluate and demonstrate many different technologies (11).

Numerous techniques have been proposed and explored by various organizations throughout the world. Some of the most notable technologies are listed below:

- Mid infrared spectroscopy (MIR) or Fourier Transform Infrared spectroscopy (FTIR)
- Near infrared spectroscopy (NIR)
- Shortwave NIR (SWNIR)
- Raman spectroscopy
- Pyrolysis mass spectroscopy (Py-MS)
- Pyrolysis IR spectroscopy (Py-IR)
- Laser-induced emission spectral analysis (LIESA)
- Infrared thermography
- X-ray methods
- Triboelectric property measurements

Each technology has its own set of advantages and disadvantages, many of which are briefly summarized in Table 2. A much more detailed discussion on these techniques is contained in reference 1. Additional discussions of plastics identification technology can be found in references 12 through 20.

No technology has yet been identified which addresses all of the needs of identification and sorting technology for durable goods, however new ones are being developed all of the time.

More Challenges

Even if all of the plastic parts from a durable goods stream can be identified and sorted into different categories, many challenges remain before most parts can be transformed into reusable material. They may contain various paint and coatings, the must be size reduced, and most will be made of many mixed materials that are attached to one another. These challenges are reviewed below.

Paints and Coatings

Paints, coatings and coverings (such as fabrics, sheets and films) are encountered among plastics from durable goods rather often, and represent challenges to both the identification and recycling of plastics. In the appliance, electronic, computer and automotive industries, paints and coatings can be used for both decorative and functional reasons.

Paint and coatings, if not removed, can cause property reductions in some recycled plastics from stress concentrations created by the coating particles. Degradation of the coating can also lead to chemical degradation of the plastic during reprocessing. The level of potential property reduction depends on the combination of the type of plastic substrate, coating type and coating thickness. Appearance properties and surface characteristics can also be effected by residual paint and coatings.

The paints and coatings must usually be removed or rendered compatible with the plastic substrate to achieve the highest possible mechanical properties of the recycled material, although there have been reports of good property retention with certain coating/substrate combinations without any special attention to the coatings (21).

The approach taken to remove or compatibilize the coating depends on the nature of the coating and its interaction with the substrate material. As noted in the Identification and Sorting Section, there are many different types of plastics used in durable products. When these are multiplied by the numerous varieties of coatings, the number of different coating/substrate combinations are staggering. It is unlikely that any single technique would be optimal for all combinations.

The chrome from plated plastics has been recovered for years with simple grinding, sometimes assisted with cryogenic methods (to enhance the liberation process and prevent the plating from being embedded in the plastic granules). This has been widely practiced due to the value of the chrome and its ease of separation from the plastic using strong magnets (some of the material in the “chrome” coating is slightly magnetic). Fine grinding of most painted plastics may result in a fair amount of liberation, but the separation of the paint and plastic particles becomes difficult, if not impossible.

The aerospace industry has developed numerous abrasive paint removal techniques in response to environmental concerns with solvent stripping methods. These techniques, however, are more applicable to large whole parts and a manual approach. Several continuous and automated abrasive techniques were investigated as part of an APC project using large flakes of coated plastics in an effort to identify a dry coating removal technique, but none proved completely satisfactory.

High temperature aqueous-based approaches demonstrated through APC projects and by other organizations, however, have shown promise on many coatings and substrates, and continue to be investigated further (22-25). The high temperature aqueous environment can hydrolyze many coatings, but the plastic substrates might also be susceptible to degradation, so the processing conditions must be very carefully controlled. In the case of olefin-based car bumpers, Toyota has demonstrated that the coatings can be changed sufficiently using a high temperature water process to compatibilize them with the plastic, and removal of the paint is not deemed necessary (26). The olefinic plastic is apparently not degraded under these conditions, however this particular plastic is less susceptible to hydrolytic degradation than some of the other engineering thermoplastics (particularly condensation polymers).

Size Reduction

Most of the plastic parts returning from EOL durable goods have other materials attached to them, such as ferrous and nonferrous metal inserts, screws, bolts, clips, brackets, etc.; metal, paper and plastic labels; foam insulation; wiring and mixed plastics. It is usually not economically feasible to remove most of these items manually, so they must be liberated and separated in an automated fashion if the plastic is to be recycled.

Before any automated separation can be performed, the parts must be size reduced and the foreign material contaminants liberated from one another. The size reduction must be sufficiently extensive and vigorous to cause even molded-in items to be liberated or to create particles in which the contaminant represents the majority of the particle volume so that its characteristics can be used to effect a separation. Furthermore, many of the downstream separation techniques require that the particles be fairly uniform in size and shape for efficient performance.

In summary, the size reduction step has three primary purposes: 1) generation of particles that can be more easily handled than bulky parts, 2) generation of uniformly sized and shaped particles that can be separated effectively in down-stream processes and 3) liberation of dissimilar materials from one another.

Plastic bottle recycling size reduction challenges have been mostly met by shredders and standard granulators. Plastics from durable goods, however, have several unique characteristics that make this step even more challenging.

- Plastic parts from durable goods come in a wider variety of shapes and are usually much larger.

- Many of the plastic parts contain significant amounts of metal that can damage traditional plastics size reduction equipment, such as granulators.
- The parts often contain other materials intimately bonded to the plastic substrate, requiring aggressive liberation.
- The parts are thicker and the materials are stronger, making size reduction more difficult.

Traditional plastics size reduction involves high-speed granulators with fixed screens or grates to control particle size. The knives of the granulators can be quickly dulled or even damaged by hard materials like most metals. In some cases, the high speed rotating knives can catastrophically fail upon hitting metal pieces and cause significant damage to the equipment. Some granulator manufacturers have developed more robust knives that can accommodate limited metal contamination, but not the full range of metal found in end-of-life durable products. Metal detectors can be placed in line before the granulation step, but this is not an effective metal removal technique for streams with significant metal content because the devices reject some of the target plastic with the metal each time metal is detected.

In some respects, shredders and hammer mills are at the other extreme of the recycling size reduction spectrum. They are used by metal recyclers to size reduce items such as entire automobiles and large appliances, and are generally designed to perform coarse size reduction and liberation with high throughputs. Shear shredders operate at low speeds and rely on stacked opposing circular cutters with "hooks" or fingers on two counter-rotating shafts to grab and shear the materials in a single pass, while hammer mills operate at much higher speeds and beat the material until it is small enough to fit through the openings in screens or grates typically fixed below the units.

None of these techniques proved viable as solitary size reduction operations for plastics from durable goods. Studies showed that traditional granulators could not accommodate significant amounts of metal, standard shredders were not effective at producing well controlled particle sizes or adequate liberation and hammer mills were noisy, were not effective at close particle size control, generated a large amount of fines and actually imbedded contaminants in the plastics in a few instances. However, a combination of these techniques used with metal removal equipment (see Separations Section) could be used to provide the necessary size control and liberation.

As a result of considerable searching, developmental efforts and trials undertaken as part of an APC project, several types of stand-alone equipment were eventually uncovered which provided the necessary size reduction and material liberation necessary for large plastic items with significant metal content: four-shaft shear shredders, modified two-shaft shear shredders and rotary grinders.

The four-shaft shear shredders are most commonly found in Europe and often with a removable fixed screen for size control. Like a standard shredder, they can accommodate high metal content material, but the four shaft design provides added cutting opportunities and an efficient recirculation function that causes the material to pass through the cutters multiple times until it can pass through the holes of the screen, thus producing a particle with the desired size characteristics and significant liberation achieved with granulators, but with the capability of accommodating higher amounts of hard materials. Some standard two-shaft shredder manufacturers have also realized the need to generate smaller and more controlled particles for some applications, and have developed narrower cutters and fixed screens that can be placed below the shredder to cause the material to experience repeated cuts until it can fit throughout the screen openings. The placement of screens on shredders, however, significantly reduces the achievable throughput rates.

Rotary grinders were initially developed to size reduce wood. The typical design employs numerous one to two-inch square teeth mounted in various patterns on a horizontally rotating shaft. These teeth take small "bites" from material that is pushed into the rotating shaft via a large sliding ram. The ram is typically equipped with a load sensor to maintain a fairly uniform pressure at the cutting interface and to indicate when the ram should retract to allow additional material to fill the grinding area. These units, which operate at speeds between that of granulators and shear shredders, can be fitted with a wide size range of screens sizes for particle size control. This type of equipment can accommodate rather large parts and moderate amounts of metal, but typically not as great in either case as a shredder.

Once the majority of the metal is removed from these streams, more traditional size reduction techniques can be used to cause further liberation, such as granulation and milling. These additional size reduction steps are usually only necessary for recycle streams containing very well-adhered foreign material requiring aggressive liberation. Alternatively, or additionally, wet and cryogenic techniques can be used to enhance liberation (see Separations Section). A summary of some of the major size reduction approaches is presented in Table 3. APC and MBA Polymers put together a report that summarizes many different types of size reduction technologies that were evaluated over several years. That report should be available through APC soon.

Materials Separations Technology

As noted above, even if the plastic part has been identified to determine the primary plastic from which it was made and sorted into groups of parts made of this plastic before size reduction, in most cases there will be many different types of materials mixed together because very few plastic parts used in durable goods have nothing attached to them. If these parts have been size reduced into sufficiently small pieces to liberate most or all the different materials from the target plastic(s), the result is a mixture of commingled flakes of various materials that may include:

- The target plastic(s)–usually the majority component(s)
- Ferrous metals
- Nonferrous metals
- Paper, plastic film and other label materials
- Foam
- Fabric
- Cables and wiring
- Glass
- Wood
- Other plastics
- Other materials

These foreign materials must be separated from the target materials for recovery. Furthermore, these foreign materials themselves should be separated into pure steams to the greatest extent possible because it enhances their recyclability as well. Technologies to facilitate these separations have been developed by entrepreneurs, equipment manufacturers and the plastics industry (8, 9 10, 27, 28). In many cases, the technologies have been borrowed from other industries, such as food processing, agriculture, mining, waste management, and plastics processing.

APC and MBA Polymers concurrently with the investigations into processes for identification technology and size reduction equipment also carried out investigations into material separation technologies. One APC Project, designated M-234, specifically investigated methods to liberate and separate automotive parts with coverings, such as seats, instrument panels and interior door panels. This project led to the development of a mechanical process to recover polyurethane foam from car seats. A report was written by APC and MBA on this project and will be available for publication soon.

The work on separation processes was much broader than that carried out under APC Project M-234. In fact, two other APC projects were undertaken: one to investigate existing separation technology (M-131), and one to investigate new and advanced mechanical recycling technology (M-132). APC worked with MBA and wTe Corporation on Project M-131 and with MBA on Project M-132. Some of the major techniques that were investigated under these projects are discussed briefly below. These were also summarized at a Workshop put together by APC and MBA Polymers for the Society of Plastics Engineers' Annual Recycling Conference in Chicago in 1998 (ARC98).

Ferrous Metals Removal

The sized and liberated materials are fed to some type of a ferrous metal removal operation, such as a rotating drum, head pulley, or overhead belt magnet containing a strong (usually permanent rare earth) magnet. This type of equipment has been used effectively in metal reclamation operations for many years, and it has already demonstrated its ability to remove essentially all of the ferrous components in durables streams investigated to date. The strongest magnets can even remove many grades of stainless steel, most of which exhibit very little magnetic character.

Nonferrous Metal Removal

While much of the metal is ferrous in nature, some hard metals, such as high-grade stainless steel, are not captured by most magnets. Even softer material, like brass inserts or cast zinc and aluminum pieces can cause damage to plastics processing equipment and need to be removed. Numerous approaches have been investigated to remove the nonferrous metallic components, such as:

- Eddy Current
- Electrostatic
- Air Classification
- Sink-float Techniques
- Mineral Jigging
- Elutriation and Rising Current Separators

The first technique is used extensively in post-consumer mixed curbside collection programs to remove aluminum cans at material recovery facilities (MRFs). It works well for nonferrous items (other than stainless steel), particularly aluminum, that have high surface area to weight ratios (such as aluminum cans) because the opposing field generated in those types of items is sufficient to repel them from the generation source, typically placed at the end of a conveyor. Plastics recycling trials using commercial equipment demonstrated good separation capabilities, however, the equipment was not completely effective at removing all of the nonferrous particles from a commingled durables stream.

Electrostatic separation methods have been used for years to recover electrically-conductive materials from various streams. A static charge is applied to the finely ground particle stream before passing it onto a rotating grounded drum. Conductive particles give up their charge to the grounded drum and fall freely from the drum and over a knife separator. Non-conductive particles retain their charge longer and cling to the drum longer, eventually falling into another collection area. The process works well to scavenge conducting material from non-conducting material, especially with multiple passes. For example, four-pass machines are used to remove aluminum caps from ground plastic beverage bottle streams. In trials, this technique was able to concentrate plastic and metal streams, but was not capable of removing all of the metal from ground durables streams. A similar technique is also being investigated for plastic-plastic separations of commingled flakes.

Air classification systems have also been evaluated for their potential of separating metal from plastics based on their significant density differences. These techniques are based on terminal velocity differences of particles in an air stream, and therefore depend on shape factors as well as density. Thin flat pieces of metal can report to the same "lights" fraction as nuggets of plastics. Air classification was found to be capable of enriching both plastic and metal streams, but not capable of completely removing all of the metal, without very significant losses of plastic. As will be discussed in the next section, however, this technique is used to effectively remove other foreign material contaminants.

Because none of the dry techniques were completely satisfactory at removing metals, wet techniques have been explored. The simplest approach is to float the plastic away from the metal using density baths, but this requires a media of rather high density, depending on the density of the target plastic. This technique will be discussed later under plastic-plastic separations.

At least two water-only density separation techniques have been investigated: mineral jigging and elutriation. Both effect a separation by subjecting the material to a water stream of controllable velocity. The jigging method comes from the mining industry, and passes the material through a series of chambers in which water is being moved upward and downward in a cyclic motion. The jig housing contains rubber diaphragms which are moved in and out mechanically. This in and out motion causes the water level inside the box to move up and down, which, in turn, increases the buoyant force of the water, causing materials slightly denser than water (such as most plastics) to "float" away from those materials much denser than the water, such as metals, glass, wires, etc. The rate and amplitude of the pulsation can be adjusted. Elutriators and rising current separators work on similar principles, except the velocity of the water is constant and in a single direction. The latter, in particular, have been used in the metal recycling industry to remove “lighter” materials from nonferrous metal streams. In this case, the target material is the metal, rather than the plastic.

Air Classification

Air classification or aspiration has been practiced for centuries in the agriculture industry. Its earliest form was practiced by agriculturally-based societies for separating wheat from the chaff using the wind. The modern techniques use more controlled forced air handling equipment. Numerous styles of air classifiers have been evaluated for removing the liberated "lights" fraction, which may contain materials such as foam, films, labels, dirt and fine particles (including dirt), but all work on a similar principle of subjecting the material to a controlled velocity air stream.

The lights/heavies cut is determined primarily by the airflow velocity, which can be adjusted by a simple baffle in the air-handling conduit. It is usually adjusted to the point where rigid plastic flakes just begin appearing in the lights stream. It is usually preferable to lose a small amount of product in an attempt to remove as much of the foreign materials as possible. Experiments have demonstrated that multiple passes through this type of equipment can result in improved separations and recovery rates. Complete separation is usually not accomplished in a single pass because materials are entangled or physically attracted to one another, sometimes due to simple static charges. This is especially the case with foam materials, which tend to maintain static charges rather well.

Plastic-Plastic Separations

Density

These techniques rely on the fact that the target plastic will often have a different density from the foreign materials, including other plastics. The target plastic stream can be separated from undesirable materials having different density, by placing the commingled material in a medium having an appropriate density. If a medium is chosen with a density between that of two different types of plastic having sufficiently different densities, a separation can be effected by simply placing the plastics in a vessel containing the medium. The material less dense than the media will float and the more dense material will sink. The most simple density separations use sink-float tanks, and various versions have been used by plastic beverage bottle recyclers for years, often using only water.

Most rigid plastics from durable goods are denser than water, so the density of the medium used in the tank must be increased to greater than that of water by adding a modifier to the water or using a different liquid to create “heavy media”. Salt-water solutions using sodium or calcium chloride can reach approximately 1.2 specific gravity, which is usually sufficient for most separations. Higher density salt or other solutions are also possible, and used frequently by other industries. The major drawbacks to using heavy media include economic and environmental considerations associated with lost heavy media and residual media contamination on the recovered plastic. Adequate rinsing can address the residual media concern for many plastics.

Assuming that the media handling and contamination issues can be addressed adequately, engineering plastics still represent a challenging feed stream because the density ranges of many types of plastics overlap, especially considering the ranges of additives, pigments, fillers and reinforcements used. Thus, this plastic-plastic separation approach is sufficient by itself only for streams containing few different plastics having definite density differences.

Sink-float systems can be found in numerous configurations such as simple tanks with paddles to encourage product movement and wetting, systems requiring the material to transverse convoluted paths to increase process residence time and inclined screw classifiers which use augers to convey the heavy material fraction from the bottom of the feed tank and dewaters it in the same step. In all cases, the light material fraction is removed from the top of the system as floaters and the heavy fraction removed from the bottom as sinkers. These streams are then usually dewatered before continuing to the next unit operation, especially if the density of the media changes from one operation to the next.

Density separation systems can suffer from several drawbacks even with simple feed streams. Any particles with voids will not seek their material's intrinsic density, unless the media displaces the air from the cells. This is a particular problem for structural foam materials because the density of structural foam parts can vary dramatically, even in the same part, due to variations in the level of foaming. Ranges of specific gravity from less than 1.0 to over 1.2 have been measured in samples from thick and thin sections, respectively, taken from the same part. Obviously, the density bracketing would have to be relatively wide to accommodate this material, allowing a wider range of possible foreign materials to report with the product stream.

Hydrocyclones are often used to enhance the effectiveness of density separations from both a throughput and purity standpoint, but their operation is less well understood. They can provide a greater driving force (centrifugal verses gravity) to the separation, enhance material wetability and increase throughput. Hydrocyclones, which have demonstrated effectiveness in some relatively simple plastic packaging recycling systems, are still under investigation with respect to plastics from durable goods. A report on hydrocyclone technology was prepared for the APC by MBA Polymers (29).

The next step in sophistication in liquid medium particle-particle density separation systems is centrifugation (30). It subjects the particles to even higher forces than hydrocyclones, which can lead to more effective separations. The major drawback to using centrifuges for this application is their very high capital cost, particularly for a given throughput.

Some of the factors affecting liquid separation performance of a given material include its wetability, its variation in density (from porosity, fillers, pigments, other additives, etc.), shape factors of size reduced particles and its level of liberation from other materials. Even surface air bubbles, which can attach to plastics due to poor wetting, surface contaminants, molded-in holes or bosses and/or edge roughness, can cause an individual flake of material to float in a solution less dense than that of the bulk material.

Non-Density Separations

A number of non-density based techniques are under investigation by researchers around the world. Many are just now going beyond the laboratory stage, especially when applied to the recovery of plastics from durables. They are mentioned here for completeness. Examples include:

- froth flotation (which comes from the mining industry)
- triboelectric (a variation on electrostatic separations mentioned earlier)
- flake identification and sorting (the most common being color and PVC sorters)

The first of these techniques, which is more broadly referred to as air flotation, depends on surface chemistry differences between different plastic types, which are common because the plastics differ in chemical structure. Some of the practical problems with this technique include coatings like paint and metals that cover the chemistry of the underlying plastic; dirt, grease and other coatings that accumulate during use and handling; and finding polymer-specific surface active agents that will cause air bubbles to attach to only the specific target polymer, floating it away from the other materials in the mix.

Triboelectric separators also depend on surface differences between plastics so these too experience problems with coated and dirty materials. Humidity and surface wetness can effect the performance of this technique since it is electrical in nature.

Wash System

This unit operation is meant to remove any remaining surface contaminants such as dirt, adhesives and labels. Its effectiveness can vary widely depending on its configuration, and its level of importance can vary depending on the feed stream cleanliness. Variables that relate to washing effectiveness include residence time, temperature, agitation rate, and chemical environment. This operation is likely more important for packaging streams which contain various surface residues (such as food, etc.), compared to durable parts.

Integrated Recycling Systems

One of the greatest challenges facing a recycler of plastics from durable goods is determining how to integrate all of the techniques that can be used for purifying plastics into a system that is economical to assemble and operate, and that can accommodate all of the streams anticipated by the recycler. MBA Polymers, Inc. has built a robust mechanical recycling line designed to accommodate a wide variety of potential feedstreams from automotive, appliance, computer, electronics, and even sporting goods. The general concept of the processing line is as shown schematically in Figure 1, and will be further discussed as part of the oral presentation at IdentiPlast II.

Table 1. Summary of Identification and Sorting Considerations

Bottles	Durables	Implications
Similar Sizes & Shapes	Odd Sizes & Shapes	Difficult to singulate parts and to capture reflected radiation for automated durables system
Thin Walls	Thick Walls	Can possibly use transmission mode with bottles (vs. reflection). More plastic per ID for durables
Clarity Related to ID	Most Parts are Opaque	Packaging can use inexpensive visible light for some ID
Collected at Curbside/Drop-off, High Volume Pieces	Collected by Recyclers, Low Volume Pieces	Automation more viable and more important for bottles
Commodity Plastics	Engineering Plastics	More value obtained per ID for durables in many cases
Labels Cover Large Percentage of Bottle area	Labels Cover Small Percentage of Most Durable Goods	Multiple readings usually required for bottles with automated systems
Paint and Coatings Rare	Paint and Coatings Common	Coatings must be removed from durables prior to ID
Black Parts Rare	Black Parts Common	NIR more viable for bottles

Table 2. Cursory Comparison of Various Rapid Plastics ID Technologies *

Technology	Advantages	Disadvantages
MIR	• Fundamental vibrations yield "fingerprints" - increased accuracy and information • Can measure black plastics • Proven technology	• Very surface sensitive • MIR fiber optics are limited in range, expensive and fragile • Remote sensing difficult • Commercial MIR instruments slower than NIR instruments
NIR	• Commercial units available • Can use "normal" fiber optics • "Portable" units already used for QC • Fast and can be done without contact • Some have no moving parts (rugged)	• Limited information in this range – overtone vs. fundamental peaks • Carbon black absorbs and scatters highly at NIR frequencies, making dark plastics difficult to probe
SWNIR	• Low cost equipment • Very small instrument with fiber optics • No moving parts (rugged)	• Only limited polymers (and colors) can be detected • Still somewhat developmental
Raman	• Can be fast and remote is possible • Fiber optic probes possible • Spectral detail similar to MIR	• Fluorescence of black pigments • Lasers expensive
Pyrolysis and Plasma Techniques	• Could obtain very accurate identifications. • Could be very fast • Additive ID possible	• Sampling could be difficult • Polymer degradation questions • Still in laboratory stage
Triboelectric	• Only known true hand-held device • Completely portable and easy to use • Fast response • Inexpensive	• Very limited in number of polymers • Can be sensitive to moisture and surface contamination • Still somewhat developmental
Thermo-graphy	• Remote probing possible • Some coatings may not be a problem • Can be very fast	• "Signatures" of many polymers very similar • Still developmental
X-ray	• Can detect heavy atom additives and components, like Cl, Br, Cd, Pb, etc. • Fast and remote • Proven technology	• Can't distinguish between different polymers • Expensive • Radiation safety issues

* It should be noted that these advantages and disadvantages represent composite opinions on general pieces of technology. They may not hold perfectly for specific pieces of equipment.

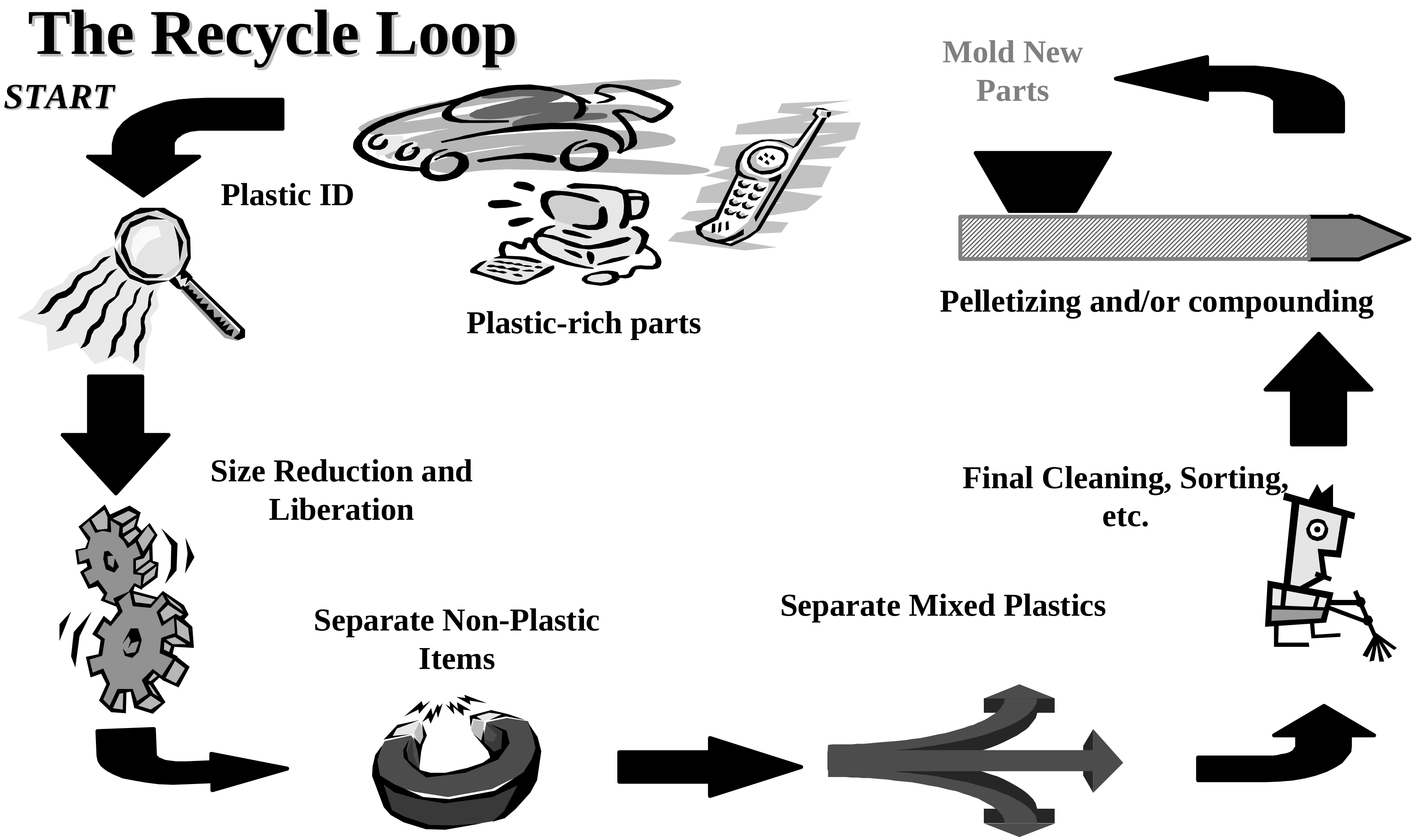
Furthermore, the technology in this area is rapidly changing, and it is possible that some of the disadvantages will be overcome with development efforts already underway.

Table 3. Summary of Major Plastics Size Reduction Equipment *

Machine	Advantages	Disadvantages
Traditional Granulators	• Can produce fine particle sizes (<1/8” mesh) • Excellent liberation of materials • Well-known technology • Can have high throughputs	• Cannot handle metals • Maintenance costs rather high • High speed and can be noisy
Granulators - Modified	• Can handle small amounts of metals • Can produce fine particle sizes (<1/8” mesh) • Excellent liberation of materials	• Newer technology and not widely available • Can’t handle large amounts of metal or thick metal
Traditional Shear Shredders	• Can handle large and heavy metal • Large feed hopper • Well known technology	• Poor particle size uniformity • Feed rams not a stock item • Difficult to replace blades • Typically no screens provided
Four Shaft Shredders and Modified Two Shaft Shear Shredders	• Can handle metal • Relatively low power requirements • Good liberation of materials • Better size control	• Not widely available • Much lower throughput rates compared to shredder with no screen • Feed rams not a stock item • Difficult to replace blades
Hammer Mills	• Can handle significant amounts of metals • High throughputs • Very robust designs • Well known technology	• Poor particle uniformity • Relatively high power requirements • Noise can be high
Rotary Grinders	• Can handle moderate metal • High throughputs • Blades easily replaced & sharpened • Relatively low power requirements • Automatic ram feed • Comes with screens • Very good liberation of materials • Reasonably easy to clean	• Cannot handle large amounts of hard metals • Cannot easily produce small particle sizes (<1/4” mesh) • Higher cost
Cryogenic Grinding	• Very fine partial sizes possible (<60 mesh) • Excellent liberation of materials	• High Cost • Low throughputs • Potentially high operating cost due to liquid nitrogen needs • Cannot handle metals

* It should be noted that these advantages and disadvantages represent composite opinions on general pieces of technology. They may not hold perfectly for specific pieces of equipment. Furthermore, the technology in this area is rapidly changing, and it is possible that some of the disadvantages will be overcome with development efforts already underway.

Figure 1. A shematic approach to the recovery of plastics from durable goods.



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