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ECONOMIC STUDY OF THE PLASTIC RECYCLING PROCESS BASED ON HYDROCYCLONE TECHNOLOGY

By

Neeracha Manidool

A THESIS

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ABSTRACT

ECONOMIC STUDY OF THE PLASTIC RECYCLING PROCESS
BASED ON HYDROCYCLONE TECHNOLOGY

By

Neeracha Manidool

New approaches for microsorting mixed plastic wastes using hydrocyclone classifier based on density, size, and shape are being developed. This research is therefore try to determine the economic feasibility of using the new approach in the recycling process. This research has investigated its applications and cost reduction opportunities. Its benefits in optimizing the recycling process, replacing several cleaning steps, and using plastic flakes as a material flow, lead to opportunities to reduce collection and processing costs. Cost savings approximately 1.2 cents per pound could come from collection improvements such as using a granulator on the collection truck and collecting more types of plastics. The combined potential cost savings in the processing cost, approximately 26 cents per pound could permit the operating cost of hydrocyclones to be lower than the typical processing cost, therefore making economic sense to recycling operations.

To my parents, for all the years of encouragement

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LIST OF ABBREVIATIONS

HDPE	High density polyethylene
PET	Poly(ethylene terephthalate)
PP	Polypropylene
PS	Polystyrene
PVC	Poly(vinyl chloride)
LDPE	Low density polyethylene
LLDPE	Linear low density polyethylene
MSW	Municipal solid waste

CHAPTER 1

INTRODUCTION

1-1. Background

Although plastic recycling is a major consideration in most waste management plans, the amount of recycled plastics and the recycling rate is relatively small. This is because residential plastics recycling has remained limited and most programs accept few types of plastics, namely PET and HDPE. Other types of plastics remain in the waste stream and are finally discarded into landfill. The major problem that discouraged recycling operations is the high cost of collection and processing. Plastic packaging material may give us a tremendous advantage due to its light weight. However, from the recycling standpoint, the high volume/weight characteristics of plastics packaging are a serious drawback. This factor results in an uneconomical collection since the weight per load from the collection vehicle is small. To help overcome this challenge, the evaluation of existing collection vehicle-mounted equipment for plastics densification is needed.

On the sorting side, current plastic separation is labor intensive because the separation is normally done by hand sorting. Manual sorting is not only expensive, but also results in high error and slow production rates. Moreover, manual sorting is unable to support the requirement for high capacity and unable to cope effectively with the complexity of mixed plastic wastes. To improve the efficiency of the sorting process and to reduce its costs, automated sorting systems are replacing manual sorting. Automated separation techniques basically fall into two categories, macrosorting and microsorting. Macrosorting can be defined as separating plastic wastes in its existing form. Microsorting is the separation of material that has been reduced by shredders, or granulators. This separation is usually based on some physical property differences such as density. Most current automated systems are still in developing stages and have limited applicability to separate certain types of plastics.

1-2. Problem Statement

Hydrocyclone technology is one of the microsorting techniques that could separate mixed plastic chips, based on differences in density, shape, or size. For this reason, it could offer a direct solution to reduce the labor expenses in the sorting process as well as increase the capacity of the process. Besides the sorting process, hydrocyclone technology could improve the collection and shipping process. Since the hydrocyclone system is able to separate plastic flakes, it is possible to granulate the mixed plastic wastes during collection to reduce the required space on the truck, and to transfer plastic wastes in the form of flakes. Obviously, hydrocyclone technology could solve many problems in the recycling process.

Conventional hydrocyclones are being used to make separation in some plastic waste streams. This type of separation can separate light materials such as PP and HDPE, from heavy materials such as PET and PVC. However, one challenge has been in case where differences of density between plastics do not exist. There is no commercial hydrocyclone technology that is available to further separate either the light or the heavy fractions. A project at Michigan State University is developing two new approaches using hydrocyclones to separate mixed thermoplastic based on differences in density, size, and shape. The first approach is a light medium hydrocyclone, using a suspension of glass microbubbles in water to separate HDPE from PP. In another approach, PET and PVC, which have no significant density difference, can be separated in hydrocyclones based on differences in either size or shape. These new microsorting processes are expected to have many applications in the recycling process. A study to prove its economic benefits is needed.

1-3. Objectives

The major objective of this research is to determine the economic feasibility of using hydrocyclone in the recycling process. The study will provide a framework on how and where this new hydrocyclone technology might fit in the existing recycling process, and to identify cost reduction opportunities from using hydrocyclones in the recycling process. The subobjectives for this study are:

1) Determine the typical recycling process and propose the places where a hydrocyclone system might fit in the existing recycling process.

2) Determine cost reduction opportunities in collection and processing from using hydrocyclone technology

3) Estimate potential cost savings in operating cost of using hydrocyclone technology.

CHAPTER 2

LITERATURE REVIEW

2-1. Plastics Consumption and Production

The first commercial plastics were developed only about a hundred year ago, but the plastic industry grew rapidly and plastic became a major consumer material. Now plastics have not only replaced wood, leather, paper, metal and glass, but also have been used to develop new types of products. As plastics have found more markets, the amount of plastics produced in the United States has significantly increased from 18 billion pounds in 1983 to approximately 77 billion pounds in 1994 (Modern Plastics, 1995).

The major market destinations of plastic production are shown in Table 2-1, with a detailed breakdown of plastic uses in the packaging industry. Consumption of the most important thermoplastics is led by the packaging industry, which accounts for 19 billion pounds. Plastic packaging materials are composed of a variety of resins and resin combinations. The amount of plastics used in packaging in 1994 is also summarized in Table 2-1. HDPE, LDPE and LLDPE

Table 2-1 U.S. Resin Distribution by Major Market,1994

Market	Quantity million pounds	%Share
Total	49,616	
Appliance	1,557	3.1
Construction	15,000	30.2
Electronics	2,253	4.5
Automotive	9,000	18.1
Medical	2,400	4.8
Packaging	19,406	39.1
PET	2,030	10.5
HDPE	6,339	32.7
LDPE	3,381	17.4
LLDPE	3,617	18.6
PP	2,034	10.5
PS	1,137	5.9
PVC	348	1.8
Nylon	93	0.5
Epoxy	28	0.1

Source: Modern Plastics Encyclopedia 1996 make up about 60 percent of the total plastics used in the packaging industry. About 600,000 tons of plastics go into films and coatings in the U.S. each year, while 450,000 tons are used for containers, and another 70,000 tons go to the production of closures (Bonis, 1994). The same report indicated that about 55,000 tons of plastics are employed in packaging-related adhesives.

2-2. Market Growth

In 1987, The Society of the Plastics Industry(SPI) performed a market forecast study (Curlee, 1990). This research examined the historical growth rates in the major plastic markets and developed future growth forecasts to the year 2000. The SPI estimated that future growth rates among the end use markets until the year 2000 would vary from 2.4 percent in the adhesive and coating market to 4.0 percent in the transportation industry. The annual market growth for plastics in the packaging industry was estimated to be 3.6 percent. However, since then, plastic markets have grown at a faster rate than projected. The recent data from Modern Plastics reveals that the actual U.S. plastic usage is growing at about 6 percent annually as opposed to under 1 percent for paper and 1.5 percent for foil (Schroeder, 1996). The same report estimated that plastic bottle growth is about 4 percent annually. Some materials such as PP, PET, and HDPE have demonstrated strong market growth. The PP market has been growing at a 7 percent average annually since the early 1980s, while HDPE and PET have an average rate of 10 percent.

2-3. Plastics in Municipal Solid Waste

The U.S. Environmental Protection Agency (EPA) 1989 Agenda for Action report states that municipal solid wastes (MSW) come from residential, commercial, institutional, and industrial sources (Mustafa, 1993). More precisely, MSW include those wastes typically collected in household refuse, as well as similar materials from commercial, office building, wholesale and retail trade establishments, and industries. Other kinds of wastes, such as sewage sludge, combustion waste, nonhazardous industrial wastes and construction and demolition wastes, are not included in this definition.

Plastic wastes may enter the solid waste stream from two major sources: residential and commercial sources. They vary accordingly in characteristics. Residences were identified as the primary source of plastics in the MSW stream, accounting for 55 to 65 percent of the plastics disposed, followed by the commercial sector which account for 45 to 55 percent (Franklin Associates, Ltd., 1995). In "Characterization of Municipal Solid Waste in the United

States: 1995 Update", Franklin Associates, Ltd. reported that plastics accounted for 9.5 percent of the total MSW generated. The contribution of plastics in MSW increased steadily from 400,000 tons in 1960 to 19.8 million tons in 1994.

The report estimates that plastics currently account for 9 percent by weight of the landfill, and nearly 20 percent by volume. The packaging industry is the largest single source of plastic wastes due to a large consumption and a short life cycle of packaging products. In 1994, it was estimated that plastic waste from packaging reached approximately 9,490 thousand tons or about 48 percent of all the plastics wastes.

2-4. Why Plastics Recycling

From the information about the production and consumption of plastics, and the level of plastics in the waste stream, it is obvious that the national trend of increasing plastic usage may cause serious problems to waste disposal operations. Landfilling has been the predominant disposal method for MSW. In 1995, 57 percent of MSW was landfilled (Boucher, 1997). However, the United States is now facing a dwindling landfill capacity and an increased flow of MSW for disposal. As the environmental problems of improperly designed and sited waste disposal facilities become more apparent and existing disposal reaches capacity, new standards for environmental protection and a revolution in the policy and practice of how we handle the waste have been initiated. The hierarchical four **R**'s approach to waste reduction, *reduce, reuse, recycle and recovery,* appears to be the most logical and promising framework for the management strategy (Mustafa, 1993).

Source reduction is the most straightforward and effective approach, and has emerged as the top solid waste management priority. After source reduction, *reusing* existing material resources is the next best way to control waste production. Well-known examples of this strategy include reusable packages such as refillable beverage bottles. The next step is *recycling* which uses waste materials in place of virgin materials to manufacture new products. The last alternative is *energy recovery* such as incineration and the Refuse Derived Fuel method (RDF).

Among the four methods, recycling gets the most attention because it is becoming legally mandatory throughout the nation. In the regulation proposed under the federal Clean Air Act, the EPA addressed the goal of managing 25 percent of the solid waste through recycling and composting (Lund, 1993). Recycling legislation is on the move in many states. In 1992, 41 states and the District of Columbia had comprehensive recycling laws and set a goal to recycle from 15 to 50 percent of waste by the year 2000 (Lund, 1993). Solid waste recycling also produces a new infrastructure for collection services. In 1995, there were about 7,375 curbside recycling programs throughout the nation, serving 121 million population (Steuteville, 1996).

In addition to the legal factor, the facts that recycling significantly conserves both material and energy, and provides a simple way to make a substantial reduction in the overall volume of waste gets attention from every sector. It is believed that recycling offers significant opportunities to reduce waste by up to 50 percent of the municipal waste stream (Mustafa,1993). Since most of the energy required in producing plastic products goes into the production of feedstock material, plastic wastes retain most of their original energy content. Thus, producing plastic products from scrap plastic instead of virgin plastic saves approximately 85-90 percent of the energy used. Moreover the economics of plastic recycling can be attractive. It is not a capital-intensive operation and can be integrated easily with existing processes. Recycling of plastics will reduce the raw materials cost to manufacturers and reduce the cost of disposal into the solid waste stream. Dupont estimated that a new PET resin plant would cost between $1.25 and $1.50 per pound to build, while a recycled resin plant would cost about $0.50 per pound to build (Richards, 1989).

Recycling of post consumer plastics is unfortunately limited by the absence of a strong recycling infrastructure, such as the lack of economical recycling programs, the scarcity of large scale recycling operations capable of handling mixed plastic wastes, and the lack of steady and demanding markets for recycled plastics. However, the type of economic benefits mentioned make recycling plastics an attractive investment. There are also some other driving forces that are accelerating and expanding the demand for recycling plastics.

1. Increased Landfill Charges: A landfill charge or tipping fee is a fee for unloading or dumping waste at landfill facilities or at transfer stations. In 1995, the cost for landfills in the U.S. was between $17 and $56 per ton, depending upon location (Steuteville, 1996). The weight average tipping fee at landfills nationwide was about $34 per ton, an increase of $3 per ton from the previous year. High landfill charges will be a powerful economic driving force to make recycling occur faster. The avoided cost of disposal or cutting the landfill charge offers a saving to recycling costs.

2. Legislation that mandates products contain recycled material: Like the successful legislation requiring recycled content in newsprint, the government is moving towards mandating recycled plastic content in products. Laws are prominently seen in California, Oregon, Virginia and Wisconsin (Guettler, 1993). In California, the law requires plastics to meet a 25% recycling rate by 1995, or all containers must meet one of several options: contain 25% post-consumer recycled content, 10% source-reduced, or reusable five times (Raymond, 1995). Oregon has a law similar to California's for rates, options, and dates on rigid plastic containers. If product manufacturers are legally forced to buy recycled material, they will have to pay the market price. Consequently, recycled materials could actually be priced higher than virgin materials. This is an attractive benefit that will drive the recycling industry.

3. *Market demand for recycled content materials:* To respond to public environmental concerns, product manufacturers realize that using recycled content material in their packaging could give them a competitive edge. They will design their package to include recycled materials. The package maker will then be forced to use recycled material rather than virgin material. This will drive the demand for recycled material up and eventually drive the economics of the recycling industry.

2-5. Current Level of Plastic Recycling

In comparison to the production level and the amount disposed in MSW landfill, a relatively small amount of plastics is recycled on an annual basis. In 1994 approximately 930,000 tons, or 4.7 percent of plastics generation was recovered from MSW (Franklin Associates, Ltd., 1995). Table 2-2 demonstrates the amount of plastics in MSW and recovery rate by resin. Plastic beverage bottles were recovered at a higher rate than any other categories, approximately 50 percent for soft drink bottles (mostly PET) and 30 percent for milk bottles (HDPE).

The usage of recycled plastics in packaging is increasing around 14 percent a year as a result of increased demand and collection (Schroeder, 1996). Recycled PET and HDPE combined account for 70 percent of the total recycled plastics. However, the market price fluctuation has a major impact on the demand rate for recycled PET and HDPE. Due to an increasing rate of the supply higher than that of the demand, industry observers thought that the usage of recycled PET and HDPE could be flattening out, resulting in a fallen recycling rate in 1996 (Lynch, 1996).

2-6. Problems in Plastic Recycling

Even though plastic recycling is now a major public concern, it is a fairly new field. A small amount of

Table 2-2 Plastics in Municipal Solid Wastes and Recovery Rate in 1994

Plastics in MSW	Generation Thousand tons	Discards Thousand tons	Recovery Thousand tons	% Recovery
PET	1,130	780	350	31.0
Soft drink bottles	640	320	320	50.0
HDPE	3,900	3,550	350	9.0
Milk bottles	570	400	170	29.8
PVC	1,440	1,440		
LDPE	5,700	5,620	80	1.4
PP	2,530	2,420	110	4.3
PS	2,560	2,530	30	1.2
Others	2,580	2,570	10	
Total	19,840	18,910	930	4.7

Source: Franklin Associates, Ltd, 1995

plastics is recycled comparing to the level of production and consumption. The reason is that current recycling systems and technologies employ the input of relatively homogeneous recycled resin such as PET soda bottles and HDPE milk jugs. There have not been many attempts to recycle mixed plastics wastes. In a report to Congress about methods of managing and controlling plastics, EPA addressed four basic factors that slow the growth of the recycling industry (Hegberg, 1992).

1. *Varieties of plastic wastes:* Plastics in MSW are a very heterogeneous collection of materials, which consist of a broad range of resins and a combination of resins. This heterogeneous nature significantly affects the recycling process. Because of this along with the amount of contaminants present, the separation of post-consumer mixed plastic wastes is very difficult.

2. *Difficulty of sorting plastic resins:* It is technically difficult to separate a relatively pure single resin from the mixed plastics collected. Commercially, recycling technologies are most focused on separating PET soda bottles and HDPE milk jugs.

3. *Low density of post-consumer plastic wastes:* Plastic occupies a high volume/weight ratio compared to other recyclables. The weight contribution of plastics to MSW is relatively small, even though the landfill volume

occupied by plastics is large. This fact adversely affects the practicality of plastics collection programs and the economics of transporting recycled plastics to processors.

4. 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.

In order to expand recycling of plastics beyond the easily recognized soda bottles and milk jugs, it is necessary to overcome these problems. Eventually, the recycling system will efficiently function in both economical and practical aspects.

2-7. Components of Recycling Program

For any recycling system to be successful, there are five basic steps that must be in place (Council for Solid Waste Solutions, 1992). These steps are:

1. Collection
2. Separation of the material into a generic type
3. Reclamation or reprocessing into densified form of consistent quality acceptable to manufacturer
4. Use in the manufacture of products or containers
5. Purchase by consumer.

Curbside recycling, the new method for collecting recyclables from households, has been introduced to waste management practice in order to assist recycling. Curbside recycling is growing at a tremendous rate. In 1995, it was estimated that about 121 million people, or 46 percent of the U.S. population, were participants in curbside recycling (Steuteville, 1996). Many curbside recycling programs have been developed across the United States, but there is no one program that will work for every community. The reason for this is the differences in the geography of each community and the large variables in each recycling program. Such variables include recyclables collected, method of sorting, participation rate, collection frequency, collection time and crew size.

The economic benefits from recycling come from the value of recycled materials. The quality of material processed from the waste stream has a major impact on its value. The fewer impurities in a recycled material, the higher value it is. In the case of plastics, the value of recycled plastic depends on its quality or purity, and its form. For example, in 1997 the price of baled, single color HDPE was reported at 28 to 35 cents per pound which is higher than the price of baled, mixed color resins (14 -18 cents per pound). The pellets of recycled clear PET can be sold at 35 to 40 cents per pound, while the flake form sells at a lower price of 25 to 30 cents per pound (Plastics News, 1997).

The major processes to obtain high qualities of recycled plastics are collection and sorting. These two processes present the major cost of recycling programs as well. The following topics present the general concepts of existing collection and sorting processes, and also the trend of technology in both processes.

2-8. Recycling Collection

Many alternatives are available for recycling recyclables from the waste stream, such as curbside collection, curbside home sorted, buy-back center and voluntary drop-off. A study by the Center for Plastics Recycling Research (CPRR) indicated that the recovery rates from drop-off and buy-back methods are 10 to 25 percent, while curbside collection obtained a higher recovery rate of 70 to 90 percent (Pearson, 1989). Thus, most attention is given to curbside collection due to its high recovery rate compared to other recycling methods.

Curbside collection can be achieved in four ways (Apotheker, 1990). Each method places the primary responsibility to complete the material separation on a different party. The first method is source separation, in which households are asked to separate recyclables before putting them at the curb. The collector does not have to sort materials at the curb. The second method is curbside separation, which refers to the process when collectors receive the commingled recyclables that residents put at the curb. The collector then sorts the recyclables into each category at the curb and puts them in the compartmentalized collection vehicle. The third method is commingled material collection. This method tries to put as little sorting responsibility on the collector as possible. The fully commingled collection puts the entire burden on the processing facility. Some commingled collection requires collectors to place recyclables into two categories, instead of multiple categories. The last method is co-collection, which involves the pickup of separated, bagged recyclables at the same time as picking up garbage.

It is believed that curbside separation can avoid processing cost due to the low levels of contamination; however it does slow the collection process. In a timing study, communities that conducted curbside separation had an average of more than 30 seconds per stop with 5 separations. These same communities could reduce time per stop between 7 and 10 seconds with commingled collection (Bullock, 1989). Time savings resulted in extending route sizes substantially. Another problem with curbside separation is the unbalance of the fill up time of each compartment. A study in San Diego, California showed that two glass compartments were only 35 percent full when the compartments for paper and mixed plastics containers were 90 percent full (Apotheker, 1990).

In summary, commingled collection is thought to have four benefits over source separation (Bishop, 1991):

1. It reduces sorting requirements to householders; that means more convenience for them.
2. It reduces collection costs because of the faster rate of collection (but increasing processing costs due to the need to perform sorting and cleaning tasks).
3. It can collect higher volumes of recyclables from households because of a longer route for the collection truck.
4. Because of more convenience provided for householders in recycling, the participation rate could increase.

Although commingled collection offers many benefits, the contamination levels from this method are high, resulting in the necessity for a more extensive and more expensive cleaning process.

The trend of collection programs is towards commingled collection. It is believed to be the most cost-effective way and to yield the maximum recovery rate. A study with a computer model showed that commingled collection cost was approximately 65 dollars per ton or about 27 percent cheaper than five-way curbside separation (Jacalone, 1992). The ideal collection program is thought to be a weekly curbside commingled collection on the same day as garbage collection, in dedicated single-driver recycling vehicles (Moore, 1992). Nevertheless, the collection volume is still a big problem in commingled collection. The commingled recyclables present high volume/weight ratios, especially when adding plastics into collection program. Plastics represent approximately 18 percent of the total weight of commingled recyclables collected, but represent half of the volume of the commingled recyclables collected (Merriam, 1993).

Current innovations aim at reducing the volume of plastics by compacting or grinding during collection (Hegberg, 1992). The study conducted by CPRR in Highland, New Jersey found that gently compacting the commingled rigid plastic containers with the compacting machine reduced the collection volume by 35 percent (Merriam, 1993). Currently, a study of 5 light packing recycling collection trucks indicates the volume reduction ratio of recyclables could run from 2:1 to 4:1 (Anderson, 1996). The program in this study collected recyclables into two categories: paper and containers. Most trucks have a similar compaction motion as in the sideloading trash packer, with a packing blade in the front of the box behind the cab. Grinding is expected to give a better result in reducing the volume but this aspect is limited by the current separation technology. It is not yet possible to separate mixed resins into homogeneous resin after grinding (Hegberg, 1992). However, there are many developing technologies to support the recycling program that collects commingled recyclables and separates them after compacting or grinding. This will be discussed in the next section.

Other innovations are being made to lessen the degree of labor intensity in collection. Several municipalities in the U.S. are in the process of evaluating the possibility of switching from conventional collection to either semi- or fully automated collection (Diaz, 1993). Semi-automated collection requires the crew members to transport containers to the collection vehicle, whereas fully-automated collection does not require the crew members to come into contact with containers. With both methods, a hydraulic device is used to grab the container and discharge its contents.

2-9. Sorting and Processing Plastic Wastes

It is typical to manually sort mixed plastics and bale them by generic types. However, manual sorting is being phased out due to the following disadvantages.

Manual sorting is labor intensive and expensive. The average labor wage is between $7 to $10 per hour (Hegberg, 1992). In some case, labor expense can result in sorting costs of more than $100 per ton of plastics processed.

Manual sorting has a limited production rate. It is estimated that one sorter can sort 1 to 6 bottles per second with a conveyor belt station. A one bottle per second pick speed with an average bottle weight of 0.14 to 0.15 pound per bottle results in a process rate of 500 to 550 pounds per hour (Hegberg, 1992).

Manual sorting produces many errors. It is difficult for the sorter to separate plastics which look alike, such as clear PET and non color PVC bottles.

These disadvantages are the driving forces motivating the change from manual sorting to automated sorting. Automated sorting can be classified into macro- and microsorting (Lund, 1993). Macrosorting involves separating plastics based on the whole form of the product such as a container. This method includes separation by using optical sensing. Microsorting, such as electromagnetic screening, air classifier and sink/float techniques, involves separation of plastics by type after they have been shredded or ground into small pieces. Microsorting is one of the fastest growing segments of plastics recycling. Several private firms and universities are now testing and developing more efficient automated systems. The current trend is to develop automated system for separation of mixed plastic wastes. The following topics present the general concepts of some current automated systems.

2-9.1. Separation by Using Detectors

Some systems are designed to sort bottles which look alike such as clear PET and non-pigmented PVC, while others are designed to separate all types of plastic bottles, including types and colors. Detectors fall into four categories: X-ray, single wavelength infrared, full spectrum infrared, and color (Powell, 1992). The sorting devices have similar features. Baled bottles are broken open and the containers are declumped. Non-plastic materials are then screened off. A variety of mechanical techniques are used to form the single stream of containers, which will pass through a sensing device. The sensing device determines a plastic container within a few milliseconds and mechanical devices are used to either let containers pass or eject them from the feed stream. In most cases, a burst of compressed air is used in the rejection mechanism.

The leading companies of PVC sorter technologies are Asoma Instrument, Inc. and National Recovery Technologies (Dinger, 1994). The leading companies in separation of all type of plastic containers are Automated Industrial Control(AIC) and Magnetic Separation Systems (MSS), Inc. The Polysort system developed by AIC uses an optical scanning device interfaced with a 486 based microprocessor to detect and analyze the color of the bottles. In addition, the system can be programmed to disregard labels on bottles. The system requires about 19 milliseconds to determine each generic type of plastic. The standard system is claimed to sort up to 1500 pounds per hour of compacted bottles (Dinger, 1994). Another system from MSS, Inc. consists of six steps in operation: debaling, screening, singulating, sensing, separating and electronic controlling (Morgan, 1992). Although the systems ensure high production rates, the systems themselves are complicated and require a well-trained worker to operate and maintain the system. In addition, many system developers reported problems during operation, such as difficulty in debaling and singulating compacted bottles, problems in matching the front-end capacity to the sensor capacity, and problems with the rejection mechanism due to the very flat and thin compacted bottles (Powell, 1992).

Flake separation technology using detection is a new wave in this area. Microsorting of plastic flakes by using optical scanning was introduced by Simco/Ramic of Medford, Oregon and by Massen Vision Systems of Konstancz, Germany (Leaversuch, 1993). The system works based on the separation of dark from light particles, followed by the separation of different colors. Similar technologies are being developed by Plastics Resin Separation Expert of Anderson, South Carolina (Mustafa, 1993). The optical sortation system recently developed by ESM International, Inc. is able to separate opaque from natural HDPE and green from clear PET in both flake or pellet form (Knights, 1995). Currently, optical-based systems dominate the plastic flake separation market (Apotheker, 1996). They are primarily used for color sorting single resins, such as separating green PET from the clear PET. Also, the technology can be used to separate resins, such as removing colored PP from natural HDPE or sorting black HDPE base cups from lighter colored PP caps. The throughput ranges from 2,000 to 7,000 pounds per hour.

2-9.2. Separation by Using Selective Dissolution

Selective dissolution involves the separation of mixed plastics on a molecular scale by dissolving plastic mixtures in the solvent. The dissolution process can be conducted in two ways: using one solvent for all resin types or using one solvent for each type of resin (Hegberg, 1992). The multiple solvent process is claimed to have an energy saving advantage over the single solvent process due to using lower temperatures and pressure. A technology based on the differential dissolution of plastics was developed at the Rensselear Polytechnic Institution (RPI) in Troy, New York, based on the work of Lynch and Nauman (Mustafa, 1993). Their concept is to use the same solvent at different temperatures to dissolve different plastics and then flash evaporation to recover each type of plastic. The work studied a coarsely ground mixture of LDPE and HDPE, PS, PVC, PP and PET, and used xylene as a solvent. The other solvents considered were dichloromethane, methylene chloride and tetrahydrofuran. The temperatures in the reactor range from 70 ^{0}C for PS to over the boiling point of xylene (135 ^{0}C) for PET. However, this technique involves a significant capital investment to achieve an economical scale, and also generates chemical solvent waste. Thus, it has not been commercialized.

2-9.3. Separation by Using Differences in Density

Early technology in this field was developed from the mining industry, where materials were separated from each other by employing differences in density (Lund, 1993). The sink/float technique is a common separation technique in this area, especially for separating HDPE base cups from PET soda bottles (Mustafa, 1993). This method simply separates the heavier-than-water materials from the lighter-than-water materials. Separation technologies based on the same principle were reported by the U.S. Bureau of Mines using a different floatation medium (water, calcium chloride and alcohol solution) to separate LDPE, HDPE, PP, PS and PVC (Mustafa, 1993). In addition, the substitution of supercritical fluids for water in the sink/float technology shows promise. Near critical and supercritical fluids composed of carbon dioxide and sulfur hexafluoride have been used in separation of PET and PVC (Beckman, 1992).

Another technology based on density differences is hydrocyclone technology. It is believed that this technique is more efficient than the conventional sink/float technique (Bradley, 1965). The simplicity and the versatility in application of a hydrocyclone makes it an attractive separating tool. Also, it requires much less space than the former technique. While the sink/float technique uses the effect of gravity (non-hydrodynamic condition), hydrocyclones use centrifugal forces to accelerate the gravitational separation. Hydrocyclones can also exploit acceleration effects caused by size and shape differences of particles. In its separation mechanism, the lighter particles than the continuous phase (medium) are forced to migrate toward the axis of a flow of the vortex. Heavier particles than the continuous phase migrate toward the outer region of the vortex. Therefore a classification between light and heavy particles can be accomplished by removing the core fluid and the outer fluid as two separate streams. A schematic of a hydrocyclone is shown in Figure 2-1.

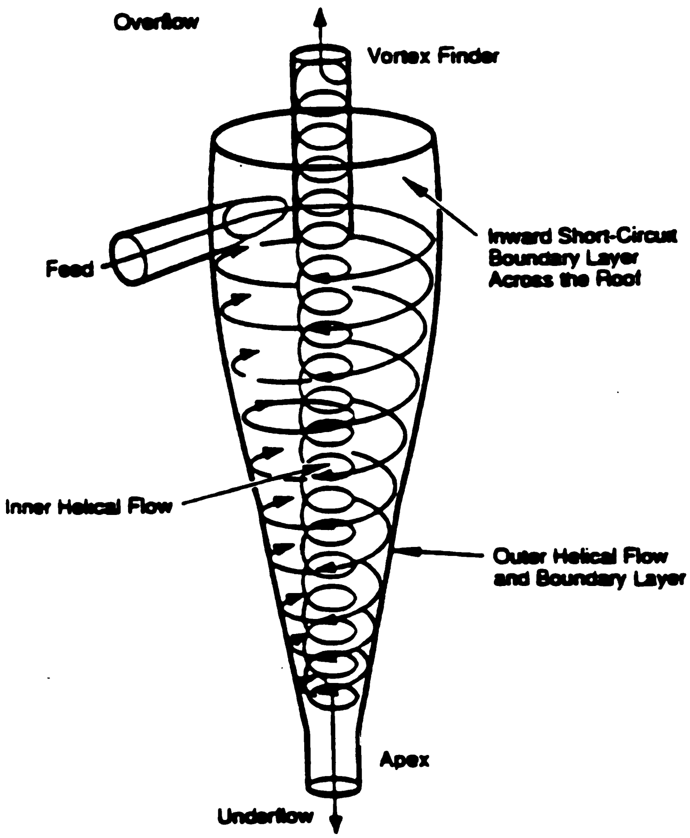

Figure 2-1 Schematic of Hydrocyclone

Hydrocyclone technology has a wide range of applications in the chemical, food, and mineral industries (Bradley, 1965: Svarovsky, 1992). It has been developed to remove plastic material from aqueous pulp suspensions and from water (Colman and Thew, 1983). In 1989 the Center for Plastics Recycling Research at Rutger University developed a beverage bottle reclamation process to separate PET soda bottles from HDPE-base cups (Hegberg, 1992). The process includes several cleaning steps including the use of a hydrocyclone to separate the light components (HDPE base cups and bottle labels) from the heavy components (PET and aluminum bottle tops). However, many plastics have densities ranges which overlap, for example PET and PVC. Traditional hydrocyclone separation based on density differences could not be used. More sophisticated techniques are being developed by many sectors to separate heavier-than-water resins or lighter-than-water resins from each other.

At Michigan State University, hydrocyclone classification processes for mixed recycled plastic bottles by managing the size and shape distributions of a mixed suspension of granulated plastics are being developed (Petty etal, 1993). The study is investigating the use of a light medium hydrocyclone for a sharp separation of light materials, namely HDPE and PP, which have densities less than water. A suspension of glass microbubbles in water was used as an effective medium for this separation. The study found that glass microbubbles, having an effective density of $0.93g/cm^3$, enhanced the separation of HDPE and PP. The PP-resin was removed with the overflow stream and the HDPE-resin was removed with the underflow stream. Figure 2-2 presents a schematic of a light medium hydrocyclone. The glass microbubble residue in the recovered plastics was found to have only a small effect on all properties tested (Akashian, 1994). Another system being investigated consists of PET and PVC, which have similar densities. Modifying the shape and size of PVC and PET by a controlled grinding technique is needed in order to aid the separation in a hydrocyclone.

2-9.4. Separation by Using Cryogenic Grinding

This technology is based on the theory that thermoplastics fracture differently at different temperatures (Lund, 1993). When plastics are ground at temperatures below 0 ^{0}C, they form different size particles, which can be separated by simple screeening. This technology has gained interest in the past few years. Separation of PVC from other plastics and paper contamination using granulating under cryogenic conditions was successfully developed by Cryogrind Corporation in Australian (Mapleston, 1991). After grinding with liquid

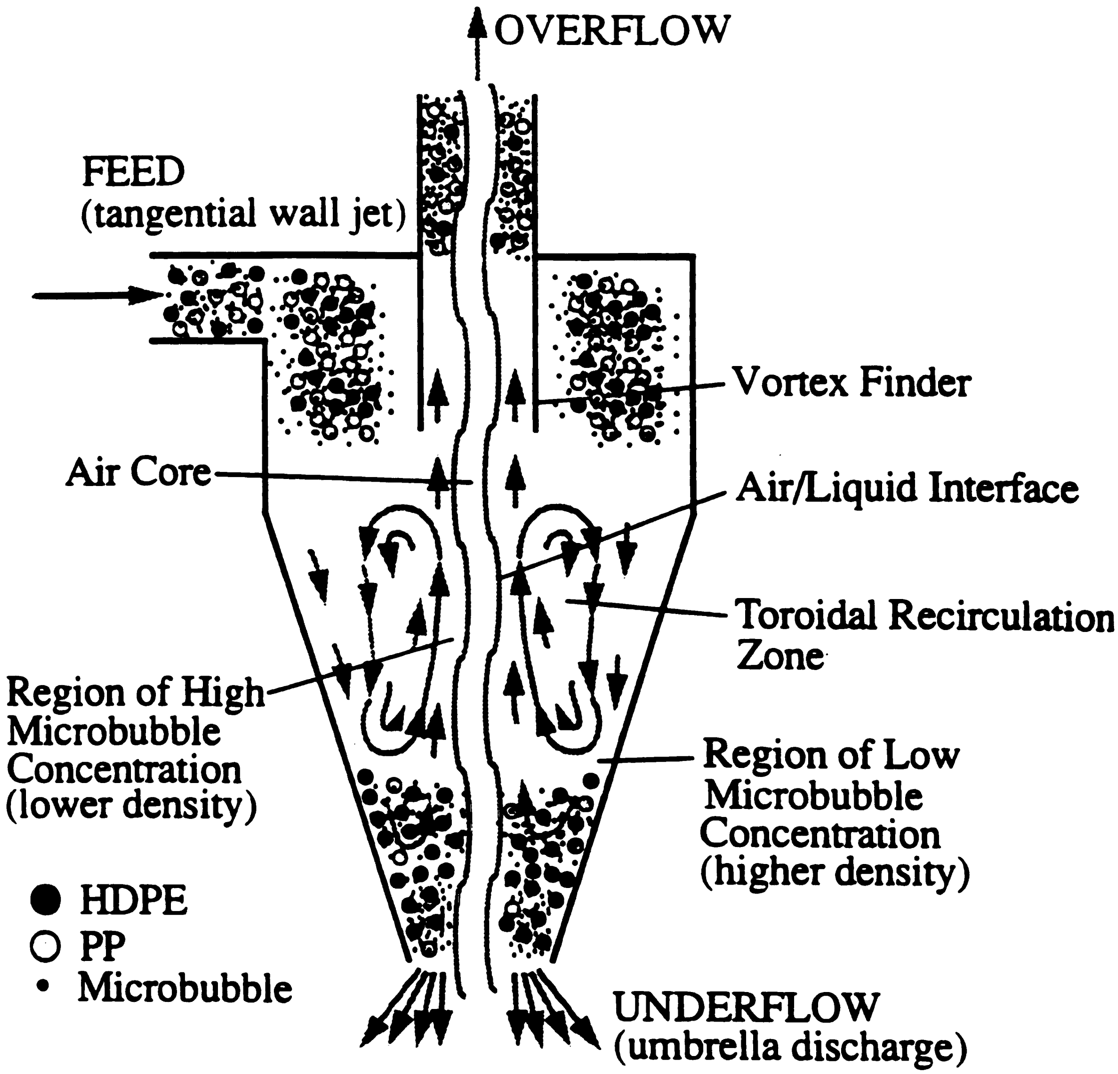

Figure 2-2 Schematic of Light Medium Hydrocyclone (Carlson, 1995)

nitrogen at temperature below -100 ^{0}C, PVC particles, which are less than 500 microns in size, are removed by screening from PET and other contaminants. Another development from Ultra Pac Inc. uses cryogenic conditions to remove PVC from PET and HDPE (Schult, 1993).

A study of selective size reduction of PVC and PET by impact grinding revealed that at cryogenic temperatures, PVC can be selectively ground to smaller particle sizes than PET (Green, 1996). This is due to PVC particles fracturing in a brittle fashion, while PET fails in a ductile fashion. Therefore separation of the two materials based on size differences is possible. The results of this study are being used to support the separation of PVC and PET using hydrocyclone technology.

2-9.5. Separation by Using the Difference of Melt Temperatures

The principle of this technology is that mixed granules of resin travel on a conveyor belt through a chamber heated to a temperature which lets one type of resin fall off at the end of the conveyor, while the other type sticks to the conveyor (Mustafa, 1993). This technology is well developed in Europe. Refakt of Germany is using this principle to separate PET from PVC. The Swedish National Waste Department is developing a similar process which offers higher production rates. However the results from their process were not satisfactory because of the very limited allowable amount of contamination of the PET stream.

2-10. Recycling Costs

The cost of recycling can be determined from three essential components of recycling programs. The first two components, collection and processing, require an expenditure of funds, while the revenue comes from marketing of recyclables. Savings from the avoided cost of disposal are another way to gain revenue. Any programs with a cost for collecting and processing which is less than sales revenue plus avoided cost are considered to be profitable. Generally, the concept for determining recycling cost was suggested to be: (Curlee, 1990).

Recycling cost	=	Revenue from sale of recyclables
(or profit)	+	Avoided cost of disposal
	-	Cost of collection of recyclables
	-	Cost of sorting/processing recyclables

The cost of recycling may be expected to add 10 to 25 percent to the existing refuse disposal cost (Hegberg, 1992). Since the major processes necessary to obtain high quality recyclables are collection and sorting, these two processes represent the major cost of recycling. In a carefully planned and efficient recycling program, it is quite common for the disposal fee plus the revenue from selling recyclables to exceed the cost of collection and sorting. The Center for Plastics Recycling Research study confirmed the economical benefit from adding recycling into the normal refuse collection (Pearson, 1989). The report also indicated that the inclusion of plastics into recycling programs was economical, although the collection costs increased.

In 1992, the study of recycling cost versus disposal system cost in four Washington cities, differing in geographic, demographic and collection/marketing approaches, showed the net average cost per ton of recycling was lower than the cost of disposal (Bogert, 1993). The results also determined that the cost of recycling was still less than disposal system cost, even when the revenue from selling recyclables was excluded. In most recycling programs, the collection cost was more expensive than for refuse collection. The reason was the necessity for careful handling and separation during collection in order to maintain material quality and value.

Today, there are many recycling programs across the United States but each program has some differences depending on its geography, demography and the recycling policy. It is therefore difficult to address the common cost of recycling programs. It was stated that case-by case examination was necessary to identify the recycling cost and the best recycling method (Crampton, 1993). The following topics introduce the general concepts of costs that are relevant to recycling programs, mainly collection costs and processing costs. These topics also discuss important factor, which will affect the cost of each component.

2-11. Collection Costs

The collection cost is the largest element of recycling program cost, comprising about 50 to 70 percent of the total cost (Gold, 1988). Collection costs vary significantly among programs. These differences are attributed to variables such as the amount of material collected, the amount of curbside separation performed, collecting frequency, collection crew size, and the type of collection truck. A study on the cost estimation of recycling options, which varied collection frequency, collection day and collection devices, reported ranges from $112 to $170 per ton (Hegberg, 1992). In 1990, the Council for Solid Waste Solutions cooperated with Research Integration System to conduct an in-depth collection analysis of 18 curbside recycling programs (Perkins, 1991). The results showed a wide range of collection costs, from $35 per ton in

Portland, Oregon to $199 per ton in Phoenix, Arizona. If the cost is calculated on each material's weight basis with the exclusion of revenue, average collection costs can be low as $50 per ton of paper collected to as high as $969 per ton of plastics collected (Siegler, 1994). To determine collection cost, two broad categories must be accounted for: operating cost and capital cost. Operating costs involve regular expenses such as labor wages, vehicle maintenance costs, and promotion costs; while capital costs involve one-time expenses such as collection vehicle costs and plastics densification equipment costs. Labor cost is the largest component of collection cost, approximately 40 to 50 percent, followed by capital cost, which is mainly for vehicles, and then operation and maintenance costs (Gold, 1988).

Collecting plastics for recycling represent a difficult economic challenge because the density of plastics is low. This means that the trucks carrying uncompacted plastics are carrying a lot of empty space. Therefore collection of undensified plastics may not be economical. In Rhode Island, it was expected that adding plastics to curbside collection programs would result in an incremental cost of $54 to $108 per ton of plastics collected (Lamp, 1990). The Council for Solid Waste Solutions conducted an impact analysis of plastic collection on existing curbside recycling programs in Minneapolis, Minnesota. Adding plastics to the existing programs resulted in an additional cost of between $0.72 and $4.32 per household per year, depending on the option chosen (Hegberg, 1992). There are, however, many attempts to develop plastics recycling collection in the most cost-effective way since there are a number of cost-sensitive factors that can be evaluated. The important factors, which must be taken into account, are:

A. Participation Rate

Participation rate is defined as the percent of households on the given route that regularly set out recyclables (Lund, 1993). With a low participation rate, travel time between stops will be greater and the amount of collected recyclables will be lower than with a high participation rate. The cost per household and the cost per ton of recyclables collected decrease as the participation rate increases (Stevens, 1988). The key to increasing participation is education. Additionally, education improves the quality of the recyclables collected by reducing the level of contamination (Glen, 1992).

B. Collection Time

The time it takes to collect recyclables has a direct impact on the economics of curbside collection. Minimizing the time spent at a stop and the total time needed to collect recyclables will result in greater program efficiency (Glen, 1992). It was suggested that there are two ways to improve collection time and, in turn, collection productivity (Siegler, 1994). The first way to reduce time is to minimize unproductive periods collectors do not spend on collecting recyclables. Another way is to improve the efficiency of collecting recyclables by finding new and efficient ways to sort or load recyclables. A study of time spent on curbside collection, conducted by the American Plastics Council, found that on average, the collection of recyclables accounted for 68 percent of a typical seven-hour day. The remainder of the day was spent in the yard (8 percent), commuting (8 percent) and unloading material at the material processing facility (16 percent) (Seigler, 1994). The study also indicated that an average 4.5 hours from 7 working hours was for collecting, leaving 2.5 hours for unproductive collection activities. Ways to increase productive collection time or to minimize unproductive time were suggested (Bishop, 1994). Examples are reducing lunch and break times, readjusting the route by avoiding turning around or crossing traffic to pick up recyclables, and using low-entry, right-side-drive vehicles.

C. Collection Crew

It is estimated that at least 50 percent of the annual operating cost goes to the salary of the operating crews (Lund, 1993). Since labor cost is the single largest cost item, it is necessary to optimize a small crew to operate on-route collection. It is therefore common that the most cost-efficient programs use a one person collection crew servicing one side of the street at a time (Moore, 1992). Recently the American Plastics Council conducted an analysis of recycling collection services in five communities in North Carolina (Bracken, 1993). The results indicated that a one person crew had a labor productivity of about 841 pounds collected per labor hour, which was higher than that of using two or three person crews, which resulted in 769 and 740 pounds collected per labor hour respectively.

D. Collection Vehicle and Collection Capacity

The largest capital expense associated with curbside recycling is collection vehicles. There are three popular types of dedicated collection vehicles for curbside collection: open-bin trucks, trailers and closed-body trucks (J.G, 1988). The price ranges from $11,000 for a trailer to $75,000 for a closed-body compartmentalized truck equipped with hydraulic loading. Today many recycling programs add plastic containers in curbside collection and some programs conduct commingled collection. Ideally, the most efficient recycling program should have recycling trucks filled to capacity at the same time at the end of the workday (Moore, 1992). Plastics, which have a high volume to weight ratio, occupy more space than other materials and quickly fill capacity, especially when residents begin putting out mixed plastic containers (Joe, 1990). As a result, there are many attempts to modify truck capacity and vehicle styles in order to fit each collection approach. Simple solutions have been suggested, such as adding a cage on the top or back of the truck to hold plastics, using netting or a bag on the side of the collection truck to hold plastics and putting plastics in an unused portion of the truck (Lund, 1993). A recent approach is to add a compactor, flattener, or baler to the collection truck. The experimental data from the Center for Plastics Recycling Research showed that the volume reduction with mixed recyclables including glass, aluminum cans, and plastics in the packer truck was approximately 35 percent (Merriam, 1993). The ability to compact recyclable containers can keep the truck on route longer, and in turn keeps labor costs down.

A study of collection cost variables by using computer analysis indicated that using a 25 cubic yard compactor truck saved 16 dollars per ton over using a 31 cubic yard compartmentalized truck (Jacalone, 1992). The effective plastic bottle compactor was reported to have a compaction ratio about 10:1 (Perkins, 1991). The average 1.0 to 1.5 cubic yard capacity compactors available on the market usually occupy between 2.6 and 2.9 cubic yards of truck capacity (Siegler, 1994). The price of on-board compactor trucks range from $80,000 to $100,000 and it can cost about $50,000 to $60,000 to modifying an existing truck (Platt, 1993).

2-12. Sorting and Processing Costs

Material processing facilities typically require substantial manual sorting as primary and secondary separation operations. The capital cost for manual processing is low, ranging from $100,000 at the low end to $1 million at the higher end ((Misner, 1992). Sorting labor is estimated to be a substantial portion of operating staff, sometimes 50 to 70 percent (Diaz, 1993). The rate ranges from 300 to 600 pounds per hour per sorter for plastic containers to 1,500 to 10,000 pounds per hour per sorter for paper. Typically, the sorter receives an average wage of $7 to $10 per hour (Hegberg, 1992). Processing costs will increase drastically with the number of manual sorts that must be made. The general cost for plastic handling and processing has been estimated by the Plastic Recycling Compendium as follows (Hegberg,1992):

-sorting	2-3 cents/pound
-debaling	3-4 cents/pound
-grinding	3-4 cents/pound
-cleaning	10-15 cents/pound
-pelletizing	5-7 cents/pound

In some cases, the approximate overall cost of sorting and baling is reported at about 10 to 12 cents per pound (Merriam, 1994). Since manual sorting is both expensive and has a low production rate, the use of semi-automatic sorting increases in order to obtain a more cost effective process. Simple separation techniques such as sink/float, can cost about 2 to 3 cents per pound in operation (Merriam, 1994). Fully automatic sorting has been a major cost-containment goal of the recycling industry. Automated sorting makes a major impact on labor and investment cost. Automated sorting is estimated to cut labor cost by a factor of 2 to 4, depending on the volume of material processed (Dinger, 1994). However investment cost significantly increases. The commercial technology of using sensing devices has been reported to reduce the amount of laborers needed from 28 to 9 people at a production rate of 5,000 pounds per hour (Morgan, 1992). The operation cost was reported at about 5 to 6 cents per pound, depending on each production scenario. The American Plastics Council estimated that autosort equipment could cost from $100,000 for a simple automated system to $950,000 for the more complicated separation of all types of plastics including color separation, at the input rate of 5,000 pounds per hour (Dinger, 1994). In most cases, this high investment reportedly paid for itself within one or two years.

CHAPTER 3

RESEARCH DESIGN AND RESULTS

3-1. Introduction

Hydrocyclone technology could enhance the feasibility of recycling mixed plastic wastes and reduce the cost of current recycling processes. The proof of these concepts will be discussed in this chapter. This research was designed to answer the question of how and why hydrocyclone technology makes economic sense to the recycling process. In order to determine the economic benefit from using this technology, this research was designed by following the three objectives mentioned in Chapter 1. The first part of this chapter focuses on evaluating the position of the hydrocyclone system in the recycling process. The discussion of cost reduction opportunities is in the second part of this chapter. This part demonstrates a model for estimating cost savings from using a collection truck mounted granulator and also discusses cost saving opportunities from collecting more types of plastics. The last section of this chapter describes an estimation of the processing cost of using hydrocyclone technology. The following topics present the details of how the research was designed and the results from each analysis.

3-2. Determination of the Typical Recycling Process and the Places for Hydrocyclone Systems in the Plastic Recycling Process

In order to evaluate the position of hydrocyclone systems in the plastic recycling process, the common recycling process has to be established. The current plastic recycling system involves four major components as shown in Figure 3-1. The system begins with a hauler or collector who collects plastic bottles and transports them to the handler. The handler prepares the recyclable plastics by sorting and baling or granulating. Next the reclaimer converts the resin from baled bottles or flakes into pellets ready for reuse in a new product. Finally the processor produces a new product from recycled plastics.

With this process, inspecting bottles occurs in the collecting, handling and reclaiming processes to ensure the quality and purity of plastic bottles. Collectors and handlers usually bale bottles and transfer them to reclaimers. Bottles are baled and debaled again before they are finally pelletized. The current system handles the recycled plastics in bulk form only at the very end of the chain between the reclaimer and the processor. Therefore the system can be optimized by reducing the number of independent operators, for instance combining the collector and handler. With this concept, the collector can focus on collecting more recycled plastic containers, and sorting or cleaning is done just once at the reclaimer's facility. Plastic bottles should be transferred in bulk form such as flakes, at an early stage of the system. This practice can only be done with the support of microsorting technology. Hydrocyclone technology offers the opportunity to optimize the recycling system because separation of mixed plastic flakes is feasible. The recycling system then will be optimized as shown in Figure 3-2.

Based on the typical separation process for mixed wastes, all mixed containers are fed on a conveying system equipped with mechanical separation devices to separate out the major classes of materials (CalRecovery, 1993). Then each category is taken to manual picking stations. Many mechanical devices have been used to minimize the labor requirements.

In the plastic separation section, plastic separation from contaminants or from undesired materials includes a number of processes adapted for plastic waste separation. These include magnetic separation for removal of ferrous materials, air separation via cyclone used to separate

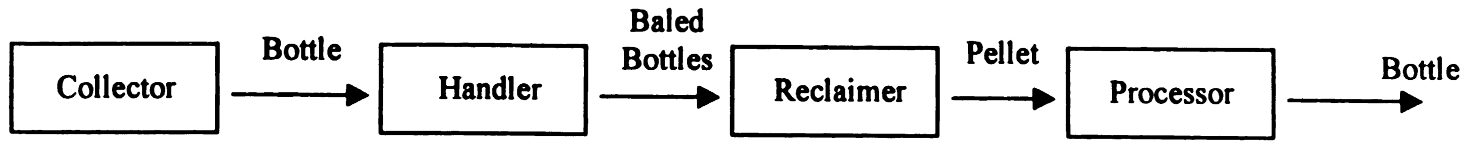

Figure 3-1 The Current Plastic Recycling System

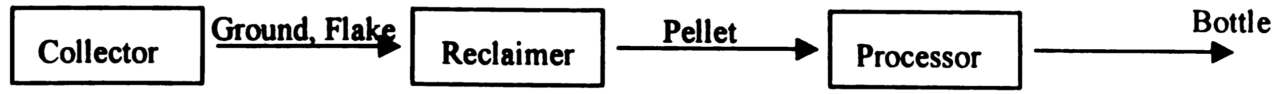

Figure 3-2 The Optimized Recycling System

paper, floatation tanks used to separate various resins and finally baling or pelletizing to obtain the ready for sale materials (Brewer, 1991; White, 1992).

A typical current separation process in this research is shown in Figure 3-3. The process consists of the following steps:

(a) Debaling of mixed baled plastic containers

(b) Removal of broken glass and dirt by screening

(c) Manual sorting for each generic type of plastic

(d) Granulating to reduce the volume of recycled plastics

(e) Cleaning, which consists of several steps: washing, float/sink separation, and air classification, to ensure the quality of recycled plastics

(f) Densification by pelletizing the recycled plastics

3-2.1 Place for Hydrocyclone System in the Existing Recycling Process

As shown in Figure 3-4, hydrocyclone systems can be easily integrated in the current separation process. The front- and back-end processes can be the same, but a set of hydrocyclone systems can replace the manual sorting and cleaning steps. Since the system separates mixed plastic flakes, the grinding process is added before mixed plastics enter the system. This research focuses on separation of

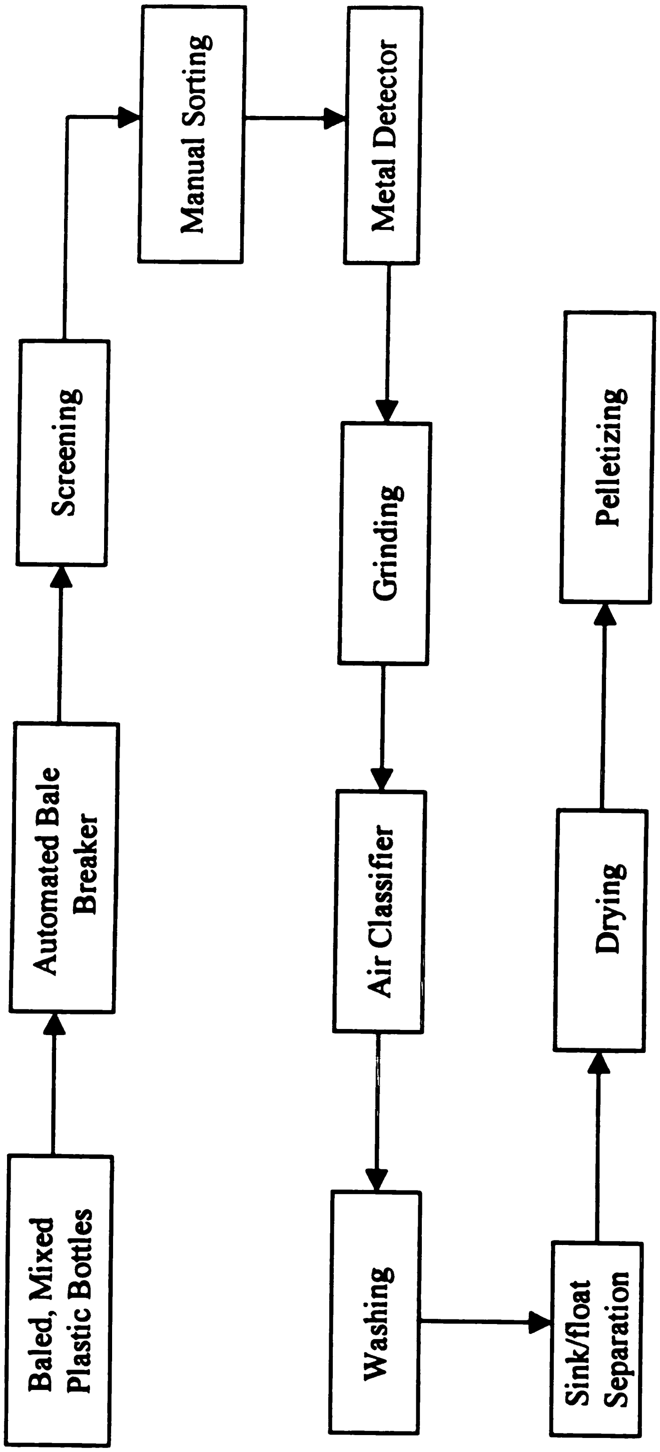

Figure 3- 3 Current Process for Mixed Baled Plastic Containers

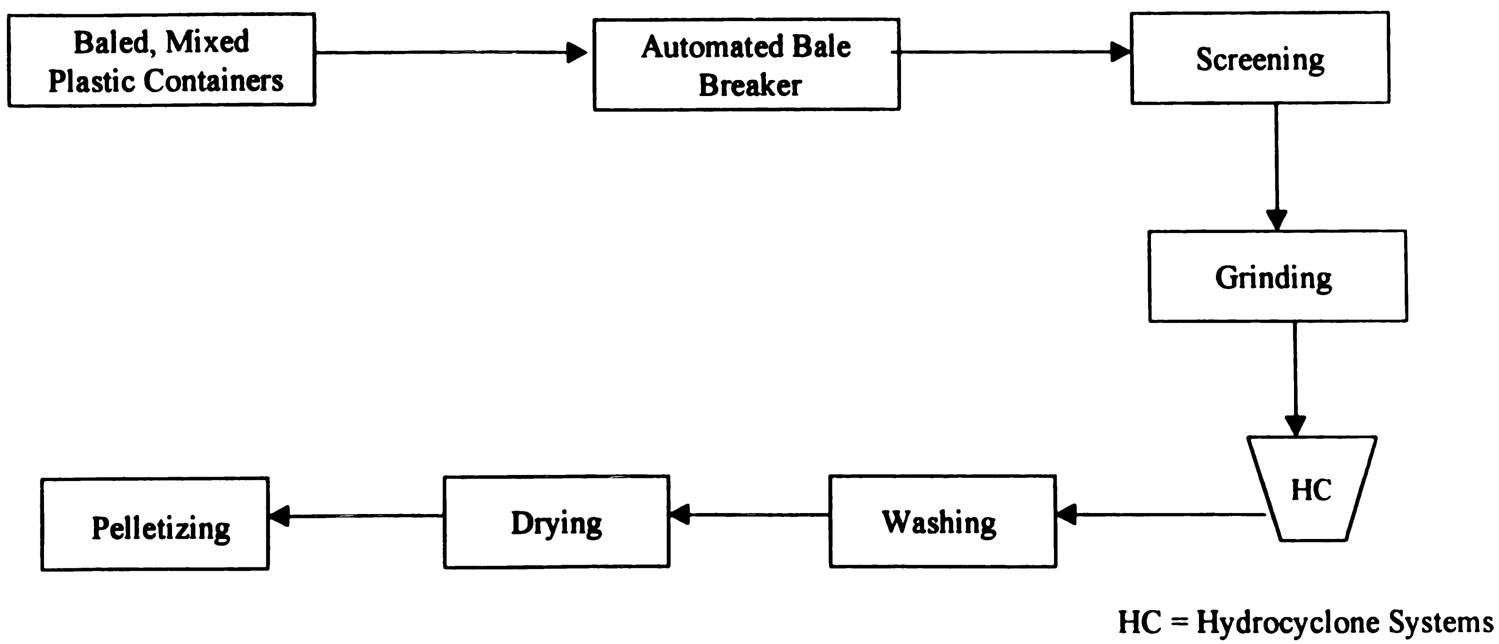

Figure 3-4 Current Process Using Hydrocyclone System

mixed plastics, namely HDPE, PP, PET, PVC, and PS. Therefore the system could accomplish separation of mixed plastic wastes by applying four classifications, as shown in Figure 3-5. The first classification is based on size and density differences. Light materials (HDPE and PP) will separate from heavy materials (PET, PVC, and PS) at this classification. Then the second classification or light medium hydrocyclone separate HDPE from PP. A light medium of glass microbubbles in water is used for this separation. The third classification will separate PS from PET and PVC using the heavy medium hydrocyclone. The last classification based on size and shape differences will separate PVC from PET. After separating, each generic type of plastic enters the washing process and then the pelletizing step.

3-2.2 The Recycling Process Using Collection Vehicle Mounted Granulating Machine

Using hydrocyclone technology not only impacts the separation process directly, but also indirectly impacts the collection and handling system. It offers a new framework for the recycling process. Collection vehicles mounted with granulating machines can be used to increase the payload of the truck. Then the more condensed form, flake, of recycled plastic is shipped to the reclaimer. The separation process

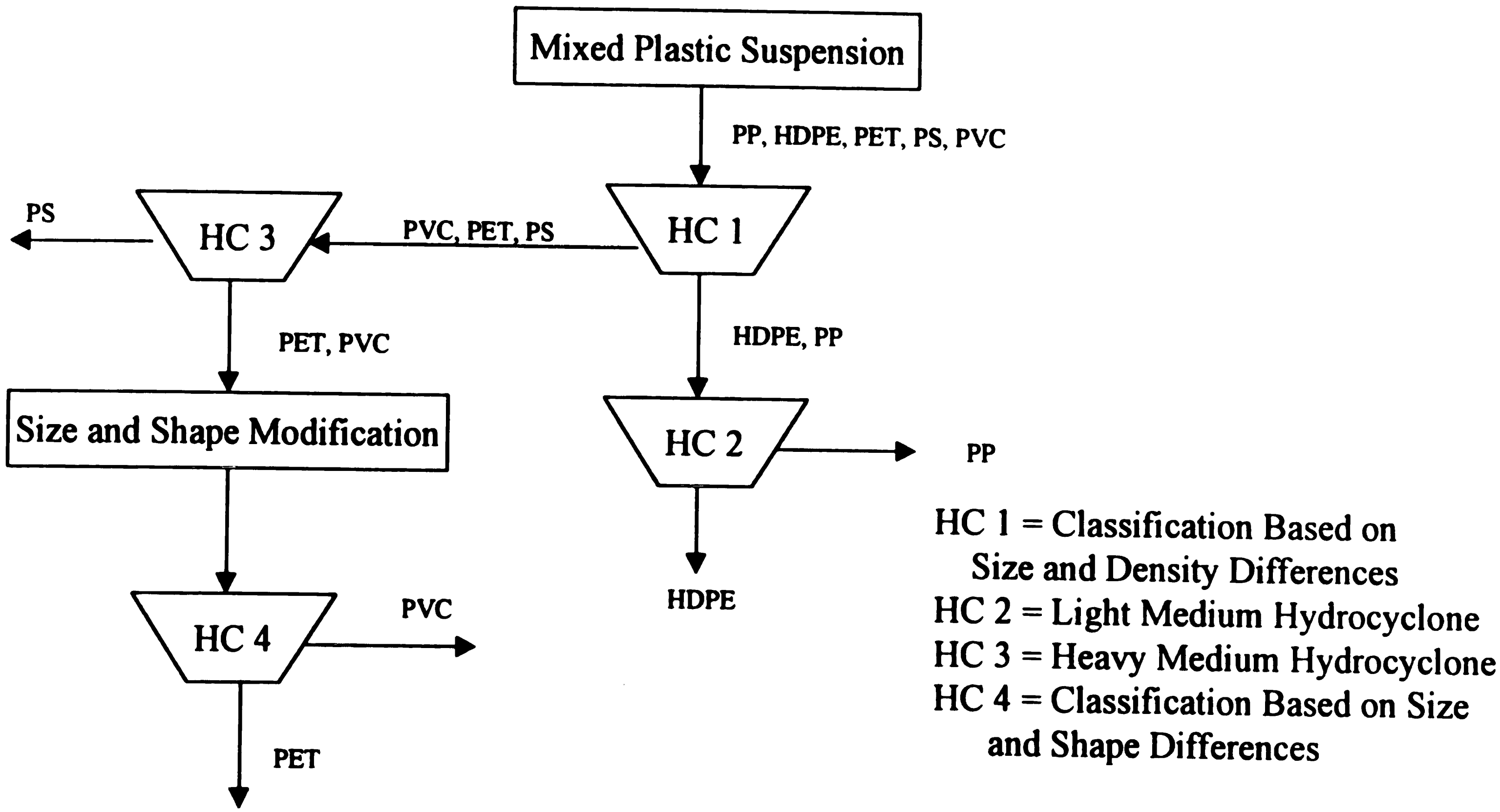

Figure 3-5 Process of Sorting Mixed Plastics Using Hydrocyclone

therefore will start with receiving mixed plastic flakes, instead of baled plastics. The separation process will be as shown in Figure 3-6. The bale breaker can be eliminated from the process. The preliminary washing and screening may be applied at the front-end of the process. Then ground mixed plastics enter the hydrocyclone system. Each generic type of recycled plastics is finally pelletized to meet the buyer's requirement.

In conclusion, because of its capability to sort mixed plastic wastes, using hydrocyclone technology can optimize the current plastic recycling process. The number of independent operators can be reduced and the length of the process can be shortened. Hydrocyclone systems can easily be integrated into the current separation process and replace many of the typical cleaning steps. Using hydrocyclone technology also offers the opportunity to collect and transfer plastic wastes in the condensed form, or flake. A vehicle mounted granulating machine can be used and the separation process can start with mixed plastic flakes, not baled plastics (Figure 3-6).

3-3. Evaluation of Cost Reduction Opportunities by Using Hydrocyclone System

As mentioned earlier, the benefits of using hydrocyclone technology in shortening the recycling process,

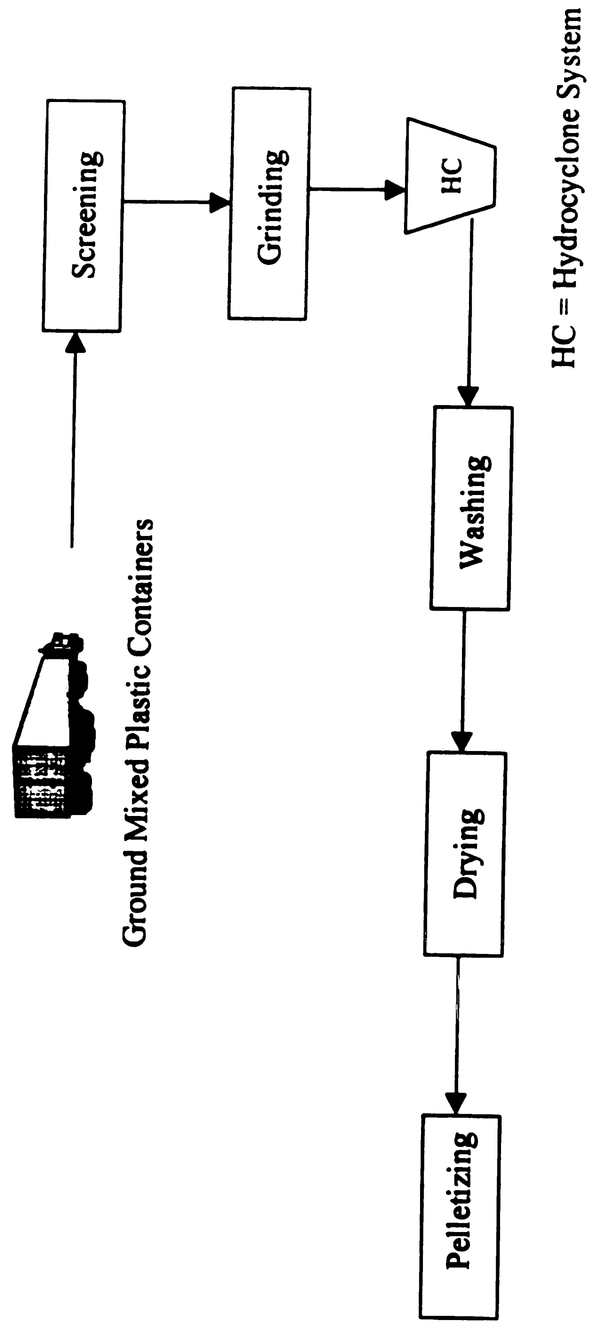

Figure 3-6 Future Process Using Hydrocyclone System

replacing several cleaning steps, and using plastic flakes as the flow of material, lead to the opportunity to reduce the cost of current collection and sorting processes.

In the collection process, hydrocyclone technology supports the possibility of collecting mixed plastics and transfers them in the bulky form (flake). The collection strategy can change to collection using collection truck mounted with granulating machines. This strategy could increase the space available to collect more recycled plastics and allow a truck to service a longer route. This could lead to a reduction of number of trucks and laborers required. Also, it could enhance labor productivity and eventually reduce collection cost. Therefore this research establishes a model to demonstrate the indirect cost saving from the improvement in collection space and also discuss the cost reduction opportunities from collecting more types of plastics.

In order to determine the total cost savings from using hydrocyclone technology in the recycling process, the proper recycling models are created to support the cost analysis. This research uses two kinds of data. The first type of data is the assumption of operation scenarios and policies for each model that allow an understanding of costs in order to generate a mathematical calculation. The second type of data is the actual cost information obtained from some other researchers. Since labor cost is the major cost in overall recycling process, it is therefore the main focus of cost saving analysis in this research.

3-3.1 Cost Reduction from Collection Improvement

A model is developed to monitor the volume that can be reduced by using a densifier machine such as a granulator to increase material density on the collection truck. The concept is to determine the number of trucks and collectors required in the model for the same size of population, participation rate, waste generation rate, and collection policy. Consequently, the labor cost and capital cost can be determined for each model. There are some key inputs as shown in Table 3-1, that should be set for a model to obtained the outputs that can be used for determining collection costs.

Table 3-1 Key Inputs and Outputs for Collection Cost Model

Key Inputs	Key Outputs
• Participation and setout rate • Number of households served • Recyclables generated per household • Density of material collected • Working capacity of a truck • Working day length • Costs by labor, equipment, and maintenance	• Tons of materials collected • Number of stops per truck load • Truck and crew size required • Operating and capital cost required • Collection cost per month

The model was developed based on these assumptions:

(A) Regional Data

The recommended size of moderate recycling program is (Lund, 1990):

Households served per month	50,000
Type of household	single family
Population per house	average 3 persons
Size of region	250 square miles
Total population	150,000

(B) Collection Policy Assumption

Moderate participation rate and set out rate are 70 and 60 percent respectively for a weekly program (Glen, 1990).

The collector operates 5 days per week and works 7 hours per day.

To minimize the amount of labor required, one crew will operate one collection truck.

According to the data obtained from field collection by the Center for Plastics Recycling Research, the average weekly waste generated per household is 16 pounds (Rankin, 1988). The details of waste generated with the distribution of type of material are listed in Table 3-2. Total plastic bottles accounted for 0.8 pounds per household per week.

The collection strategy is curbside separation, which involves collecting recyclables and sorting them into five

Table 3-2 Volume of Recyclables Generated per Household

Recycle stream	Weight lbs/setout	%weight	Density lbs/cubicyard	Volume gallon	%volume
newspaper	7.8	48.4	500.0	3.1	23.2
glass container	6.0	37.5	700.0	1.7	13.0
metal cans	1.0	6.3	144.0	1.4	10.7
aluminium cans	0.5	3.1	49.0	2.1	16.0
plastics bottles uncrushed					
PET	0.5	2.8	40.0	2.3	17.6
HDPE	0.3	1.9	24.0	2.5	19.0
total	16.0	100.0		13.1	100.0

Source : Center of Plastic Recycling Research (Rankin,1988) categories: newspaper, glass bottles, metal cans, aluminum cans, and mixed plastic bottles.

A compartmentalized, closed body truck with hydraulic loading is used in the recycling model (J.G., 1988). The full capacity of the truck is 30 cubic yards. The working capacity is approximately 80 percent of the full capacity, or 24 cubic yards. The modified vehicle mounted granulator is assumed to have the same capacity as the regular collection truck. The granulator has the capacity to finish grinding during the time that the truck travels from one stop to another. Therefore the time required to grind plastic into flakes does not affect the total collection time.

The volume reduction ratio obtained from using a granulator can be determined from the data listed in Table 3-3. PET soda bottles typically have a bulk density of 37.5 pounds per cubic yard for the uncrushed form and 756 pounds per cubic yard for the flake form. The volume reduction ratio that can be achieved is 20 to 1. HDPE bottles have a bulk density of 24.3 pounds per cubic yard for the uncrushed form and 714 pounds per cubic yard for the flake form. The volume reduction ratio that can be achieved is 30 to 1. Therefore, this research assumes that the granulator will achieve a volume reduction ratio at least 20 to 1.

Table 3-3 Typical Properties of HDPE and PET Bottles

Description	PET bottle		HDPE bottle	
	*lb/ft3	#lb/yd3	*lb/ft3	#lb/yd3
weight/bottle, lbs	0.14		0.15	
bottles/lb, number	7.10		6.10	
bulk density, uncrushed.	1.50	37.50	0.90	24.30
bulk density, stepped-on	3.00		1.80	
Typical quantities for gaylord size of 34"*43"*38"				
uncrushed, weight/gaylord	48		29	
stepped-on, weight/gaylord	96		58	
uncrushed, bottles/gaylord	341		194	
stepped-on, bottles/gaylord	682		389	
Typical quantities for bale size of 31"*45"*63"				
weight/bale, lbs	750		600	
target minimum of shipping,	15		12	
Processed resin properties				
pellet density	50		35	
flake density,5/16" max size	29		27	
flake density, 3/8" max size	28	756	26	702

Source : Plastic Recycling Compendium (Hegberg, 1992)

(C) Cost Information

The collector is paid $18.50 per hour and fringe benefits and insurance account for 30 percent of the monthly salary (Hegberg, 1992).

The capital cost for a regular collection truck is estimated at the base cost of $84,000 per truck with a seven-year life (J.G., 1988). A modified truck with an added granulator is estimated to cost $100,000 per truck. Thus, the annual cost is $12,000 for the regular truck and $14,280 for the modified truck. In the other words, the equipment cost per month for the modified truck and the regular truck is $1,190 and $1,000 respectively.

The operating and maintenance cost is approximately 13 percent of the total equipment cost (Hegberg, 1992).

3-3.1.1 Cost Savings from Reduction of Collection Space

Space reduction is obtained by using a granulator to reduce the volume of plastic containers. The cost analyses of regular collection with a granulator on the truck and without a granulator on the truck are summarized in Table 3-4 and 3-5 respectively.

With a reduction ratio of 20 to 1, plastic containers account for approximately 121 cubic yards per week in the collection without using a granulator on the truck, but it accounts for 6 cubic yards per week in the collection using

Table 3-4 Cost Analysis of Collection Using Regular Truck

Decision Parameters			
participation rate			70%
setout rate			60%
households served			50,000
actual household served			
per month			21,000
per week			5,250
recycle stream	pounds per household	yd3 per household	yd3 per week
total	16.00	0.063	331
*newspaper	7.75	0.015	79
*glass bottles	6.00	0.008	42
*metal cans	1.00	0.007	37
*aluminium cans	0.50	0.010	53
*PET bottles	0.45	0.011	58
*HDPE bottles	0.30	0.012	63
cu.yds/day			66
working capacity per truck			24
No. truck required per week			3
No. of day operated per week			5
working hours per day			7
working hours per week			35
total working hours per week			105
Operating cost			
labor costs per hour			18.5
total working hour per week			105
labor costs per labor per week			1,943
total labor costs per month			7,770
total benefit costs per month			2,331
total operating cost per month			10,101
Capital cost			
equipment cost per month per truck			1,000
total equipment cost per month			3,000
maintainance cost per month			390
total capital cost per month			3,390
total cost per month			13,491
total recyclables collected per month (ton)			168
cost per ton			80

Table 3-5 Cost Analysis of Collection Using Truck Mounted Granulator

Decision Parameters			
participation rate			70%
setout rate			60%
households served			50,000
actual household served			
per month			21,000
per week			5,250
recycle stream	pounds per household	yd3 per household	yd3 per week
total	16.00	0.063	331
*newspaper	7.75	0.015	79
*glass bottles	6.00	0.008	42
*metal cans	1.00	0.007	37
*aluminium cans	0.50	0.01	53
*PET bottles	0.45	0.011	58
*HDPE bottles	0.30	0.012	63
plastic densifying ratio			20/1
space reduction, cubic yard, plastics			6
space saving cubic yard			115
cu.yds/week			216
cu.yds/day			43
working capacity			24
No. trucks required per day			2
collection day per week			1
No. of day operated per week			5
working hours per day			7
working hour per week			35
total working hours per week			70
Operating cost			
labor costs per hour			18.5
total working hour per week			70
labor costs per labor per week			1,295
total labor costs per month			5,180
total benefit costs per month			1,554
total operating cost per month			6,734
Capital cost			
equipment cost per month per truck			1,190
total equipment cost			2,380
maintenance cost per month			309
total capital cost			2,689
total cost per month			9,423
total recyclables collected per month (ton)			168
cost per ton			56

a granulator on the truck. The space of approximately 115 cubic yards per week is reduced. The total volume of recyclables per day is 43 cubic yards, instead of 66 cubic yards for collection without granulator. At the working capacity of 24 cubic yard per truck, the number of trucks required per day reduces from 3 to 2 trucks.

For serving 5,250 households per week or 1,050 per day, the total households served per truck are therefore 350 households for collection using a regular truck and 525 households for collection using a truck mounted granulator. According to the time study, collection time for curbside separation program (weekly) is about 30 seconds per stop, resulting approximately 540 stops per day (Bullock, 1989). In general, reviews of recycling routes have indicated that an average of 500 stops per day can be achieved (Glen, 1990). Therefore, the number of households served per day from this analysis is in the practical range. As a result, the more households which are served, the more the payload of the truck at the end of the working day.

Using one crew person per truck, the amount of labor required reduces from 3 persons to 2 persons. The reduction of number of trucks and labor leads to the reduction in operating cost and capital cost.

For the labor cost of $18.50 per person and the total working hours of 105 hours per week, the labor cost is

$1,943 per week or $7,770 per month for collection using a regular truck. In collection using a truck mounted granulator, the total working hours for two crew persons are 70 hours. As a result, the labor cost in this case is $1,295 per week or $5,180 per month. After including the fringe benefits, the operating cost per month is $10,101 using a regular truck, and $6,734 using a truck mounted with a granulator.

The capital cost can be calculated in a similar way. According to the vehicle cost of $1,000 per month, the total equipment cost per month for using regular trucks is $3,000. Operating and maintenance cost is about $390 per month. Therefore the total capital cost for using regular trucks is $3,390 per month. A similar calculation applied to collection using trucks mounted with granulators results in the total capital cost of $2,689 per month.

The total collection cost for each case results from the sum of the total operating cost and the total capital cost. The collection cost per month for collection using trucks mounted with granulators is less than that of using regular trucks, even though there is an additional cost for the truck mounted with a granulator. For the total recyclables collected per month of 168 tons, the cost per ton is $80 for collection using regular trucks and $56 for collection using trucks mounted with a granulator.

Therefore the cost saving is $24 dollars per ton or 1.2 cents per pound. The details of cost analysis for both cases are listed in Appendix A.

Since the key inputs used in this cost model can vary depending on demographic and geographic conditions of different communities, a cost saving in collection can be different from program to program. However, the cost saving obtained from the proposed cost model is an estimation that can demonstrate how hydrocyclone technology can have an indirect economic impact on collection costs.

3-3.1.2 Cost Saving Opportunity from Collecting All Type of Plastic Containers

Since hydrocyclones are capable of sorting mixed plastic flakes, they offer the opportunity to collect more types of plastics, beyond PET and HDPE from soft drink bottles and milk jugs. Collection programs can collect all rigid plastic containers such as ones that are made from PVC, PS, and PP. The study in Minnesota by the Council for Solid Waste Solution compared the annual amounts of plastics collected among three collection strategies for plastics: soft drink and milk bottles, all plastic bottles, and all rigid plastic containers (Krivit, 1991). The study found that the amount of plastics (pounds per household) in all-rigid-plastic-container collection increased about 60 percent from soft-drink-and-milk-bottle collection. Another study by the American Plastic Council in Portland and Eugene, Oregon indicated a 35 percent increase in the amount of plastics when collection changed from all-plastic-bottle collection to all-rigid-plastic-container collection (Engel, 1996). The study also indicated an increase in participation rate and set out rate in plastic recycling when people did not have to choose which plastic containers to set out. Due to the limited data on composition of other type of plastic collected, this research could not estimate a direct cost saving from this approach. However, if we look at the following cost structure for recycling cost, it is possible that the effect of collecting more types of plastic could reduce the net recycling cost.

Recycling Cost = + Revenues from sale of recyclables
+ Avoided cost of disposal
- Cost of collection
- Cost of sorting/processing

Collecting more plastics results in more pounds of plastics collected. As a result, it could further reduce the collection cost per ton. In addition, revenues from recyclables could increase because of the additional revenues from other type of plastics. According to the selling price of recyclables (plastics, newspapers, aluminum can, and glass), plastics represent a valuable component of the mixture. They have the second highest value next to aluminum. An increase in the amount of recycled plastics should have a major impact in increasing revenues.

In conclusion, hydrocyclone technology offers the opportunity to collect mixed plastic waste and utilize the space on the collection truck more efficiently. Mixed plastic wastes can be collected and ground during collection. The truck can serve a longer route and collect more plastic wastes when the space required for plastic wastes is reduced. The estimated cost savings from increasing space for more plastic wastes is approximately $24 per ton of recyclables collected. Collecting more types of plastics will have an effect on the recycling cost. The collection cost per ton could decrease because of an increase of plastics collected. The additional revenues from other types of plastics could increase the total revenues. Both factors therefore could reduce the total recycling cost.

3-4. Potential Cost Saving in Operating Cost of Using Hydrocyclone

The last part in this research is to determine the operation cost of using hydrocyclone system in the recycling process. Because of the limited data during the development stage of the hydrocyclone system, this research could not determine the exact cost of using the system. However this research can use the cost saving obtained from the first and second parts along with the current data of plastic processing costs to estimate the operation cost for hydrocyclone system.

In determining the operating cost, there are two major costs that could incur for this operation. The first category is the labor cost. Since hydrocyclone system can replace manual sorting, the amount of labor required to operate the system would reduce significantly. The second category involves the non-labor operating cost, which could incur from using hydrocyclones. This includes the cleaning and recovering cost for the medium used in the hydrocyclone system.

According to the typical cost of plastic handling and processing by manual sorting, the total processing cost was estimated at 28 cents per pound (Hegberg, 1992). This cost can be used as the benchmark for hydrocyclone operating cost. The cost comprises of five operations:

- Sorting average at 2.5 cents per pound
- Debaling average at 3.5 cents per pound
- Grinding average at 3.5 cents per pound
- Cleaning average at 12.5 cents per pound

- Pelletizing average at 6.0 cents per pound

Labor Operating Cost

By replacing manual sorting with hydrocyclone system, laborers required could be merely eliminated. This would result in a significant cost reduction. One study estimated that automated sorting (optical separation) could reduce the processing cost as much as 4 cents per pound (Morgan, 1992). Hydrocyclone systems could have the same level of cost reduction as other automated systems.

Non-Labor Operating Cost

Although the labor cost is the major cost reduction in operating, the effect of the system on other parts of the process is also critical. High purity of recycled materials depends on the separation efficiency and cleaning process required. In microsorting using optical technology, the system needs to be rerun because of inevitable ejection of some good materials into the bad materials (Apotheker, 1996). The optical flake sorting reported the operating cost of 3 cents per pound for utility and parts (ejector, light source, etc.). For a hydrocyclone system, the washing process is needed in order to clean the medium from the desired material. Processes followed by separation could result in additional operating costs.

In the heavy medium hydrocyclone that uses magnetite in water as a medium, the recovery process is done by applying a magnetic method to clean and recover the medium from the desired material (Perry, 1973). The loss of the medium was reported as low as 0.005 lb. medium per pound of dry feed material. The total operating cost was reported at 2 to 5 cents per pound.

For the light medium hydrocyclone, the losses of glass microbubbles from washing and breakage will significantly affect the operating cost. This is because of the high cost of microbubbles (currently about $4 per pound) and the amount used in the suspension medium (approximately 3 percent). The investigation of the expected losses of microbubbles and the technique for recovering them more efficiently are underway. However, if the technique could incur a cleaning cost at the same level as in the heavy medium hydrocyclone, using a light medium hydrocyclone could be economical.

Based on the potential cost reduction from labor costs and non-labor costs (cleaning), the hydrocyclone operating cost could be less than that of the typical process. Further cost reduction could occur in the future when plastic flakes are widely accepted by most buyers. As mentioned earlier, to optimize the recycling process, recycled plastics should be handled in the form of flakes at an early stage. Reclaimers could start sorting and cleaning plastic flakes without the debaling step, resulting in a reduction of processing costs. In addition, using plastic flakes as the flow material in the process could eliminate the final step needed in processing recycled plastics such as pelletization. Although most recycled plastic sold today is in pellet form, pelletization may not always be necessary. Most buyers pelletize recycled plastics because it is the easy way to screen out fine contaminants. Therefore, if a microsorting technology like the hydrocyclone system could produce reasonably clean and properly sized flakes, the final pelletization could be eliminated, resulting in further cost reduction.

CHAPTER 4

SUMMARY AND RECOMMENDATIONS

4-1. Summary

This research has provided a framework for a studying the economic feasibility of using hydrocyclone technology in the recycling process. Hydrocyclone technology is one of the key technologies that shows promise of enhancing the efficiency of plastic recycling process. It can overcome many challenges that recycling operators are facing today. The diversity of plastics is no longer the major problem in separation because a hydrocyclone system is capable of separating mixed plastics. The material constraints due to the low bulk density of plastics can be solved since the system operates by using the condensed form of plastics, or plastic flakes. In addition, the system can operate at high production rates.

This research has shown the impact of this technology on the recycling process. Its capability to separate mixed plastic wastes has a direct impact on the typical recycling process. The process can be optimized by reducing the number of independent operators and shortening the length of the process. Hydrocyclone systems can easily fit in the current separation process by replacing the manual sorting and many of the typical cleaning steps. The flow of material would be in form of plastic flakes, instead of baled plastic bottles.

Using hydrocyclone technology also has the indirect impacts on collection processes. It offers the opportunity to collect and transfer plastic wastes in form of plastic flakes. Therefore vehicle mounted granulating machines can be used and the separation process can start with mixed plastic flakes.

Its benefits in optimizing the recycling process, replacing several cleaning steps, and using plastic flakes as the flow of material, lead to opportunities to reduce the cost of the current collection and sorting process. This research has provided a model to determine cost saving opportunities from using hydrocyclone technology.

Indirect cost saving comes from using a granulator on a collection truck and collecting mixed plastic wastes. This strategy results in the reduction of collection space needed for plastic wastes. As a result, the truck can serve a longer route and the payload per truck increases. Consequently, fewer trucks and collectors are needed, which leads to cost savings in the collection process. An estimate of a cost saving from the proposed model is approximately $24 per ton. In addition, collecting more types of plastics is possible when hydrocyclone technology is in practise. This strategy could increase the amount of plastics collected, and further reduce the collection cost per ton. Also, more types of plastics could increase revenues from selling them. Therefore these two factors show a potential to reduce the recycling cost.

Lastly, this research has provided an estimation of the processing cost of using hydrocyclone technology. The potential cost reduction from labor and non-labor operations could result in lower operating costs than the typical processing cost. However, due to the limited data during the developing stage of this technology, this research could not determine exact operating costs. Non-labor operating costs such as washing and recovering the medium (microbubbles) used in hydrocyclone could have a major impact on the total processing cost due to its cost, the level of usage, and the losses.

Further cost reduction could be possible in the future when plastic flakes are widely accepted by most buyers and are reasonably clean. The typical baling and pelletizing would not be necessary, resulting in further reduction of the processing cost.

These cost savings make economic sense to use hydrocyclone technology in the recycling process. The saving from each sector may be small but the multiple saving opportunities from each sector, as summarized in Table 4-1, will be attractive. This will permit recycled plastics to compete favorably with the virgin plastics for many end markets.

Table 4-1 Cost Reduction Opportunities

Cost Reduction Opportunities	Cents per pound
Collection :using truck mounted with a granulator	1.2
Processing : sorting : cleaning : pelletizing	 4.0 12.5 6.0

4-2. Recommendations

Although this research has provided a framework for studying the economic feasibility of using hydrocyclone technology in the recycling process, a number of areas of this research need further investigation. First, the research demonstrates a multiple cost saving from using hydrocyclones in the recycling process, however, these savings could vary in actual situations.

In determining the cost reduction opportunity in the collection process, cost savings could vary from one program to another. The variables used in the model depend on collection policies, geography and demography of the community being investigated. In addition, the volume reduction could be determined more precisely. This can be done by examining the real volume reduction ratio from varieties of granulators that could fit into the collection truck.

A model cost saving from collecting more types of plastic and using a truck mounted with a granulator could be further developed. The data from recent collection program that collect all types of containers could be used to determine the space needed on the truck.

The estimation of the expected loss of microbubbles and their recovery cost could be useful in estimating the hydrocyclone operating cost. Also, the estimation of investment cost of the hydrocyclone system also needs to be determined whenever the pilot project is ready. Cost savings, operating costs, and capital costs can be used in estimating a number of years that the system could pay off its investment.

Since this research proposed the use of plastic flakes as a flow of material in the recycling process, the final recommendation is to conduct a market study for plastic flakes. This study could be useful to support this claim. The study could include the demand for plastic flakes and the number of processors who are willing to and able to process the plastic flakes.

APPENDIX A

DETAILS OF COST ANALYSIS OF COST SAVING FROM USING GRANULATOR ON THE COLLECTION TRUCK

APPENDIX A

Collection Using Regular Truck

1. Decision parameter

Participation rate = 70%
Set out rate = 60%
Households served = 50,000
Actual households served = 50,000 * 0.7 * 0.6
= 21,000 per week
= 21,000/ 5
= 5,250 per day

2. Collection space

Total cubic yard per week = 331
Total cubic yard per day = 331/5
= 66
Working capacity per truck = 24
Number of truck per day = 3
Total working hour = 5*7
= 35

3. Operating cost

Labor cost per hour = $18.50
Total working hours per crew per day = 35 hours
Crews per day = 3
Total working hour per week = 3 * 35
= 105 hours
Total labor cost per week = 105 * 18.5
= $1,943
Total labor cost per month = 1,943 * 4
= $7,770
Fringe benefit = 30 % of monthly salary
Total fringe benefit = 7,770 * 0.13
= $2,331
Total operating cost per month = 7,770 + 2,331
= $10,101

4. Capital cost

Equipment cost per month = $1,000
Total truck needed = 3 trucks
Total equipment cost per month = 1,000 * 3
= $3,000

Operation and maintenance cost = 13 %of equipment cost
Operation and Maintenance cost = 3,000 * 0.13
= $390
Total capital cost per month = 3,000 + 390
= $3,390

Total cost per month = 10,101 + 3,390
= $13,491
Total pounds collected per month = 16 * 5,250 * 4
= 336,000
= 336,000/2,000
= 168 tons
Cost per ton = 13,491/ 168
= $80

Collection Using Truck Mounted Granulator

1. Decision parameter
Participation rate = 70%
Set out rate = 60%
Households served = 50,000
Actual households served = 50,000 * 0.7 * 0.6
= 21,000 per week
= 21,000/ 5
= 5,250 per day

2. Volume reduction
Volume reduction ratio = 20:1
Volume of plastics per household = 121 cubic yard
Volume reduction = 6 cubic yard
Space saving = 121 - 6
= 115 cubic yard
Volume per week = 331 - 115
= 216
Volume per day = 43
Capacity per truck = 30 cubic yard
Working capacity = 80% of full capacity
Working capacity per truck = 24 cubic yard
Trucks required per day = 43/24
= 2
Crews per day = 2

3. Operating cost
Labor cost per hour = $18.50
Total working hours per crew per day = 35 hours
Crews per day = 2
Total working hour per week = 2 * 35
= 70 hours
Total labor cost per week = 70 * 18.5
= $1,295
Total labor cost per month = 1,295 * 4
= $5,180
Fringe benefit = 30 % of monthly salary
Total fringe benefit = 5,180 * 0.30
= $1,554

Total operating cost per month	=	5,180 + 1,554
	=	$6,734

4. Capital cost

Equipment cost per truck per month	=	$1,190
Total equipment cost	=	2 * 1,190
	=	$2,380
Maintenance cost per month	=	0.13 * 2,380
	=	$309
Total capital cost	=	2,380 + 309
	=	$2,689
Total cost per month	=	6,734 + 2,689
	=	$9,423
Total tons per month	=	168
Cost per pound	=	9,423/ 168
	=	$56

5. Cost saving

Using regular truck	=	$80
Using truck mounted granulator	=	$56
Cost saving	=	80 - 56
Per ton	=	$24
Per pound	=	1.2 cents

LIST OF REFERENCES

Akashian, Edward, "Effects of Polymeric and Glass Microbubble Contamination on Recovered Materials from a Light Medium Hydrocyclone Separation of HDPE from PP", Master Thesis, School of Packaging, Michigan State University, 1994

Anderson, Peter, "The Impact of Light Compaction on Curbside Recycling Collection", Resource Recycling, pp.28-38, May 1996

Apotheker, Steve, "Curbside Collection: Complete Separation versus Commingled Collection", Resource Recycling, pp. 58-63, October 1990

Apotheker, Steve, "Flake and Shake, Then Separate", Resource Recycling, pp. 20-25, June 1996

Beckman,J.E., M.R. Enick,and S.M. Super, "Separation of Thermoplastics by Density Using Near-Critical and Supercritical Carbon Dioxide and Sulfur Hexafluoride", Emerging Technologies in Plastics Recycling, American Chemical Society, Washington DC., 1992, pp.173-185,

Bishop, S. Richard, "...and the Role of MFRs in Residential Waste Recycling", Resource Recycling, pp. 37-41, October 1991

Bishop, S. Richard, "The Best Practise for Collecting Recyclables Curbside", Resource Recycling, pp.58-62, July 1994

Bonis, J. Laszio, "Plastics Are Dominant Over Paper, Metal, and Glass in Most Materials", Modern Plastics Encyclopedia' 95, pp. A36-A37, Mid-November 1995

Boucher, Marie, "Boom Market Boost national Recovery Rate", Resource Rcycling, pp. 33-38, May 1997

Bogert, Susan, and J. Morris, "The Economics of Recycling", Resource Recycling, pp.76-80, September 1993

Bracken, Robert, "Collection Curbside Recyclables Efficiently", Resource Recycling, pp.68-75, September 1993

Bradley, D., The Hydrocyclone, Pergamon, New York, 1965

Brewer, Gretchen, "Plastic Bottles Close the Loop", Resource Recycling, pp.88-95, May 1991

Bullock, Dave, and D. Burk, "Commingled versus Curbside Sort, Biocycle, pp.35-36, June 1989

CalRecovery, Inc., and PEER Consultant, Material Recovery Facility Design Manual, C.K. Smoley, Boca Raton, Florida, 1993

Carlson, Dave, Personal Communication, 1995

Colman, D.A., and M.T. Thew, "Correlation of Separation Results From Light Dispersion Hydrocyclone", Chemical Engineering, pp. 233, July 1983

Council of Solid Waste Solution, Implementing Plastics Recycling Program, Washington DC, 1990

Crampton, Norm, "Full-cost Accounting: What is it? Will it help or hurt recycling", Resource Recycling, pp.57-61, September 1993

Curlee, T.Randall, and S. Das, "Plastics in Municipal Solid Waste", Plastics Waste, Noyes Data Cooperation, New Jersey, 1990

Diaz, F.Luis, M.G. Savage, L. Eggerth, and G. Clarence, "Recycling-MRF'S", pp.77-91, Chapter 2, Composition and Recycling Municipal Solid Waste, Lewis Publisher, Florida, 1993

Dinger, W. Peter, "More Efficient Techniques Overcome Previous Cost and Quality Hurdles", Modern Plastics Encyclopedia' 95, pp. A35-38, Mid-November 1994

Engel, Steve, "Small Weights, Big Difference", Resource Recycling, pp.20-27, October 1996

Franklin Associates, Ltd., Characterization of MSW in the United States: 1995 Update, U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington D.C., 1995

Glen, Jim, "Curbside Recycling Reaches 40 million", Biocycle, pp. 30-37, July 1990

Glen, Jim, "Efficiencies and Economics of Curbside Recycling", Biocycle, pp.30-35, July 1992

Gold, Marion, and A. Marks, "Rhode Island Tackles Curbside Recycling", Waste Alternatives/Recycling, pp.34-38, June 1988

Green, L. Janet, "Selective Size Reduction of Poly Vinyl Chloride and Poly Ethylene Terephthalate by Impact Grinding", a Dissertation, Department of Chemical Engineering, Michigan State University, 1996

Guettler, Jay, "A Survey of State Market Development Activities", Resource Recycling, pp.44-48, September 1993

Hegberg A.B., R.G. Brenniman, and H.W. Hallenbeck, Mixed Plastics Recycling Technology, Noyes Data Corporation, New Jersey,1992

J.G, "Recycling Collection Vehicles", Biocycle, pp.39-40, May/June 1988

Jacalone, P. Down, "Curbside Recycling Collection Cost Variables", Resource Recycling, pp.72-78, October 1992

Joe, Salimando, "Call Him Separatin'Sam", Waste Age, pp.44-48, Febuary 1990

Knights, Mikell, "Machines Sort Colored PCR from Natural", Plastics Technology, pp.45, April 1995

Krivit, Dan, "Plastics Recycling Collection Pilot Project Leads to Success", Resource Recycling, pp. 71-76, May 1991

Lamp, Jennifer, and M. Chertow, "Plastics Collection", Biocycle, pp.62-63, April 1990

Leaversuch, D. Robert, "Color-Sortation Technologies Improve PCR Quality and Value", Modern Plastics, pp.100-101, June 1993

Lund, F. Herbert, "Plastics", Chapter 14, The McGraw-Hill Recycling Handbook, McGrow Hill Inc.,New York, 1993

Lynch, Meg, "Recycling Markets in 1996: Hope Springs Eternal", Resource Recycling, pp. 29-32, December 1996

Mapleston, P., "Cryogenics Improve PVC Separation", Modern Plastics, pp. 80-83, November 1991

Merriam, C. Neale, D. Morrow, G. Chang, and J. Pappas, "Collecting All Clean Plastics: data and results", Resource Recycling, pp.20-25, January 1993

Merriam, Neal, Personal Communication, November 1994

Misner, Micheal, "Modern MRFs: Muscles vs. Machines", Waste Age, pp.27-30, February 1992

Modern Plastics, pp.63-68, January 1995

Moore, Patricia, " Cost Effective Collection of Recyclables", Biocycle, pp.36-37, July 1992

Morgan, R.D, and R.G. Kenny, "Automated Separation of Commingled Plastic Containers", Paper presented at National Waste Processing Conference, 1992

Mustafa, Nabil, "The Legacy of Landfill and Landfill Legislation", Plastics Waste management, Marcel Dekker, Inc, New York, 1993

Pearson E.Wayne, Plastic Beverage Containers Enhance Multi-Material Curbside Collection Programs, Plastics Recycling Foundation Inc., 1989

Perkins, Ron, "Collection Economics for Plastics Recycling: A New Methodology", Resource Recycling, pp.66-69, May 1991

Perry R.H., and C.H. Clinton, Chemical Engineering Handbook, 5th Edition, McGraw Hill Book Co. Inc., New York, pp. 21-33, 1973

Petty, A. Charles, S.K. Ali, E.A. Grulke, and S.E. Selke, "Hydrocyclone Classifiers for Microsorting Mixed Thermoplastics from Consumer Waste", Proceedings of Waste Stream Minimization and Utilization Innovation Concepts-An Experimental Technology Exchange, vol. 1, pp.4.1-4.11, April 1993

Platt, A. Brenda, "Co-collecting recyclables and mixed waste: problem and opportunities", Resource Recycling, pp. 39-50, March 1993

Plastic News, June 1997

Powell, Jerry, "Automated Plastic Bottle Sorting: An Emerging Technology, Resource Recycling, pp.62-69, August 1992

Rankin, Sidney, Plastics Collection and Sorting-including plastics in a multi-material recycling program for non-rural single family homes, Center of Plastics Recycling Research, New Jersey, 1988

Raymond, Micheal, " Recycling Legislative Update", Modern Plastics Encyclopedia'96, pp.A43-47, Mid-November 1995

Richards, B., and A.K. Naj, "Dupont and Waste Management Plan to Build Largest U.S. Recycling Plant", Wall Street Journal, pp. A4, April 1989

Schroeder, O. George, "Plastics Keep Edge Over Competing Materials in Packaging Markets", Modern Plastics Encyclopedia' 96, pp. A35-39, Mid-November 1996

Schult, J., "Cryogenics Remove PVC from PET and HDPE Recycle", Plastic Technology, pp. 28-29, April 1993

Siegler, Ted, "Collecting Plastics Bottles More Efficiently",Resource Recycling, pp.27-42, September 1994

Stevens, J. Barbara, "Cost Analysis of Curbside Program", Biocycle, pp.37-38, May/June 1988

Steuteville, Robert, "The State of Garbage of America", Biocycle, pp.54-61, April 1996

Svarovsky, L., and M.T. Thew, Hydrocyclones: Analysis and Applications, Kluwer Acadamic Publisher, Dordrechet, 1992

White, S. Francis, "Bottle-to-Bottle Recycling Systems for HDPE", pp.80-90, Plastics Reycling as a Business Opportunity, Plastics Institute of America Inc., New Jersey, 1992