1. Introduction

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 post-consumer plastics recycling beyond the easily recognized milk jugs and soda bottles for technical, economic and social reasons [U.S. EPA, 1990a]:

- *The variety of plastic wastes* Plastics in municipal solid waste (MSW) are a very heterogeneous collection of materials that encompass not only a broad range of types made from a single resin, but also an increasing number of items that include a blend of resins, either mechanically or chemically bonded together. The varieties are made additionally diverse through the use of plastic additives to yield specific product qualities.

- *The difficulty of sorting plastic resins* It is technically difficult to obtain relatively pure resins from mixed plastics collected for recycling. Commercially demonstrated separation technologies are almost exclusively limited to processes that separate polyethylene terephthalate (PET) and high density polyethylene (HDPE).

- *Low density of post-consumer plastics wastes* Plastics occupy a high volume/weight ratio compared to other recyclable constituents in MSW, and this adversely affects the practicality and economics of plastics collection in a recycling program. Landfill diversion rates are measured on a weight basis and the weight contribution of plastics to MSW is relatively small (even though the landfill volume occupied by plastics is large). The large volume occupied by plastics in a recycling truck can displace the ability to collect other "heavier" recyclables.

- *Limited history of plastics recycling* For many plastics recycling alternatives, only limited data exist from which to extrapolate costs, participation rates, technological or institutional barriers, and other factors which affect long-term viability.

However, in order to expand the recovery and recycling of plastics and decrease the amount of waste disposed in landfills, it will be necessary to overcome these difficulties. Because of its heterogeneous nature and the amount of contaminants present, separation of post-consumer mixed plastic waste is the most difficult. Waste plastics from industrial operations are cleaner and more homogeneous in resin type and scrap form than post-consumer plastics. The term "mixed plastics" has been used to describe broad scale processing of post-consumer plastic waste, although no formal definition yet exists. In its broadest sense, mixed plastics means a collection of a mixture of plastic resins or a mixture of package/product types which may or may not be the same plastic type or color category, and may not have been fabricated using the same 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 types of polymers together, the resulting physical properties are less desirable than those of the original components. General strategies for the separation of mixed plastics (and therefore strategies for increased recycling of plastics), with their respective advantages and disadvantages are shown in Table 1.1. Of the five approaches shown, three require substantial technological advances or governmental intervention (or both): "Separation after compaction or shredding," "Container labeling and automated separation" and "Standardization of resin use for certain product applications." Technological research regarding large scale separation of mixed plastic waste streams is being conducted, but some of it is far from commercial application. The advances in plastic separation technology are discussed in Part II of the book.
Governmental regulations regarding standardization for product applications and sortation would most likely not have widespread acceptance. The remaining two approaches, "Manual separation by consumer or collection agency" and "Collection focused on specific resin or container type," are currently in use. They are limited due to the cost of manual labor and a more narrowly defined plastic type, but have the potential for application to wider ranges of plastics than is currently collected by most recycling programs. The purpose of this report is to identify methods used for plastics collection, plastic collection compositions and generation rates, program costs, processing and end market use of mixed plastics in recycling. Attention is given to curbside collection of recyclables due to its high recovery rate[1] versus other collection methods [Morrow and Merriam, 1989]:

Type of Recycling Program	% Recovered
Curbside commingled	70 - 90 %
Curbside home sorted	60 %
Buy-back centers	10 - 15 %
Voluntary drop-off centers	10 - 30 %

[1]Recovery rate is defined as the amount of a recyclable disposed in a recycling collection container compared to the total amount of a recyclable disposed by a household.

Table 1.1 Advantages and Disadvantages of Alternative Strategies to Allow Separation of Resin Types from Mixed Recyclable Plastics [U.S. EPA, 1990b]

Strategy	Advantages	Disadvantages
Separation after compaction or shredding	Convenience to consumers; does not require consumers to separate wastes	Currently not possible to separate into homogeneous resins after shredding
	Minimizes sorting, storage and transportation requirements for collecting agencies	Shredding yields mixed plastics not amenable to processing into products displacing virgin resins
	Allows collection stategies capturing large volume and variety of MSW plastics	
Container labeling and automated separation	Convenience to consumers; does not require consumers separate wastes	Technology not currently in place
	Promises to allow separation into homogeneous streams	May require a centralized storage and separation facility with associated costs
	Minimizes manpower requirements required for sorting	
Manual separation by consumer or collection agency	Simple technology	Potentially prohibitive manpower requirements
	Convenience to consumers if collecting agency performs separation	May require large storage and transportation facilities
	Allows collection strategies capturing large volumes of MSW plastics	Inconvenience to consumers if they are required to perform separation

Table 1.1 Advantages and Disadvantages of Alternative Strategies to Allow Separation of Resin Types from Mixed Recyclable Plastics (Continued)

Strategy	Advantages	Disadvantages
Collection focused on specific resin or container types	Facilitates collection of homogeneous resin streams Allows recycling efforts to focus on high-value, high-volume recyclable products Convenience to consumers who are required to collect only a subset of plastic wastes Relatively low cost to recycling agencies Consistent with collection strategies offering financial incentives to recycle	Inconvenience to consumers if they are required to store and transport recyclables to central collection point Captures only a small portion of potentially recyclable plastics
Standardization of resin use for certain product applications	Facilitates collection of homogeneous resin streams	May imply significant governmental intervention in private markets May be difficult to enlist voluntary industry cooperation May be applicable to only a small percentage of recyclable products

1.1 National Production and Recycling Levels of Plastics

Plastic products are found in abundance in the homes we live in, places where we work, clothes we wear, and the transportation we use to get about. Plastics are used to manufacture nondurable goods[2] such as shoes, pens and garbage bags, durable goods[3] such as refrigerators, automotive parts and computers, and packaging such as food tubs, film wraps and bottles. The 1989 U.S. sales of all plastics (including export sales) totaled 58.2 billion pounds, with nearly all of it (92%) being U.S. domestic demand [Modern Plastics, 1990]. Of this, eight plastic types make up the majority of the annual demand (Table 1.2). Six of the types (HDPE, LDPE, PET, PP, PS and PVC) 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, meaning they are produced in the largest volumes at the lowest cost, and have common characteristics among producers. Polyurethane can be formed as a thermoplastic or a thermoset, the latter of which is a resin which has undergone a chemical reaction leading to a relatively infusible state (that cannot be reformed). Phenolics are a family of thermoset resins.

The major market destinations of plastics production are shown in Table 1.3, with a detailed breakdown of plastic uses in the packaging industry. Consumption of the six thermoplastics is led by the packaging industry (13,568 million pounds), accounting for 36% of the annual demand of the six thermoplastics (37,814 million pounds).

It has been estimated by the U.S. EPA [1990b] that 29 billion pounds of plastic are disposed in the MSW stream each year and that only 1.1% of the waste plastic stream, or 400 million pounds annually, are recovered[4] (Table 1.4). Municipal solid wastes come from residential, commercial, institutional and industrial sources, but do not include wastes such as construction debris, household hazardous waste, or other wastes regulated by Resource Conservation and Recovery Act Subtitle D. Seventy percent of discarded plastic is composed of nondurable goods and packaging materials.

Similar to the EPA estimate of the annual recovery of plastics, a study for the Plastics Recycling Foundation estimated that 340 million pounds were recycled in 1989[5].

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[2]Nondurable goods are usable only for a short period of time, a lifetime generally less than three years.
[3]Durable goods remain usable for a long period of time, generally products having a lifetime of more than three years.
[4]"Recovery" refers to the removal of materials from the waste stream for the purposes of recycling or composting. This includes materials which may have been removed for recycling, but were stored, landfilled or incinerated due to a depressed market condition.
[5]The primary components of recycled plastics were as follows: 160 million lbs. PET soda bottles, 100 million lbs. HDPE, including 40 million lbs. of soda bottle base cups, 60 million lbs. PP car battery cases, 12 million lbs. PET X-ray film and 10 million lbs. all else [Schut, 1990].

Table 1.2 1989 U.S. Consumption of Leading Plastic Resins

Abbreviation	Resin Type	SPI [a] Code Number	1989 Demand [b] (million pounds)	% of Total [c]
LDPE	Low Density polyethylene [d]	4	9,696	18.1
PVC	Polyvinyl chloride [e]	3	7,564	14.1
HDPE	High density polyethylene	2	7,405	13.8
PP	Polypropylene [e]	5	6,207	11.6
PS	Polystyrene	6	5,037	9.4
PUR	Polyurethane	none	3,245	6.1
none	Phenolic	none	3,140	5.9
PETE or PET	Polyethylene terephthalate	1	1,905	3.6
		Total	44,199	82.6%

a. Society of the Plastics Industry
b. From Modern Plastics, 1990.
c. Percent of total production of all plastics.
d. Includes LLDPE (linear low density polyethylene - 3,286 million lbs) and EVA (ethylene-vinyl acetate - 949 million lbs).
e. Includes copolymers.

This value accounts for only 2.5% of the 1989 domestic packaging demand of the six thermoplastics and less than 1% of all virgin thermoplastic resins. Only one specific bottle 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].

Plastic resins are often difficult to distinguish from one another. Communities performing recycling of plastic containers often train participants to identify a particular container type (such as milk jugs) rather than the actual resin. As an initial answer to this problem, the Society of the Plastics Industry (SPI) established a resin identification system for the six thermoplastics for use in the packaging and container industry (see Table 1.2). The state of Illinois passed legislation requiring the SPI resin identification code on all plastic bottles with a capacity of 16 fluid ounces or more and all other rigid plastic containers with a capacity of 8 fluid ounces or more that are manufactured for use in the

Table 1.3 Major Resin Markets, with Emphasis on Packaging, 1989 [Modern Plastics, 1990]

Market Category			Quantity (10^6 lbs)
Appliances			1,197
Building			11,390
Electrical/Electronics			2,202
Furniture			1,190
Housewares			1,362
Packaging			
	Closures		
		HDPE	81
		LDPE	32
		PP	420
		PS	190
		PVC	36
		Other	20
		sub-total	779
	Coatings		
		HDPE	51
		LDPE	730
		PET	10
		PP	30
		PVC	21
		Other	251
		sub-total	1,093
	Containers		
		HDPE	3,400
		LDPE	311
		PET	1,049
		PP	454
		PS	1,306
		PVC	352
		Other	146
		sub-total	7,018
	Film		
		HDPE	541
		LDPE	3,421
		PP	612
		PS	211
		PVC	310
		Other	107
		sub-total	5,202
Packaging (total)			14,092
Toys			729
Transportation			2,200
Major Market Total			34,362

Table 1.4 Generation, Recovery and Disposal of Plastic Products, 1988 [U.S. EPA, 1990b]

Product Category	Generation (10^6 tons)	Recovery (10^6 tons)	Recovery (%)	MSW Discards (10^6 tons)
Durable Goods	4.1	< 0.1	1.5	4.1
Nondurable Goods				
Plastic plates and cups	0.4	-	-	0.4
Clothing and footwear	0.2	-	-	0.2
Disposable diapers	0.3	-	-	0.3
Other misc. nondurables	3.8	-	-	3.8
Subtotal	4.6	-	-	4.6
Containers and Packaging				
Soft drink bottles	0.4	0.1	21.0	0.3
Milk bottles	0.4	-	< 0.1	0.4
Other containers	1.7	-	-	1.7
Bags and sacks	0.8	-	-	0.8
Wraps	1.1	-	-	1.1
Other plastic packaging	1.2	-	-	1.2
Subtotal	5.6	0.1	1.6	5.5
Total Plastics	14.4	0.2	1.1	14.3

state beginning January 1, 1991. The code is as follows: PET or PETE - 1, HDPE - 2, PVC - 3, LDPE - 4, PP - 5, PS - 6, and all others - 7. Twenty-six other states, including Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio and Wisconsin have also passed legislation that requires coding by resin type for various plastic containers [Ackerman, 1990]. 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 by weight 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.

1.2 Plastics in Municipal Solid Waste

Recycling of the plastics shown in Table 1.2 has the potential for reducing the waste stream and extending the life of landfills. Currently plastics make up an estimated 9% by weight and 20% by volume of landfill discards [U.S. EPA, 1990b], and most of it (83%) is the six thermoplastics.

The broad identification of disposal routes and types of plastic disposed in MSW landfills on a national basis has been performed by Franklin Associates in a study for the Council for Solid Waste Solutions (CSWS), a program of SPI, which is supported by major petrochemical and polymer production companies. The study examined the disposal routes of the 15 largest resins produced according to 1988 sales and identified which were disposed in MSW and which were not disposed in MSW (Table 1.5). Non MSW-disposed wastes included industrial waste, construction and demolition debris, sludge and incinerator residues. There is a lack of documented information regarding disposal routes of specific plastics and therefore a substantial portion of the research was based on communication with industry manufacturers and resin producers. The data show that for the most part disposal of specific resins is via either MSW or non-MSW methods of disposal (rather than both) and that PVC is the only resin of the leading six that is not disposed predominantly through MSW. Overall, the analysis shows that 61% of plastics are disposed in the MSW stream and 39% in the non-MSW stream. Residences were identified as the primary source of plastics in the MSW stream, comprising 60% of the plastics disposed, followed by the commercial sector contributing 25% and the institutional sector contributing 15% (Table 1.6). The determination as to what plastic products could be apportioned to the three categories of residential, commercial and institutional waste was based on market sales information, grouping of product types, and assumptions on the part of the project team as to where end use of the plastic product would likely occur [Franklin Associates, 1990].

Table 1.5 U.S. Plastic Disposal, 1988 [Franklin Associates, 1990]

Resin	Total Disposed (10^6 lbs)	Non-MSW Disposal (10^6 lbs)	Non-MSW Disposal %	MSW Disposal (10^6 lbs)	MSW Disposal %
Plastics Disposed Primarily through MSW Route					
ABS	1,093.3	383.1	35.0	710.2	65.0
HDPE	6,528.8	975.3	14.9	5,553.5	85.1
LDPE	7,690.8	577.2	7.5	7,113.6	92.5
PET & PBT	1,475.5	176.2	11.9	1,299.3	88.1
PP	5,274.0	1,016.9	19.3	4,257.1	80.7
PS	4,767.9	529.7	11.1	4,238.2	88.9
Subtotal	26,830.3	3,658.4	13.6	23,171.9	86.4
Plastics Disposed Primarily through non-MSW Routes					
Acrylic	686.0	663.3	96.7	22.7	3.3
Nylon	461.6	329.2	71.3	132.4	28.7
Phenolic	2,975.1	2,869.0	96.4	106.1	3.6
PUR	2,794.8	1,510.7	54.1	1,284.1	45.9
PVC	7,566.0	5,799.4	76.7	1,766.6	23.3
Unsat. Polyester	1,319.3	1,183.0	89.7	136.3	10.3
Urea & melamine	1,459.2	1,346.7	92.3	112.5	7.7
Subtotal	17,262.0	13,701.3	79.4	3,560.7	20.6
Total	44,092.3	17,359.7	39.4	26,732.6	60.6

Table 1.6 Sources of Plastic Disposed in MSW in the U.S., 1988 [Franklin Associates, 1990]

Resin	Quantity Disposed (10^6 lbs)	Residential (10^6 lbs)	Residential %	Commercial (10^6 lbs)	Commercial %	Institutional (10^6 lbs)	Institutional %
LDPE	7,113.6	4,606.5	64.8	1,641.8	23.1	865.3	12.2
HDPE	5,553.5	3,783.3	68.1	1,007.1	18.1	763.1	13.7
PP	4,257.1	2,138.6	50.2	1,439.9	33.8	678.6	15.9
PS	4,238.2	2,308.0	54.5	1,202.5	28.4	727.5	17.2
PVC	1,766.6	1,033.2	58.5	347.6	19.7	385.7	21.8
PET & PBT	1,299.3	664.9	51.2	286.0	22.0	348.3	26.8
PUR	1,284.1	877.1	68.3	260.9	20.3	146.1	11.4
ABS	710.2	229.0	32.2	370.0	52.1	111.1	15.6
Unsat. Polyester	136.3	68.2	50.0	40.9	30.0	27.3	20.0
Nylon	132.4	98.4	74.3	23.6	17.8	10.5	7.9
Urea & melamine	112.5	88.3	78.5	12.5	11.1	11.7	10.4
Phenolic	106.1	63.7	60.0	32.3	30.4	10.1	9.5
Acrylic	22.7	9.1	40.1	5.7	25.1	8.0	35.2
Total	26,732.6	15,968.3	59.7	6,670.8	25.0	4,093.3	15.3

1.3 Mixed Plastics in Post-Consumer Recycling

Plastics recycling programs usually start with the simplest container/package recognized by consumers and then move on to include additional types. In like manner, classifying post-consumer plastic waste collection could initially begin with a few types and expand to include additional plastic products later. In each recycling program, the consumer/homeowner is taught differently how/what to recycle. This can lead to confusion and inaccurate comparisons between separate recycling programs. It is important to recognize exactly what plastic is being collected if comparisons are going to be made.

The following is a list of plastic types collected in differing curbside recycling programs:

Container / Package Type Collected	Resins Involved
Milk jugs (often includes water & juice)	HDPE clear (unpigmented)
Soda bottles	PET clear or green HDPE base cup (colored)
All #1 PET items	Any container labeled with SPI 1 (An extension of soda bottle collection)
Beverage bottles	PET (Typically first HDPE 2 categories)
Detergent and bleach bottles (often includes juice & windshield)	HDPE colored
All #2 HDPE items	Any container labeled with SPI 2 (An extension of milk jug and detergent bottle collection)
All plastic bottles	PET (colored and clear), HDPE (clear and natural), PVC, PP, and some multilayer
All rigid plastic containers (RPC)	PET, HDPE, PS, PVC, PP, multilayer
Any #1 - #7 item	Any plastic labeled with SPI 1 through 7
All RPCs plus film (including plastic bags, film wraps and packaging)	PET, HDPE, LDPE, PS, PVC, PP, multilayer
All clean plastic products	Any plastic emptied of its original contents and rinsed

While there is overlap among the above categories, the list increasingly includes more plastic/product types from top to bottom. Near the bottom of the list, the requirement to identify specific plastic by product type becomes less necessary.

Some recycling programs which are in the middle of the above list (e.g. detergent and bleach bottle category, all plastic bottle category) have lengthy identification/instruction sheets for the homeowner in order to preclude collection of specific containers which are not blow molded (discussed in Part II) or which contain difficult to clean products such as oil containers. The lengthy instruction requirements can lead to non-participation because of homeowner effort and confusion. Confusion can also lead to participants depositing all plastics "just to play it safe." A less confusing approach would be to collect all #1 and #2 bottles, all plastic bottles, or all RPCs, since it has been shown that even a narrowly defined plastic stream (such as plastic beverage bottles) results in a significant portion (>10%) of the plastic deposited not being what was asked for.