

Part II

Recycling Technology

The information in Part II is from *Technologies for Recycling Post-Consumer Mixed Plastics—Plastic Lumber Production, Emerging Separation Technologies, Waste Plastic Handlers and Equipment Manufacturers*, prepared by Bruce A. Hegberg, Gary R. Brenniman, and William H. Hallenbeck of the University of Illinois Center for Solid Waste Management and Research for the Illinois Department of Energy and Natural Resources, Office of Solid Waste and Renewable Resources, March 1991.

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Summary

Broad scale recycling of post-consumer plastic waste is technically difficult because of the variety of plastic resins which exist and the difficulty of sorting them. While further work in processing and separating waste plastics is necessary for widespread plastics recycling, there are methods to utilize mixed plastic waste and methods to clean and separate some types of plastics. The latter is primarily an emerging field of research in recycling technologies. The purpose of this report is to discuss technologies which have been developed for the separation and processing of mixed plastic wastes.

Although there are many types of plastics, eight types comprised 76% of the 1989 U.S. sales (including export sales) of all plastics: low density polyethylene (LDPE), polyvinyl chloride (PVC), high density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), polyurethane (PUR), phenolic, and polyethylene terephthalate (PET). Efforts in recycling have concentrated on the thermoplastics HDPE, LDPE, PP, PS, PVC and PET because thermoplastics can be repeatedly softened by temperature increases and hardened by temperature decreases. These thermoplastics are also referred to as commodity resins because they are produced in the largest volumes at the lowest cost and have common characteristics among producers. Consumption of these six thermoplastics is led by the packaging industry. PUR can be formed as a thermoplastic or a thermoset (a resin which has undergone a chemical reaction leading to a relatively infusible state that cannot be reformed). Phenolics are a family of thermosetting resins.

There are numerous manufacturing methods used in the production of plastic goods. Post-consumer thermoplastic products are typically made using an extrusion mold, blow mold or injection mold process. An extruder consists of a rotating screw in a barrel to melt plastic pellets and force the molten resin out the end through a die. Extruders typically precede blow mold and injection mold dies. Extruders are also used directly to form film plastics (such as dry cleaning bags or sheet wrap) or profile extrusions (such as pipe or window framing). Blow molding, which is how bottles are formed, involves the insertion of a tube of resin melt from an extruder into a mold and then blowing on the inside of the tube with a gas to form the melt against the inside walls of the mold. Injection molding is used to inject resin melt into a mold from an extruder barrel. It forms solid parts (such as lids or caps), allows precise definition (such as sharp corners) and permits close tolerances.

Plastic manufacturing involves the use of compatibilizers. Compatibilizers are types of plastic additives that can have a direct affect on the recycling of plastic mixtures. They allow for the bonding of two otherwise unadhering plastics when blended together.

This can allow for higher end use of a plastic mixture than without a compatibilizer additive. Compatibilizers exist for polyethylene (PE)/PVC blends, PE/PS blends, PVC/PS blends and other more specialized plastics.

The manufacture of flow molded linear profiles, or plastic lumber as it is commonly referred to, has received a great deal of attention as a solution to using mixed plastics. It is a method to utilize plastic containers and films en masse which could not otherwise be collected in quantities significant enough to justify separation. Plastic lumber is also a method to utilize "tailings," the miscellaneous plastic resins left after a recycle stream has been "mined" of higher value HDPE and PET bottles. Tailings may also typically be the plastics collected by recycling that were not specified by the collecting agency. Although, from a polymer science point of view, such a diverse combination of plastics are not considered to be readily capable of "blending" into a compatible product, the mixture can easily be processed by extrusion into large cross-section items that have significant strength and utility.

Although the manufacture of plastic lumber from mixed plastics without separation has large potential as a solution to mixed plastics, there are associated problems. Depending on market prices and proximity to the manufacturer, it may be necessary to pay a manufacturer to take the waste plastic (there are no mixed plastic lumber producers in Illinois). The cost of shipping can have a large impact on the recycling operation economics. It may also be necessary to separate plastics to obtain a desired color or appearance of the finished lumber product or to attain a product with reasonable quality standards. While dark browns, blacks and grays are possible with mixed plastic bales, lighter colors such as blue, yellow and light gray are not possible without using separated clear and white HDPE/LDPE. A large proportion of LDPE, both granulated and molded, produces articles which are very elastic. Similarly, a large proportion of PP will produce articles which are brittle. Consequently, blending of granulated material by polymer may be important depending on the product to be manufactured. If separated with enough quality control, the separated resins will bring a better price than through the plastic lumber market. Finally, the manufacturer may require that a municipality collecting mixed plastics buy the product following recycling.

There are approximately nine companies producing lumber from mixed plastics collection programs, with three in the midwest area. While most companies possess a proprietary machine or license, the basic principles of each machine are the same. Post-consumer bottles or rigid plastics must first be ground and films must be densified and ground. The material is fed into an extruder barrel, forced through a die and cooled. Additives may be provided in the feed to enhance properties or set the color. LDPE,

HPDE, PP and PS all work well with the process. PVC can be used with additives. Higher melting point plastics such as PET become a filler if used in plastic lumber production. The physical properties of plastic lumber have been shown to improve significantly with the addition of PS to mixtures.

Because the manual sorting of heterogeneous plastic mixtures is the current level of technology in all but a few applications of plastics recycling, methods to effectively separate them on a more automated basis are being attempted. Methods for sorting rely on responses to differing environments such as specific gravity changes, x-ray diffraction, optical recognition and dissolution in solvents. Each of these methods is capable of separating types of plastic to a certain extent and therefore any one process cannot individually sort any type of plastic mixture. These methods can be classified into macro, micro or molecular scale sorting. Macro sorting involves separating plastic based on an entire product, such as using optical sensing to separate whole bottles by color. Manual separation is also a macro sorting method. Micro sorting involves the initial processing to a uniform criteria, such as size, with subsequent separation. An example of micro sorting is the commercially viable PET bottle/HDPE base cup separation method, where bottles are ground up and sent through a hydrocyclone; the PET and aluminum cap grind sinks while the HDPE floats. Molecular separation involves processing plastic by dissolving the plastic and then separating plastics based on temperature.

Methods to separate clear glass and PET plastic bottles from colored glass and PET plastic bottles are being evaluated at one university and a recycling center in Illinois. It involves the use of an optical sensor activating a diversion device to assist in the separation of a majority of clear bottles from colored bottles. Early testing indicated separation effectiveness was high. The device is estimated to cost about \$2,000 to \$4,000 for a small unit which would process 60 tons/year PET and 1,000 tons/year glass and be used less than 200 hours annually. Processing ten times as much would make better use of operating time and result in a payback of less than one year.

The separation of PVC bottles from other plastic in sorting programs has become important due to the adverse effects of even small amounts of PVC present in other plastic (e.g., PET). Upon being melted with PET, which is what PVC is most often mistaken to be, hydrochloric acid can form and corrode the metal parts used in plastic extrusion machines. A study of PVC bottles in a mixed plastic recycling program showed that manual separation is about 80% accurate in identifying which bottles are PVC. Research is being conducted to provide automated separation methods for PVC bottles. Most use x-ray fluorescence to detect characteristic backscattering from chlorine atoms in PVC which is higher than that detected by polyolefin plastic without chlorine. Mechanical separation can

then occur. There are still some problems because the chlorine x-ray is weak, it does not penetrate paper labels and there is a rapid decrease in intensity as a bottle is moved away from the detector. It is projected that a minimum of 10 bottles/second could be analyzed with multiple detections per bottle. Even with automated x-ray separation, additional cleaning is necessary, and a method to perform cleaning and foreign plastic separation using a 1.35 and 1.30 specific gravity calcium nitrate solution is being studied.

The Center for Plastics Recycling Research (CPRR) at Rutgers University has developed a process for the reclamation of PET soda bottles that can be transferred to the public to increase recycling of such bottles. This was done because there are a number of companies in the U.S. which recycle PET soda bottles, but their methods are generally proprietary and not licensed out. The license and technology are available for a fee of \$3,000 which includes a technology transfer manual with detailed equipment and process description, process economic estimates, safety and health parameters and quality control requirements and measurements. The Rutgers Beverage Bottle Reclamation Process is not meant to separate PET soda bottle colors or other type plastics, but rather to provide clean PET flake separated from caps, labels, base cups and adhesives. The process also provides clean polyolefin flakes which are mainly the HDPE base cup and PP caps, and aluminum chips from caps. A detailed cost estimate was performed by CPRR for a 20 million pound per year facility in a leased building which was based on attaining 20¢/lb for PE flake and 34¢/lb for aluminum. Plant operation was based on 24 hours/day and 330 days/year. A return on investment of 34%/yr at a PET flake price of 31¢/lb has been estimated.

Selective dissolution involves the separation of mixed plastics on a molecular scale by dissolving resin mixtures in a solvent. This method is currently being studied at a laboratory level. There are two methods being approached in the dissolution process. The first method uses one solvent to dissolve all resin types and the second method uses one solvent to dissolve one particular type of resin, but not others. Both methods have received attention because the plastic stream can be heterogeneous in nature and contaminants such as metals, glass, cellulose and some pigments can be removed. Selective dissolution can allow for microdispersion of polymer combinations, thereby rendering innocuous certain plastic components that may lead to manufacturing difficulties or poor physical properties. Promising solubility and recovery has been achieved thus far.

Recovered plastic can be marketed for reuse by directly dealing with a company which uses waste plastic in manufacturing, by directly dealing with a plastic processor which will buy waste plastic and market the cleaned and decontaminated product, by listing the recovered waste plastic in a waste exchange for marketing or by marketing the

recovered waste plastic through a scrap resin broker. A resin broker or a plastic scrap handler is typically where plastic scrap is marketed after being collected at the post consumer, post commercial, or industrial scrap level. Shipments in truckload quantities are typically preferred, but smaller loads down to bales are usually accepted with an accompanying reduction in price paid. There are approximately 14 resin brokers or scrap handlers in Illinois with 11 in the Chicago metropolitan area, 2 in Joliet and 1 in Decatur. Five of the companies in metro Chicago are strictly brokers of plastic scrap. There are 20 additional brokers/processors in states neighboring Illinois: 8 in Wisconsin, 7 in Michigan, 2 in Iowa, 1 in Indiana, 1 in Kentucky and 1 in Missouri. Waste exchanges are typically sponsored by a state and provide a waste listing free of charge. Because of the extensive number of sources and types of plastics in waste, waste exchanges should generally be utilized only after other marketing methods (e.g., scrap resin brokers, plastic recycling companies) have been tried. There are 17 such waste exchanges in the U.S. and Canada; one is sponsored by the state of Illinois.

Specifications exist for non-plastic contaminants and other plastic contaminants in waste plastic loads. As may be expected, higher prices are paid for material with lesser amounts of contamination. Limits for non-plastic contaminants are typically no metals, less than 0.005% to less than 3% (by weight) non-plastic, and the material must be clean. Limits for plastic contaminants are typically less than 1% to less than 5% (by weight) other plastic, less than 1% (by weight) color on clear/natural bottle loads, no motor or vegetable oil bottles, and no PVC bottles. One method of addressing plastic contamination in general is to link recycle product prices to product quality on a commonly accepted standardized system such as the American Society for Testing Materials (ASTM). The ASTM D-20 Committee, which addresses plastic recycling and degradable plastics, is developing standards regarding waste plastic contamination and recycling.

1. Introduction

1.1 Plastics in Municipal Solid Waste

Recycling of plastic discards is one method of reducing municipal solid waste. They are beginning to join glass, steel, aluminum and paper as waste stream components that have been accepted into recycling programs across the country. It is difficult, however, to expand plastics recycling because of the variety of plastic wastes, the difficulty of sorting different types of plastics, the low density of post-consumer plastics wastes in comparison to other recyclables and the limited history of plastics recycling. Because of its heterogeneous nature and the amount of contaminants present, separation of post-consumer mixed plastic waste is the most difficult. Waste plastic from industrial operations are cleaner and more homogeneous in resin type and scrap form. The term "mixed plastics," a mixture of plastic types or a mixture of package/product types which may or may not be the same plastic type or color category, has been used to describe broad scale processing of post-consumer plastic waste. Mixed plastics also includes products which may be the same resin type but which have been fabricated using differing manufacturing techniques.

While it is possible to market recycled mixed plastic waste with limited separation, greater value and broader applications are achieved with homogeneous resins. Although it is possible to mix different type polymers together, the resulting physical properties are less desirable than the original components. Technological research regarding large scale separation of mixed plastic waste streams is being conducted. The advances in plastic separation technology are discussed in this report.

The 1989 domestic consumption of all plastics totaled 53.5 billion pounds, with 44.2 billion pounds, or 83%, being eight plastic types: low density polyethylene (LDPE), polyvinyl chloride (PVC), high density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), polyurethane (PUR), phenolic, and polyethylene terephthalate (PET) [Modern Plastics, 1990a]. HDPE, LDPE, PP, PS, PVC and PET are thermoplastics, capable of being repeatedly softened by increases in temperature and hardened by decreases in temperature. They are also referred to as commodity resins because they are produced in the largest volumes at the lowest cost and have common characteristics among producers. Consumption of these six thermoplastics is led by the packaging industry. Polyurethane can be formed as a thermoplastic or a thermoset. Thermosets are resins which have undergone a chemical reaction leading to a relatively infusible state that cannot be reformed. Phenolics are another family of thermosetting resins.

Although somewhat synonymous with "resin" and "polymer," the term "plastic" refers to a resin which includes additives for the purpose of providing a manufactured product. "Resins" (or polymers) are the basic materials for plastic products, and most often denote a polymerized material without consideration of specific additive.

A study of the 15 leading resins based on 1988 production identified that 44 billion pounds were disposed of in some manner [Franklin Associates, 1990]. Of all resin types produced, 29 billion pounds are disposed in the municipal solid waste (MSW) stream each year and only 1.1% of the waste plastic stream is recovered [U.S. EPA, 1990a]. The remainder is disposed as incinerator residue, sludge, industrial, or construction/demolition waste. In 1988, plastics comprised 9.2% by weight and 19.9% by volume of material discarded in MSW [U.S. EPA, 1990b]. One specific plastic type, PET beverage bottles, which have been targeted for recycling through curbside collection and container deposit legislation, has reached notable recycle rates of 23% in 1988 and 28% (175 million pounds) in 1989 [Plastic News, 1990a]. The increased cost of landfilling waste, the volume occupied by disposed plastic products, the value of the plastic waste material, as well as the mandate of 25% recycling of solid waste set by the state of Illinois make the addition of plastics to recycling programs a necessity. Increasing the recycle of plastic containers, film, and packaging in general from the waste stream is a logical next step in increasing recycle rates.

The numeric coding of six popular types of plastic by the Society of the Plastics Industry (PET - 1, HDPE - 2, PVC - 3, LDPE - 4, PP - 5, and PS - 6) with subsequent acceptance of such number coding of containers into law by a number of states across the country has made post-consumer plastics recycling more prevalent than ever. Municipalities and cities are beginning to collect plastic bottles, any type of rigid plastic container, and in some cases plastic films. Film is often the most predominant component of plastic on a weight basis. Further development of process and separation technologies is necessary for mixed plastics if widespread recycling of plastic bottles, containers and film is to be increased. This report discusses technologies which have been developed for the separation and processing of waste plastics.

Parameters of curbside plastics recycling such as the characterization, collection and costs are discussed in Part I of the book.

The following section 1.2 is an overview of plastic resin production and the primary methods utilized in manufacturing consumer goods and recycling waste plastics into new products. Also discussed are factors influencing the recyclability of waste plastic mixtures and compatibility between polymer types.

1.2 Plastic Resin Production and Product Manufacture

Production of plastic goods involves three primary steps:

- Resin manufacture by reacting oil or natural gas products into solid molecules
- Incorporation of additives to alter physical or aesthetic characteristics, or to permit processing of the resin
- Product manufacture, typically from pellet form for thermoplastics and liquid form for thermosets

Resin Manufacture

Different resins are manufactured from different petroleum based feedstocks (Table 1.1). Monomers, compounds which can be used to react with itself or another similar compound or molecule, form polymers. The feedstocks shown in Table 1.1 are either monomers or used to form monomers. For example, ethylene is a monomer for producing polyethylene, and benzene is used to produce styrene, the monomer for polystyrene.

Polymer resins are formed when a chemical reaction takes place in which the molecules of a relatively simple substance (the monomer) are linked together to form large molecules whose molecular weight is a multiple of the monomer (termed polymerization). In short, polymerization is the bond forming reaction between small molecules with the potential of proceeding indefinitely. Almost all polymerizations are exothermic, and the heat of reaction must be removed in order to maintain the process. Polymerization can occur using a number of methods and can be carried out in batch or continuous operating modes in reactors. The reactor maintains different pressure, temperature and catalyst levels necessary to produce different type polymers. Step-growth polymerization, where two components are used in a conventional chemical reaction to form a polymer which grows in steps, is another polymerization process. The most important example of this is the mixing of ethylene glycol and terephthalic acid to form polyethylene terephthalate (PET), widely used in beverage bottles, textile fibers, transparent films, electrical parts and strappings.

A homopolymer is a polymer resulting from the reaction of one monomer, meaning it consists of a single type of repeating unit. A copolymer is the polymerization of two distinct monomers incorporated into the same polymer chain. For example, ethylene and propylene are monomers used to make copolymer PP; homopolymer PP can also be made from propylene. HDPE, LDPE, PS and PVC can be either homo- or copolymers. PET is a copolymer. Copolymerization is the most general and powerful method of effecting systematic changes in polymer properties, and it is widely used in the production of

Table 1.1 Feedstock Chemicals for the Production of High Volume Plastics [U.S. EPA, 1990a]

Feedstock Chemical	Possible Polymer Product ^a
Acetylene	PVC, PUR
Benzene	PS, PUR, ABS
Butadiene	PUR, ABS
Ethylene	HDPE, LDPE, PVC, PS ABS, PET, PUR, Polyesters
Methane	PET, PUR
Napthalene	PUR
Propylene	PP, PUR, Polyester
Toluene	PUR, Polyester
Xylene	PS, PET, ABS. Polyester, PUR

a. Refer to the glossary (Appendix D) for abbreviation and polymer description.

commercial polymers and in fundamental investigations of structure-property relations [Tirrell, 1990]. Different monomers are used to create the same copolymer resin.

Copolymerization can widely vary resin properties such as melting point, glass transition temperature, crystallinity, solubility, elasticity and chemical reactivity. The crystallinity of a resin refers to the amount of ordered three dimensional structure (a property which imparts rigidity to a molecular resin structure). For example, PET is referred to as a crystalline polymer (one whose crystalline properties can be controlled by processing). The glass transition temperature (T_g) refers to the midpoint temperature of a temperature band. When the temperature is above the midpoint, the resin structure is unfrozen and in a rubbery state and will eventually melt with increasing temperature. When the temperature is below the midpoint, the resin is in a hard, glassy condition.

Polymers are characterized according to many parameters. Some of the more basic characterizations are the molecular weight (MW) of the polymer produced, density and the melt point. The density is affected by the MW of the polymer produced, among other things. The melt flow index (MFI) is a simplified measurement for determining grades

within a polymer type. It is most widely used in classifying polyethylene (PE) resins. The MFI device involves forcing a polymer melt through a specific size orifice die at a fixed temperature with a specific weight piston. The extrusion device is described by ASTM D1238. The weight expelled in a 10 minute period is known as the MFI, which can typically range from 0.1 to 20. The MFI is inversely proportional to MW, with a MFI=20 being a low MW and 0.1 being a high MW polymer. While the MFI is a simple index, it is only a single point approximation for polymer viscosity, and should only be used to compare polymers in the same family. Therefore values for PE should not be compared with PP or PS. However, it is widely used by polymer suppliers to compare grades.

Table 1.2 shows some of the density, melting points and overall properties of the six primary thermoplastics. Following is an overview of the six primary thermoplastics:

Polyethylenes (PE) The basic structure of the homopolymer PE is the chain $-(CH_2-CH_2)_n-$, made from polymerization of the gas ethylene, C_2H_4 . In commercial PE, n may vary from 400 to more than 50,000. It is the variation of n and the addition of copolymer substitutes which allow for the variation of melt index, density, and numerous physical properties. There are three basic polyethylene types: Low density polyethylene (LDPE), medium density polyethylene (MDPE) and high density polyethylene (HDPE). LDPE has the variations of linear LDPE (LLDPE), Ultra LDPE (ULDPE) and Very LDPE (VLDPE). HDPE also has the variation of ultra high molecular weight polyethylene (UHMWPE), respectively. This discussion is limited to the two LDPE types (LDPE and LLDPE) and HDPE, as the others are not as broadly used. LDPE used in films is usually a homopolymer. PE as a family has become the largest commercially produced resin in the world. LLDPE is characterized by linear molecules without long-chain branches. In contrast, LDPE contains many long chain branches off the backbone molecules. LLDPE is easier and less energy intensive to produce. HDPE contains a small number of chain branches that are introduced by copolymerization. A low melting point and high chemical stability facilitate the processing of HDPE using injection, extrusion and blow molding.

Polypropylene (PP) The basic structure of homopolymer PP is linked propylene monomer. Copolymerization with ethylene also occurs frequently. Hundreds of grades of PP are sold in the U.S. Its density is among the lowest of all plastics.

Polystyrene (PS) PS is produced by the styrene monomer. Styrene is very reactive and readily undergoes homo- and copolymerization. General purpose PS is often called crystal PS because of the clarity of its appearance. Its commercial success is due mainly to transparency, lack of color and thermal stability. There are three commercial grades of general-purpose PS: easy flow, medium flow and high heat.

Table 1.2 Commodity Thermoplastic Characteristics

Resin Type ^a	Density (g/cm ³)	Softening or Melting Range (°C)	Properties/Applications
LDPE	0.910-0.925	102-112	Largest volume resin for packaging; moisture proof, film transparent
LLDPE	0.918-0.942	102-112	Use generally grouped with LDPE
HDPE	0.940-0.960 0.950 (colored bottles) 0.960 (clear bottles)	125-135	Tough, flexible and translucent material, used primarily in packaging; product examples include milk and detergent bottles, heavy-duty films, wire and cable insulation
PP	0.90	160-165	Stiff, heat and chemical resistant, used in furniture and furnishings, packaging and others; product examples include drink straws, fish nets, butter tubs, auto fenders
PS	1.04-1.10	70-115	Brittle, clear, rigid, easy to process, used in packaging and consumer products; product examples include foamed take-out containers, insulation board, cassette and compact disc cases
PET	1.30-1.40	255-265	Tough, shatter and wear resistant, used primarily in packaging and consumer products; product examples include soft drink bottles, photographic and x-ray film, magnetic recording tape, shipment strapping
PVC	1.30-1.35	150-200	Hard, brittle and difficult to process, but processed easily using additives; a wide variety of properties and manufacture techniques are possible using differing copolymers and additives; product examples include sheet bottles, house siding, cable insulation

a. Refer to the glossary (Appendix D) for abbreviation and polymer description.

Polyethylene terephthalate (PET) PET is a thermoplastic polyester made by condensing ethylene glycol and terephthalic acid. PET is stable in a wide range of chemicals and possesses good mechanical, electrical, and thermal properties. It has one of the highest densities of the six primary thermoplastics.

Polyvinyl chloride (PVC) Vinyl chloride is the monomer used to produce homopolymer PVC. It can also be copolymerized with many monomers to produce polymers with a wide variety of properties. PVC is popular because of its versatility. PVC can be injection, extrusion or blow molded.

Additives

Plastic additives are categorized as being either a modifier or protective additive. They are used to alter physical appearance, to alter physical properties of plastics or to retard (or stop) an undesired chemical reaction. Common modifying additives are reinforcing fillers, non-reinforcing fillers, plasticizers, colorants, blowing agents (for foaming) and impact modifiers (for toughness). Protective additives protect the polymer or stabilize it. Examples include UV stabilizers, heat stabilizers, inhibitors to retard degradation and antioxidants. Seventy-five percent of the additives produced are either fillers or plasticizers.

Compatibilizers are a family of additives that have a direct affect on the recycling of plastic. Compatibilizing agents can allow for a bonding between two otherwise unadhering polymers when blended together. Deficiencies in the properties of a resulting polymer mix can be overcome by compatibilizer addition. Polymers may be grafted with a compatibilizer to increase recyclability. A grafted polymer refers to a polymer comprising molecules in which the main backbone chain of atoms has randomly attached side chains containing atoms or groups different from those in the main chain. The main chain may be a copolymer or may be derived from a single monomer. Examples of compatibilizers include use of methyl methacrylate (MMA)-grafted PE or chlorinated polyethylene (CPE) for PE/PVC blending, styrene grafted PE copolymers for PE/PS blends and styrene grafted PVC for PVC/PS blends [McMurrier, 1990]. There are also compatibilizers for PS/LDPE blends. The use of compatibilizers then allows for higher end use and larger markets than may be expected without them. The general compatibility of differing polymers is shown in Table 1.3.

Product Manufacture

There are eight basic types of polymer molding: extrusion, pultrusion, blow molding, thermoforming, injection molding and compression molding, transfer molding and rotational molding. Extrusion, blow molding and injection molding are the primary manufacture methods for non-durable goods and waste plastic found in MSW.

Table 1.3 Compatibility of Polymers [McMurrier, 1990] ^{a, b}

Polymer Type	LDPE	LLDPE	ULDPE/VLDPE	Ethylene Copolymers	HDPE	PP	EPM/EPDM	PS (general purpose, high impact)	SAN	ABS	PVC	NYLON	PC	ACRYLIC	PBT	PET
LLDPE	1	1														
ULDPE/VLDPE	1	1	1													
Ethylene Copolymers	1	1	1	1												
HDPE	1	1	1	1												
PP	4	2	(1)	2	4											
EPM/EPDM	4	4	(1)	3	4	1										
PS (general purpose, high impact)	4	4	4	4	4	4	4									
SAN	4	4	4	4	4	4	4	4								
ABS	4	4	4	4	4	4	4	4	1							
PVC	4	4	4	(2)	4	4	4	4	2	3						
NYLON	4	4	4	(1)	4	4	(1)	4	4	4	4					
PC	4	4	4	4	4	4	4	4	2	2	4	4				
ACRYLIC	4	4	4	(3)	4	4	4	4	4	4	4	4	4			
PBT	4	4	4	(2)	4	4	4	4	4	4	4	4	1	4		
PET	4	4	4	(3)	4	4	4	4	4	4	4	3	1	4	1	
SBS	4	4	4	4	4	4	4	1	3	2	3	3	4	4	4	4

a. Refer to the glossary in Appendix D for polymer description.

b. Compatibility designations: 1=excellent, 2=good, 3=fair, 4=without compatibility. Designations (1), (2), (3)=compatibility level, depending on composition.

Extrusion Molding

Extrusion forces a plastic or molten material through a shaping die on a continuous basis (Figure 1.1). The feedstock may enter the extruder device in a molten state, but generally consists of solid material that is subject to extruder melting, mixing and pressurization. The feed may be powder, pellets, flake or reground material. Most plastic extruders incorporate a single screw rotating in a horizontal cylindrical barrel with an empty port mounted over one end and a shaping die located at the discharge end. A typical simple screw design for a solid fed single screw extruder must convey the plastic entering the screw into a heated compacted environment where the shear force developed by the

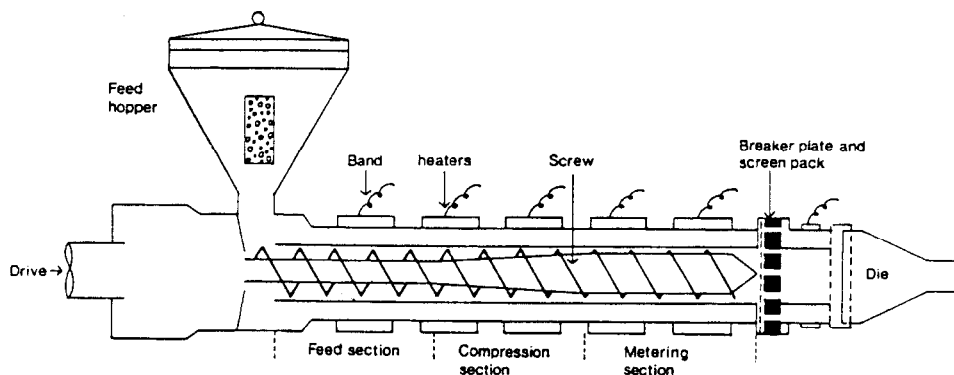


Figure 1.1 A Single Screw Extruder [Morton-Jones, 1989]. The machine consists mainly of an Archimedian screw fitting closely in a cylindrical barrel with just enough clearance to allow its rotation. Solid polymer is fed in at one end and the profiled molten extrudate emerges from the other. Inside, the polymer melts and homogenizes. Twin screw extruders are used where superior mixing or conveying is important.

rotating screw melts the plastic and mixes it to a reasonably uniform temperature while pressurizing the melt and pumping it uniformly through the die.

Both blow molding and injection molding are downstream extensions of the extruder and are discussed separately. Profile extrusion is the direct manufacture of a product from the extruder die. The products are a continuous length with a constant cross section. Examples of profile extrusions include plastic pipe, garden hose and PVC window framing. Profile extrusion is the method now being used to create plastic lumber from mixed plastics. Extruders can also be arranged as coextruders where different layers

of polymers are forced through the same die. This allows for multiple layers of polymers to form sheets, films or foam core products. It also allows for sandwiching of barriers (such as a gas permeation barrier) into a product.

Blow Molding

Blow molding produces hollow objects and is performed in three ways: extrusion blow molding, injection blow molding and stretch blow molding. In extrusion blow molding, the melted resin is extruded as a tube into the air (Figure 1.2a, 1.2b). This tube, called a parison, is captured by two halves of the bottle blow mold. A blow pin is then inserted into the mold and air pressure blows the melt against the cavity and cools it. The mold opens, the bottle is ejected, and the bottle trimmed. Extrusion blow molding is generally used for bottles greater than 0.25 liters. Coextrusion blow molding is also being used on a mass production basis to encapsulate scrap/recycle plastic into products. Coextrusion entails multiple extruders feeding resin into separate chambers within the die head used to manufacture a product (Figure 1.3).

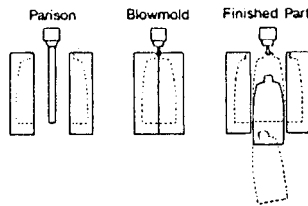


Figure 1.2(a) Extrusion Blow Molding of a Bottle [Miller, 1983]. The parison (plastic hollow tube) is extruded from the die head, the molds close, the part is blow molded, the molds open, and the part is ejected.

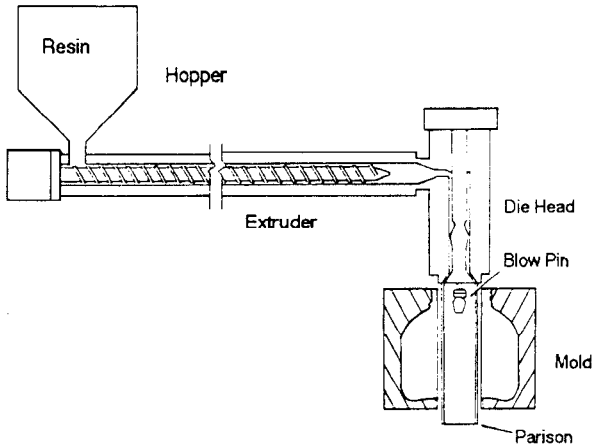


Figure 1.2(b) Extrusion Blow Molding of a Bottle [Miller, 1983]. Hopper, reciprocating extruder screw, die head, extruder parison, and molds shown in open position. The extruder rotates and reciprocates continuously, providing continuous mixing of resin with intermittent extrusion of parisons.

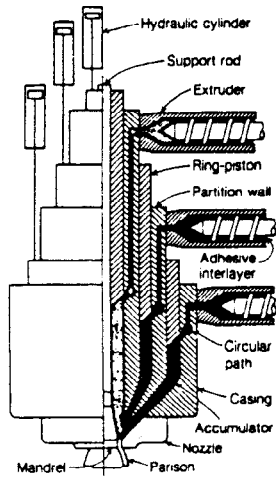


Figure 1.3 Coextrusion Three Layer Blow Molding Die Head [Miller, 1983]. Three independent extruders shown force melt into the die head. Coextrusion is used to install barriers to prevent permeation across bottle walls, add color onto a base polymer, and sandwich recycled resin in between virgin resin.

In injection blow molding, the melt is injected into a parison cavity around a core rod (Figure 1.4). The test-tube shaped parison, while still hot, is transferred on the core rod to the bottle blow mold cavity where the bottle is blown and cooled. Injection blow molding is generally used for bottles less than 0.5 liter in size. This type of blow molding allows for a scrap free product and for design of intricate shapes such as tamperproof closures. It is impractical for containers with handles.

In stretch blow molding, a heated pre-formed melt is positioned in the blow mold (Figure 1.5). A center rod extends which stretches the preform with axial orientation. Blown air then expands the preform in the mold, forming a bottle with radial orientation. The stretch process takes advantage of the crystallization behavior of the resin and requires the pre-form to be temperature conditioned and then rapidly stretched and cooled. PET soft drink bottles are formed using the stretch method. PET bottles are also formed using extrusion blow molding.

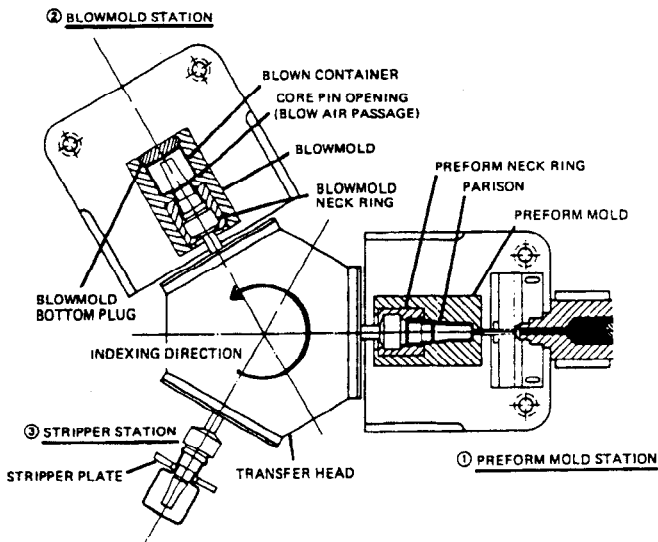


Figure 1.4 Three Station Injection Blow Molding Machine [Miller, 1983]. The parison is injection molded on a core pin (instead of as a tube in free air, as with extrusion blow molding) at the preform mold station (1). The parison and neck finish of the container are formed there. The parison is then transferred on the core pin to the blow mold station (2) where air is introduced through the core pin to blow the parison into the shape of the blow mold. The blow container is then transferred to the stripper station (3) for removal.

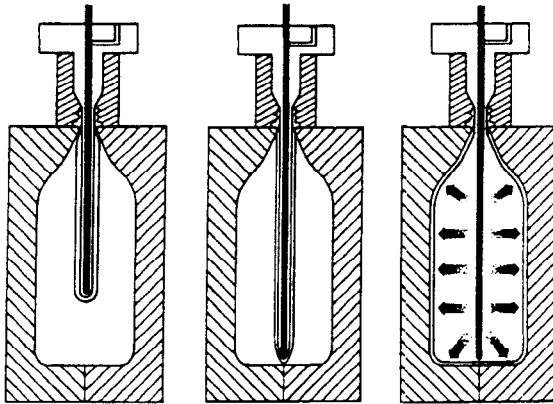


Figure 1.5 Stretch Blow Molding of Bottles [Miller, 1983]. A heated preform melt is positioned in the blow mold. A center rod descends, stretching the preform with axial orientation. Blown air expands the preform into the mold, forming the bottle with radial orientation.

Injection Molding

Injection molding produces solid parts in large volumes at high production rates. It permits close tolerances and the manufacture of very small pieces which are difficult to fabricate in quantity by other methods. Scrap losses are minimal compared to other forming methods because it is one of the only commercial processes where scrap can be reground and remolded at the machine. Melt material is injected into the mold from an extrusion barrel where it is maintained under pressure (Figure 1.6). When the part has sufficiently solidified, the mold opens and the part is ejected.

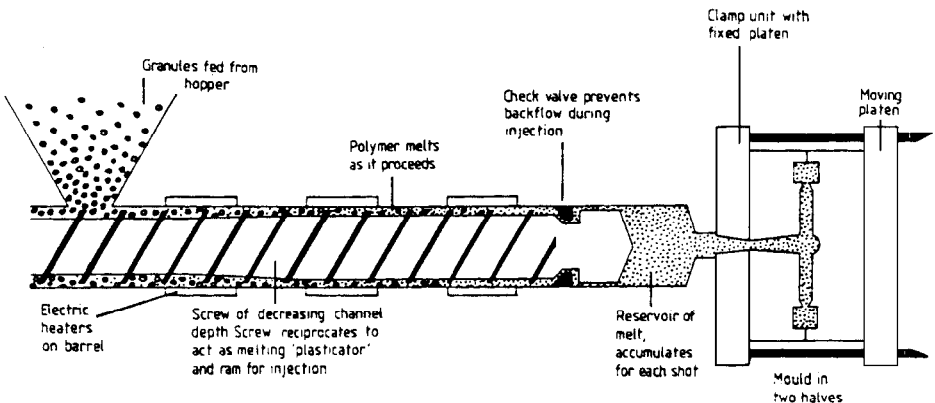


Figure 1.6 Simple Injection Mold Machine [Morton-Jones, 1989]

Film Manufacture

Blown film extrusion and slit die extrusion are the basic methods used to manufacture plastic films. Blown film extrusion produces tubular film and slit die extrusion produces flat film. Tubular film may be cut to produce flat film.

A typical blown film extrusion device is shown in Figure 1.7. The molten polymer from the extruder enters the die and is forced around a mandrel and emerges from a ring shaped die. The extruded film tube is then expanded to a specific diameter by air pressure from the center of the mandrel. As the bubble expands, film thickness decreases. The "frost line" shown in Figure 1.7 is the line where solidification of the extrudate commences.

Slit die extrusion or flat film extrusion as it is also called, is produced by extruding molten polymer through a slit-die and then cooling it on chilled rollers or in a water bath (Figure 1.8). With flat film extrusion, it is important to cool the material within a short distance of the die head so that a clear film is produced and necking (reduction in width) does not occur.

Melt Flow Indexes

Different properties of plastics are preferred for different fabrication methods. The viscosity of the resin melt is typically measured against a standard test referred to as the melt flow index (MFI). The MFI and resin density characteristics of some of the primary applications are shown in Table 1.4. As can be seen, the MFI and density properties vary with fabrication method. To allow for high tolerances and precise definition, injection molding utilizes a resin melt which is runny ($MFI=5-400$) in comparison to blow mold grade resin ($MFI=0.01-0.2$) or extrusion grade resin ($MFI=0.3-2$). Blow mold resin tends to be more taffy like so that it will retain thickness while pressure is applied inside a mold. This viscosity difference limits the type of recycling production methods possible because different melt viscosity resins do not mix homogeneously. If different melt viscosity resins are not separated prior to reuse, the resin properties will not be uniform in production. There is currently no automated method to separate differently produced types of plastics.

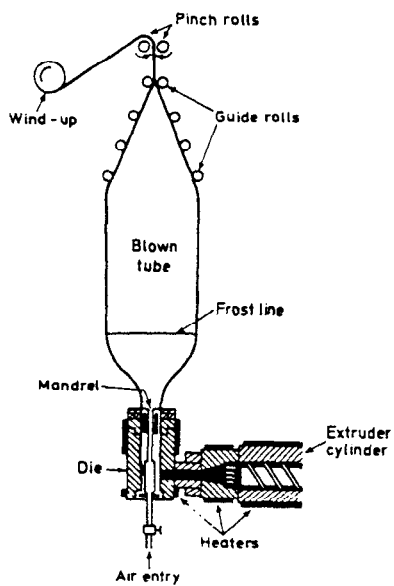


Figure 1.7 Blown Film Extrusion of Tubular Film [Briston, 1989]

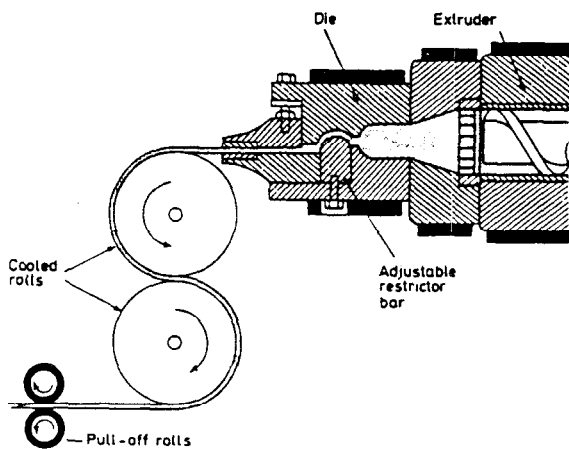


Figure 1.8 Slit Die Extrusion of Flat Film [Briston, 1989]

Table 1.4 Densities and Melt Flow Indexes of Production Polymers

Resin Type ^a	Density (g/cm ³)	Melt Flow Index (g/10 min)
LLDPE film	0.918-0.927	0.1-2.5
LLDPE injection molding	0.915-0.928	5-400
LLDPE pipe and sheet	0.928-0.942	0.8-2.0
HDPE injection molding	0.958-0.968	5-400
HDPE blow molding	0.956-0.964	0.01-0.2
HDPE film	0.946-0.955	0.02-0.3
HDPE pipe and sheet	0.946-0.969	0.3-3.0
PP sheet extrusion	0.902-0.903	0.4-0.8
PP injection mold, general purpose	0.903	4-12
PP injection mold, thin complex parts	0.902	35
PS easy flow injection mold	1.04-1.08	16
PS medium flow injection mold	1.04-1.08	7.5
PS high heat injection mold	1.04-1.08	1.6

a. Refer to the glossary (Appendix D) for abbreviation and polymer description.