Materials and Energy Recovery from the Dry Stream of New York City's Municipal Solid Waste

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Abstract

The New York City Department of Sanitation must handle 13000 tpd of residential waste. Until recently, most of this material was sent to the city's only landfill, Fresh Kills on Staten Island. The city and state governments decreed that this landfill would close by the end of the year 2001. Source reduction efforts and increased recycling have alleviated some of the problems caused by the closure of this landfill; however, these efforts are hardly enough. Hence, the city has come up with a plan to ship most of its waste out-of-state to landfills, mostly in Virginia and Pennsylvania. New Jersey is to be used as a stop over for some of the waste on its way to the landfills. Many public officials in these states have come forward to voice opposition to this plan. This and the fact that the plan relies too heavily on landfills are evidence that the city needs to develop an alternative strategy.

Integrated waste management provides this alternative. Integrated waste management means that all possible strategies are used to handle the municipal waste. This includes the three already mentioned, source reduction, recycling, and landfilling, and waste to energy and bioconversion of organics. The city has prematurely abandoned waste to energy as a waste management technique. Modern facilities operate with very low emissions and mesh easily with recycling programs. This avoids two of the biggest historic faults of waste to energy.

This study advocates a new system for New York City's waste. Separation of organics by the citizen would allow for aerobic or anaerobic digestion to produce a compost product. The rest of the waste would be sent to modern material recovery facilities to recover recyclables. These modern designs would most likely lead to higher recovery percentages than the present methods and would allow for the combustible residue left after this recovery to be processed into a fuel. The fuel could then be used in a dedicated waste to energy facility or as a co-fuel in a coal-fired power plant. It could even be combined with shredded tires before energy recovery. This plan would leave a manageable amount that must be sent to a landfill. New York City has the two-headed problem of high levels of waste and low levels of land for disposal that make developing a waste management plan difficult. Therefore, it must fully embrace the ideas of integrated waste management if it is to develop a sustainable plan for dealing with its waste. This study is a step in that direction.

1. Introduction

The problem of municipal solid waste (MSW) is one that faces every community. According to the US Environmental Protection Agency (EPA), the US generated about 217 million tons of MSW in 1997 (Franklin Associates, 1998). The best way to deal with this problem is through an integrated approach, since no one solution will solve the whole problem. This viewpoint has led to the concept of integrated waste management (IWM), which seeks to integrate various techniques of dealing with MSW. These techniques include source reduction, recycling, treatment of organic waste, energy recovery, and landfilling. IWM recognizes that waste management plans are location specific; that is, what works in one place may not work in another. It also helps ensure that the maximum use is gotten out of waste before the final option, landfilling, is considered.

New York City is facing many tough issues regarding its waste. The city and state governments decreed that the city's only remaining landfill, Fresh Kills, would close by December 31, 2001. Therefore, the Department of Sanitation must come up with a new waste management plan for the 13000 tons per day (tpd) (New York City DOS, 1998) of residential solid waste that it currently handles. So far, the city's plan has been to ship its waste out of town, mostly to Virginia and Pennsylvania. Some waste may be sent to an incinerator in Essex County, NJ as well. Along these lines, less and less waste is being sent to Fresh Kills, while more is shipped away from the city in order to phase out dependence on the landfill. This plan may not be sustainable for several reasons. For one, the cost per ton may become prohibitively high with time. In addition, opposition from the receiving states continues to grow, as seen by the various conflicts that have already erupted between the city and New Jersey and Virginia. Moreover, heavy reliance on landfilling, which is the least desirable alternative from an environmental perspective (Dennison, 1996), means that much of the material and energy in the waste are not put to use.

New York City and its citizens should begin to realize that an IWM approach is desperately needed. While the city has used some aspects of IWM relatively successfully, it has not really developed an overall IWM plan. Recycling continues to be promoted and composting has been investigated, but further efforts must be made to ensure adequate re-use of the city's waste.

Columbia University has been investigating the various facets of IWM and how they could be applied to New York City. This research has focused on the treatment options available if the city were to collect the organic fraction (food waste, etc.) as one waste stream and the rest of the waste as another, with the possibility of a separate paper stream. The treatment of the organic fraction, or "wet stream," is discussed in another paper (Themelis, 2000). This paper focuses on the treatment of the rest of the waste, or the "dry stream." The dry stream would undergo processing to recover recyclables and prepare the residue for use as a fuel. The same recyclables that are recovered today would be recovered in this new system, probably to even higher levels. Furthermore, much of the material that is currently landfilled would be used for producing electricity. This would reduce not only the volume of material that must be transported to landfills in other states but also the consumption of non-renewable fossil fuels.

2. New Collection System

Collection has historically accounted for anywhere from 50 to 70 percent of the total cost of solid waste management (Tchobanoglous et al., 1993). Thus, any change in the collection system can have a significant effect on the economics of a plan. Today, New York collects three different streams of waste. One is made up of paper; a second is commingled containers and household metal. These two undergo processing to extract recyclables. The third stream is made up of all other trash and is slated for some means of disposal, usually landfilling.

The plan discussed in this paper would not increase the number of streams that the city collects presently, so it avoids the potential cost increases inherent in more complicated collection. In one manifestation of the new plan, one stream would be paper as before. The second stream, called the "wet" stream, would consist of the matter containing moisture, that is, food waste, leaves, yard trimmings, etc. This stream would ideally be sent to a processing facility, either aerobic or anaerobic for the production of compost and other possible fuels, such as methane or ethanol; however, it may also be disposed in landfills. Non-moist materials would constitute the third, or "dry," stream. It would include non-recyclable paper, plastics, metal, glass, etc., and would be sent to a materials recovery facility (MRF) for removal of recyclables. Ultimately, however, there would be a significant amount of this stream that is not recyclable. This remaining material is the residue from the MRF processing operations, which has been sent to landfills in the past. In this plan, additional MRF equipment would process this residue into a fuel to be used for producing electricity. Thus, the residue is a form of refuse-derived fuel (RDF). Energy recovery from this RDF ensures that MSW is used to the fullest extent possible.

There are obvious variations on this plan. Paper may or may not be collected separately. If it is not collected separately, alterations in MRF design are necessary to allow for separation of paper at that stage. If the paper is collected separately, the residue from its recycling could be mixed with the dry stream residue to make additional fuel. Whatever the means of handling the paper stream, it will obviously have an effect on the properties of the resultant residue. This is examined in another section of the paper.

3. Recycling Compatibility of New System

One of the criticisms of waste-to-energy (WTE) in the past has been that it inhibited efforts to recycle. Historically, most WTE plants have used mass burn technology, which usually does not include recycling. All waste is fed to a combustor with little pre-processing. In contrast, recycling is an integral part of the proposed plan. The recovery of some materials actually increases the heat content of the resultant fuel. This fact is made clear in subsequent sections of this paper with numbers and graphs. In addition, the segregation of the wet stream from the dry facilitates both transport and processing of the two streams. Possible designs for MRFs that would process the dry stream are put forth in the second part of this paper. It is shown that glass, plastic, and ferrous and non-ferrous metals can be recovered to a greater degree than under the current waste management plan for New York City. This is possible through the simplification of the collection system. Under the current recycling plan, many recyclables are lost because they do not get collected in the two recyclable streams that go to MRF's. The rejects from the wet stream could possibly be sent to the MRF so that misplaced recyclables might be recovered. Paper is subject to variations that are explained in another section.

4. Energy Recovery

After the removal of recyclable materials, the remainder is processed into a fuel. This fuel would be used to recover energy from the non-recyclable waste, thereby getting some use out of it. There are many different ways that the actual energy recovery can be achieved. The most basic method is to burn the residue in a dedicated WTE facility, although it could be burned as a co-fuel in other facilities. The main difference between facilities is in the combustion technology. Several types of combustion are explained further in the sections below with some historical examples as well as some information about emissions and ash management.

4.1 Combustion Techniques for Energy Recovery

4.1.1 Mass Burn

This is the historical method of choice for incineration of waste. In fact, this method led to the name incineration, as it was often carried out only for volume reduction and not for energy recovery. One of the advantages of mass burn is that it requires no pre-processing of the waste, apart from manually removing bulky items like “white goods”. The waste is conveyed over a metal grate in a combustion chamber for incineration. Residual material or ash exits the chamber and is prepared for disposal. There have been improvements over the years in combustion efficiency and pollution control, but this technique has been surpassed by newer technologies that are discussed in the following sections of this report.

4.1.2 Fluidized-Bed Combustors

This is the technique of choice in Japan, although some European countries have been pursuing it as well. In this type of combustor, the shredded waste is fed into a fluidized bed of sand or limestone. Combustion under these conditions is more efficient and results in higher energy recovery and reduced amounts of non-oxidized materials leaving the combustion chamber. This method, however, does require some pre-processing of the waste. Glass and metal do not burn l, so they should be removed before the waste is introduced into the fluidized-bed. Unlike mass burn incinerators, fluidized-bed combustors can burn waste with variable moisture content, which means that less paper or wood need be present for good combustion. Thus, paper recycling prior to combustion is possible without detrimental effects on the energy recovery. This shows that fluidized-bed combustors are more compatible with a recycling program than mass burn incinerators.

4.1.3 Refuse-Derived Fuel (RDF)

Although the above combustors can be said to use refuse-derived fuel (RDF), the term usually refers to MSW that has been processed sufficiently to result in a uniform fuel that is ready for combustion. This combustion can even take place in some conventional thermoelectric plants. The processing generally entails separation of certain materials, size reduction, and densifying (e.g. pelletizing). This processing allows for the removal of both recyclables and hazardous materials, but it is also expensive given the current state of separation technology. The resulting pellets are more easily transported, stored, and incinerated than raw waste. For a full discussion of RDF consult the source from Hasselriis (Hasselriis, 1984).

Due to concerns over the formation of dioxins and hydrochloric acid (HCl) production in waste combustion, very stringent standards have been enacted to control these compounds. RDF offers storage and transport advantages. RDF can be produced on a small scale at several locations and used as a fuel in a large plant where emission controls are more effective. In addition, the processing that leads to RDF can include the introduction of calcium compounds that capture any chloride compounds in the gas cleaning stage after combustion. Thus, RDF can lead both to lower emissions and higher energy conversion efficiency.

4.1.4 The SEMASS WTE plant (Sutin, 1999)

The SEMASS facility in Rochester, MA is an excellent example of a state-of-the art WTE plant. Energy Answers Corporation (EAC) designed and built this facility, presently operated by American Ref-Fuel. EAC has made use of several innovative techniques that make the plant very clean and efficient. It should be noted that this facility processes waste from the entire waste stream, not from a wet/dry separate collection system. The facility takes in waste from 40 surrounding communities, within a 65-mile radius, and processes nearly 3000 tons per day (tpd) in three combustion units. Waste is brought to SEMASS by rail and truck and dumped on a tipping floor. The waste is loaded onto conveyors that pass inspectors who look for bulk waste that could jam the shredders or hazardous waste that are removed and disposed in a proper location; approximately 1.6% of the incoming material is removed at this point. Next, the waste is shredded in large hammermill shredders that produce a blended material of –6 inches (-15 cm) size. The shredded material is conveyed under overhead belt magnets for an initial round of ferrous metal recovery. The recovered ferrous metal, which at the SEMASS facility amounts to about 2.6% of the incoming material, is recycled and the remaining material, now known as processed refuse fuel (PRF), is sent to a storage building. This PRF can be stored for long periods as it does not attract rats or flies and has negligible odor.

The PRF is conveyed to bins and from there to feed chutes that introduce it into three separate combustion chambers. Much of the PRF is combusted "in suspension" to produce steam that is used to generate electricity. This is achieved by a combination of the design of the feed chutes and blown air. At the point that the feed chutes enter the boiler, there is a small deflector so that the PRF is fed upwards into the furnace. Air is blown from under the feed chutes to cause even more material to be carried upwards in the furnace. Material then catches fire in midair and, thus, burns "in suspension." This process allows for high temperature combustion that assures that any dioxins/furans in the PRF are destroyed inside the furnace. The feed rate of PRF into the boilers is adjusted based on automated temperature controls to ensure optimum utilization of the boilers. The boilers at SEMASS are waterwall type, without refractory linings. The steam produced is superheated for the generation of electricity, some of which (about 100kWh/ton of PRF) is used to run the plant while the rest (550 kWh/ton) is sold to the local utility.

Air pollution is controlled by a variety of means. The third combustion line was implemented in 1995 and has the most sophisticated gas cleaning system: A solution of urea in water is injected into the furnace to control the level of nitrogen oxides. After the combustion gases have exited the boiler and passed through water and air preheaters, they enter a spray drier that injects lime slurry to neutralize acid gases and trap any chlorides and dioxins/furans that may have persisted or re-formed during the cooling stage of the gas. Finally, a fabric filter captures fine particles before the gases are discharged through the stack.

The bottom of the combustion chamber consists of a moving grate that collects non-combustibles and heavy combustibles that fall after being blown into the boiler. The grate moves at a variable speed, but generally travels the full length of the boiler at a speed that provides a residence time of the ash bed of about one hour. Heavy combustibles are further combusted over the first two-thirds of the grate. The final one-third allows for the ash to be cooled by air that is blown through the grate. Finally, the ash "clinker" falls onto another conveyor that transports it to the ash processing facility. Ferrous and non-ferrous metals are recovered from this bottom ash leaving a granular material, which EAC has named Boiler

Aggregate™. The use of this aggregate as a replacement for crushed stone is being tested; the ash is currently used as alternate daily cover (ADC) at a nearby landfill. Fly ash from the air pollution control equipment contains most of the heavy metals that were present in the waste and is landfilled. EAC utilizes a patented stabilization system to bind heavy metals so that they do not leach out during various tests performed on the ash.

Based on the performance of the EAC system at the SEMASS facility, approximately 76.7% of the incoming waste is converted into energy; 13.7% of the incoming material is recovered through ferrous and non-ferrous metals separation; and 9.7% of the material is sent to the nearby SEMASS backup landfill. Figure 10 (page 44) shows the flowsheet of the SEMASS facility with actual numbers from the facility included. The facility generates electricity 24 hours a day, but the fuel preparation portion of the process operates only 16 hours each day and the ash processing is carried out in only 8 hours each day. The EAC process results in efficient and clean production of energy from waste and significant reductions of material that must be sent to a landfill.

4.1.5 Co-Firing with Coal

Another use for the fuel derived from the dry stream residue is as a fuel for use in coal-fired power plants. The residue fuel, or coal substitute (CS), can be mixed with coal before it is fed into a boiler or inside the boiler itself. An obvious advantage of this system is that it takes advantage of an already existing plant. Thus, the large capital cost of a WTE facility is avoided. As the state of New York and the US EPA file litigation against power plants for their violation of the Clean Air Act, another advantage of co-firing emerges. The addition of CS to coal in a power plant may lower some of the problem emissions, like sulfur. This possibility needs further investigation before it can be ensured. Several plants in the United States have tried this combination with varying degrees of success.

The co-firing of coal and a fuel derived from MSW has been attempted a few times in the US, such as in St. Louis, MO, South Dakota, and Lakeland, FL. The St. Louis plant was the first attempt to co-fire processed MSW and coal in a utility boiler. This project took place in the 1970s during a time that significant money and effort were put into research on resource recovery. A demonstration was organized to co-fire prepared MSW and coal in suspension-fired utility boilers. For a full discussion of this demonstration, consult the reference from Horner &

Shifrin, Inc. (Horner & Shifrin, Inc., 1970). Their study concluded that this technology was feasible under the proper conditions. They recommended using a combination of 10% prepared MSW to 90% coal. The success of the demonstration project led the Union Electric Company to decide to go ahead with full-scale plans at its Merramec power plant. This project soon failed due to several factors, such as community opposition to a transfer facility, financial constraints, and inadequate supply of waste. None of these reasons, though, reflected a problem with the technical aspects of the project. The demise of this project is discussed in Brenda Harrison's book (Harrison, 1980).

Another test was carried out in South Dakota under the supervision of the US Department of Energy's (DOE) Argonne National Laboratory (ANL), the National Renewable Energy Laboratory (NREL), and the Otter Tail Power Company in 1992. This test combined 12% (by weight) binder-enhanced densified refuse-derived fuel (b-dRDF) with 88% coal prior to introduction to a cyclone furnace. ANL had performed full-scale tests in a spreader-stoker combustion unit, but decided that the technology should be tested in the cyclone furnace since this type is more prevalent in industry. This test showed that the boiler efficiency was only decreased by about one percent upon the addition of b-dRDF to coal, and emissions were about the same. Most emissions decreased while some metals increased slightly. The small reduction in efficiency was attributed to moisture in the waste, which could be avoided by the separate collection of the wet stream. All ash samples from this test passed the EPA's toxicity characteristic leaching procedure (TCLP) tests. For a thorough examination of this test, consult the report from ANL (Ohlsson, 1994).

Another application of the mixing of MSW and coal is ongoing in Lakeland, FL. This application does not involve the separation of the moisture-containing materials as is being advocated here. However, it is an example of an operation that continues to make use of MSW as a co-fuel in a coal-fired power plant. The McIntosh Power Plant has been burning co-fuel since 1983, and uses 10% RDF to 90% coal. It was designed to use up to 500 tons per day of RDF (Clarke, et al., 1991).

4.1.6 Mixing of RDF with Tire Derived Fuel (R/TDF)

Refuse derived fuel can also be mixed with shredded tires to produce a fuel with higher calorific value. This technique would have the added benefit of putting the substantial number of discarded tires that accumulate every year to a practical use. These discarded tires numbered about 253 million in 1996 (Serumgard, 1997). If these tires are discarded in a heap, or tire pile, they present a fire and air pollution hazard, and also an ideal breeding ground for mosquitoes. The latter problem is even more important after the recent outbreaks of mosquito-borne diseases in the New York City area. Tires alone have been tested as a co-fuel mixed with coal in power plants (US EPA, et al., 1993). These attempts have been successful and would facilitate acceptance of this type of mixed fuel to be used as a coal substitute. The rapid growth of the use of discarded tires as a fuel source also provides encouragement for the use of the residue as a fuel. In 1990, the Scrap Tire Management Council estimated that only 11% of generated scrap tires could be utilized by the current market. However, by the end of 1996, over 75% of the scrap tires were being consumed by the market, and the largest component of this market is tire-derived fuel (TDF) (Serumgard, 1997).

4.2 Other Techniques

4.2.1 Gasification

In general, gasification refers to the conversion of a solid or liquid feed to a gas through partial oxidation at elevated temperatures. Partial oxidation is achieved by restricting the supply of air. The product gas from waste gasification contains carbon monoxide, carbon dioxide, methane, hydrogen, water, nitrogen, and small amounts of hydrocarbons. The gas may also contain particulate matter and/or tars that should be removed before combustion. Gasification is an old technology but is still being adapted to waste applications.

4.2.2 Pyrolysis

Pyrolysis, or thermolysis, occurs when a material undergoes thermal degradation in the complete absence of any oxidizing agent. As in gasification, the oxidizing agent is air or oxygen, but its complete removal is unlikely so some oxidation will occur. When MSW undergoes pyrolysis, complex molecules are broken down into simpler ones. The products are gas, liquid, and a char residue. The relative amounts depend on several factors, such as the temperature of the process, the time of exposure to this temperature, and the make-up of the material.

4.3 Emissions Issues

A contentious issue when discussing energy recovery from waste is that of air emissions. Emissions of mercury, hydrochloric acid, and dioxin have been the most worrisome problems in the past. However, such emissions have been reduced to very low levels in modern plants by means of reduction of the precursors in the feed, better combustion practices, and much improved pollution control mechanisms, such as the advanced dry-scrubbing and filter bag technologies that are used in the SEMASS plant discussed earlier. Mercury is less and less of a problem as it has been removed from household batteries, replaced by digital technology in thermometers, and reduced in the feed by separate collection of fluorescent lights.

All of the air emissions have been reduced by the improved air pollution control mechanisms that are required in today's WTE facilities. In the co-firing tests conducted in South Dakota discussed above, sulfur dioxide and carbon monoxide emissions were much lower than those observed in coal-fired tests; hydrochloric acid and particulates increased, but only slightly, and dioxins and furans were well below federal and state regulated levels (Ohlsson, 1994).

Modern, dedicated WTE facilities perform similarly well. Table 1 compares air emission levels for the SEMASS plant in Massachusetts and the Robbins Resource Recovery Facility in Illinois with the current EPA standards. It can be seen that the emission levels actually attained are substantially lower than those mandated by EPA.

Table 1: Emissions from WTE Facilities Compared to EPA Standards

Emission	EPA Standard[1]	SEMASS[2]	Robbins[3]
Particulates (gr/dscf)	0.010	0.002	0.0015
Sulfur Dioxide (ppmdv)	30	17	1.0
Hydrogen Chloride (ppmdv)	25	4.4	4.6
Nitrogen Oxides (ppmdv)	150	148	73.1
Carbon Monoxide (ppmdv)	150	47.1	4.4
Cadmium (µg/dscm)	20	0.426	<detection limit
Lead (µg/dscm)	200	11.9	3.6
Mercury (µg/dscm)	80	3.43	15.8
Dioxins/Furans (ng/dscm)	13	1.08	2.1

gr:grains; dscf:dry standard cubic foot; ppmdv:parts per million dry volume; µg:microgram; dscm: dry standard cubic meter; ng:nanogram

The standards and data are corrected to 7% O_2, dry basis, and standard conditions.

[1] 40 CFR Part 60, Subpart EB for new RDF-fired Municipal Waste Combustors.

[2] EAC, 1999.

[3] Studley, 1997.

4.4 Ash Reuse and/or Disposal

Companies and individual researchers have been investigating ways of treating ash residues from WTE facilities. Ash consists of residues left in the combustion chamber (bottom ash) and in the air pollution treatment devices (fly ash). Concerns about the ash include dioxins, furans, and heavy metals. Treatment of ash usually involves the vitrification at high temperatures in order to immobilize the metals. It should be noted that the bottom ash produced in efficient combustion systems, such as the SEMASS plant, reach high temperatures during the combustion process. This means that the metals are not leachable, as determined by standard EPA tests, such as the toxicity characteristics leaching procedure test (TCLP).

Treatment of ash is a much more mature technology than re-use. The main aim is to prevent the toxic constituents of the ash, especially heavy metals, from escaping into the environment after disposal. Solidification is the first step in this prevention, but it is not the only necessary action. Vitrification and the application of various chemicals are further means of decreasing the chances of leaching by metals. Phosphate has been shown to stabilize heavy metals in dusts that result from the vitrification of incinerator ash (Eighmy, et al., 1998). Some researchers have attempted to use the ash as a substitute for aggregate in road base and other applications of crushed stone and concrete. Comprehensive assessments of the re-use of ash can be found in the papers by Wiles (Wiles, 1995) and Chang (Chang, et al., 1998).

5. Characteristics of New York City's Waste Stream

This paper makes use of a characterization study of New York City's waste stream from 1990, conducted by SCS Engineers (SCS Engineers, 1992). The report covered residential, institutional, and commercial waste and broke data down by season, borough, and types of waste using demographic factors to ensure the accuracy of the characterization. This study uses the data covering annual, citywide residential waste composition. For the residential sector, the study used nine sampling levels based on income and population density. Table 2 shows the residential waste composition for New York City, divided into a wet stream and a dry stream, as used in this study.

Table 2: NYC Waste Composition (1990)

WASTE COMPONENT	% BY WEIGHT	TONS PER DAY (tpd)*
Dry Stream	**61.7**	**8021**
Paper	*31.3*	*4069*
Corrugated Cardboard	4.7	611
Newspapers	9.2	1196
Office/Computer Paper	0.8	104
Magazines/Glossy Paper	2.7	351
Books	0.8	104
Non-Corrugated Cardboard	2.5	325
Mixed Paper	10.7	1391
Plastics	*8.9*	*1157*
Clear HDPE Containers	0.5	65
Colored HDPE Containers	0.6	78
LDPE Containers	0.1	13
Films and Bags	4.8	624
Green PET Containers	0.1	13
Clear PET Containers	0.4	52
PVC	0.1	13
Polypropylene	0.1	13
Polystyrene	0.8	104
Miscellaneous Plastics	1.3	169
Glass	*5.0*	*650*
Clear Glass Containers	2.9	377
Green Glass Containers	1.0	130
Brown Glass Containers	0.9	117
Miscellaneous Glass	0.2	26
Aluminum	*0.9*	*117*
Ferrous Metal	*3.9*	*507*
Food Containers	2.0	260
Miscellaneous Ferrous Metal	1.9	247
Miscellaneous	*11.7*	*1521*
Wood	2.2	286
Textiles	4.7	611
Rubber & Leather	0.2	26
Fines	2.3	299
Other	2.3	299
Wet Stream	**28.0**	**3640**
Food Waste	12.7	1651
Grass/Leaves	3.4	442
Brush/Prunings/Stumps	0.7	91
Disposable Diapers	3.4	442
Miscellaneous Organics	7.8	1014
Hazardous Waste	**0.4**	**52**
Bulk Items (appliances,furniture,etc)	**9.9**	**1287**

Adapted From: SCS Engineers, 1992 *At current rate of generation of 13,000 tons per day (tpd)

6. Recovery of Recyclables from Dry Stream

An important aspect of the plan under examination is that it provides for the recovery of recyclable materials from the waste stream. Currently, some paper, glass, ferrous metals, non-ferrous metals, and some plastic are sorted for recycling at the paper and metal, glass, and plastic (MGP) MRF's. Under the new system, these same materials would be recovered, possibly at higher levels. Recycling would be carried out in different ways depending on the level of sophistication of the MRF, which would also be used to prepare the residue for use as a fuel. Depending on the objectives of separation, the MRF would consist of different unit operations for the recovery of various recyclables. The most common of these and some advanced unit operations are described in the next section. Several scenarios for possible MRF's are then illustrated with flowcharts to show the recovery of recyclables and the preparation of the residue for use as a fuel.

6.1 Unit Operations

The following sections describe unit operations that are used to some extent currently. The most common measure for judging the performance of a unit operation in a MRF is the recovery efficiency. This is expressed as the ratio of material recovered for recycling to the amount of that material that entered the unit operation. That is, if 100 tons of ferrous metals enter the unit operation and 90 tons are recovered, the recovery efficiency is 90%. These efficiencies are provided for several of the unit operations. Some unit operations have an efficiency that is determined slightly differently, but the overall assessment is similar. The shredder and flail mill do not have efficiency ratings as they are only used for material processing and fuel preparation, not for recovery. There are numerous sources that provide details about these unit operations (Stessel, 1996; Wills, 1997; Vesilind, 1981; Swartzbaugh, et al., 1992)

6.1.1 Hand Sorting

The oldest and most basic unit operation is hand sorting or manual removal of materials. All too often, this is the most used method of separation. Hand sorting is usually only profitable for the recovery of a high-value material. The general layout of this operation is as follows. A conveyor belt carries material past any number of people lined up on both sides of the belt.

These people look for whatever material they are to separate and pull it off the conveyor as it moves. The recovered material is dropped into bins where it can later be processed for delivery. This processing may include shredding, compacting, and/or baling. The recovery efficiency for this method varies widely and is affected by the type of material to be recovered, the speed of the conveyor, the thickness of the material on the conveyor, and other factors. One source lists this method as being 60-95% efficient in recovering the selected material (Swartzbaugh, et al., 1993). Hand sorting is slowly being replaced in more and more applications by mechanical means of separation that save both money and time and increase the sorting capacity of the MRF.

6.1.2 Shredding

Several types of shredders are used in MSW applications, but all are used for the purpose of size reduction, also known as comminution. The advantages of shredding MSW include ease of transport, odor reduction, and better combustion. The shredders germane to this study are the flail mill and the hammermill, although others, including the ring grinder, can be used as well. Since NYC's residential waste is collected in bags, the first step in a MRF is debagging, which is accomplished by the flail mill. Debagging allows for preliminary recovery of materials before the waste is introduced to the main shredder in the MRF. This main shredder is often the hammermill. A hammermill shredder is very true to its name. It consists of several hammers, rotated by a shaft, that strike feed material dropped into the shredder. The material is moved through the shredder by the rotation of the hammers and is discharged after being reduced to a size that allows passage through a grate in the bottom. These openings or screens can be changed to allow for different levels of size reduction. This unit operation requires a high level of supervision to ensure optimum performance. A shredder is often the largest energy user in a MRF so optimum performance can reflect significantly on the operation's bottom line. Shredder operating problems are jamming by oversize or fibrous materials and explosion risks, but these problems are infrequent and manageable.

6.1.3 Air Separation

Air separation can be accomplished by means of different devices, but the theory is the same. Materials of varying densities will behave differently in the presence of a moving fluid, such as air. The two devices important in this work are the air knife and the zig-zag air classifier. In both designs, the flow of air is adjusted to the optimum flow for the materials that are undergoing separation. The air stream forces the low-density materials to move farther than the high-density materials, thereby creating different streams. These streams are often called the "lights" and the "heavies." Basic drawings of the air knife and the zig-zag air classifier are included in Figures 1 and 2, respectively. Air classifiers generally have a recovery efficiency of 80-85% (Vesilind, 1981). This means that 80-85% of the low-density material is ejected with the "lights" stream, or the high-density material with the "heavies."

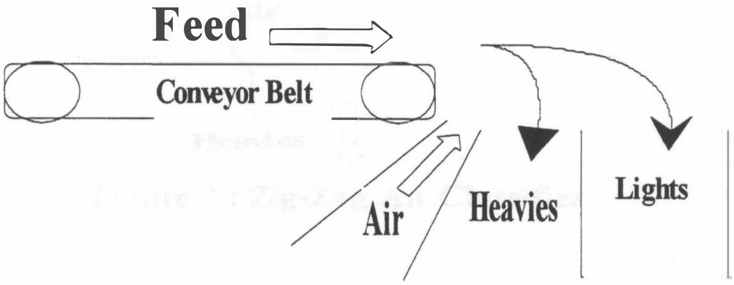

Figure 1 : Air Knife

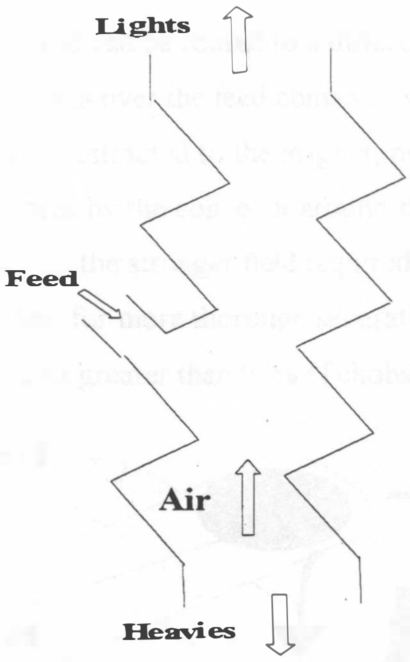

Figure 2 : Zig-Zag Air Classifier

The air knife would be useful if the MRF design called for the separation of plastic film and some types of paper. The zig-zag air classifier would be used to separate the light-density materials from the high-density materials downstream in the layout of the MRF. This air classifier would concentrate the high-density materials to allow better recovery by other unit operations in the MRF.

6.1.4 Magnetic Separation

Magnetic separation is used to recover ferrous metals from the waste stream. As with all of the other unit operations, there are several ways to accomplish this separation. Only the most appropriate will be discussed here. For further discussion, the reader is referred to the sources listed above. Ferrous metal recovery takes advantage of the iron present to manipulate it in the presence of a magnetic field. The magnets used can be either permanent magnets or electro-magnets. The choice is dependent on several factors, including placement in MRF layout and energy cost. The two main types of magnetic separators are overhead belt magnet and tail-rotor magnet separators, with the overhead belt being the more desirable. The tail-rotor magnet is shown in Figure 3 and is often cheaper and easier to operate. It consists of a magnet, usually a permanent magnet, in the tail-rotor of a feed conveyor. Ferrous metals are attached to the conveyor for a longer time and can be routed to a different place for recovery. The overhead belt magnet, seen in Figure 4, hangs over the feed conveyor with the magnet located inside another conveyor. Ferrous metals are attracted to the magnet, pulled up from the feed conveyor, and transferred to a collection area by the conveyor around the magnet. This apparatus generally uses an electro-magnet due to the stronger field required. However, this approach takes advantage of gravity to allow for more thorough separation. Magnetic separation devices have achieved recovery efficiencies greater than 95% (Tchobanoglous et al., 1993).

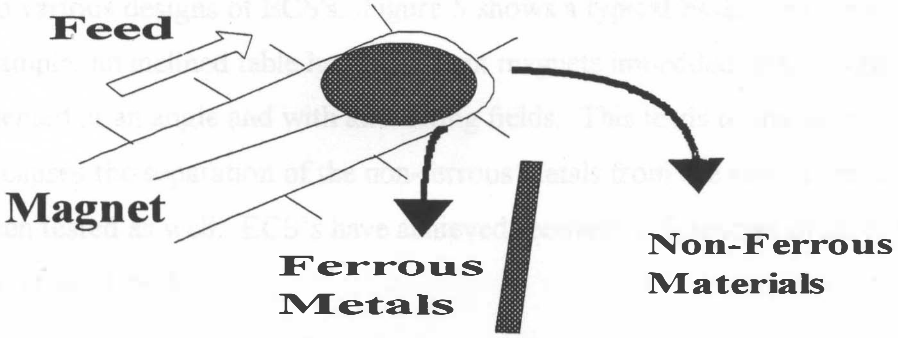

Figure 3 : Tail-Rotor Magnet

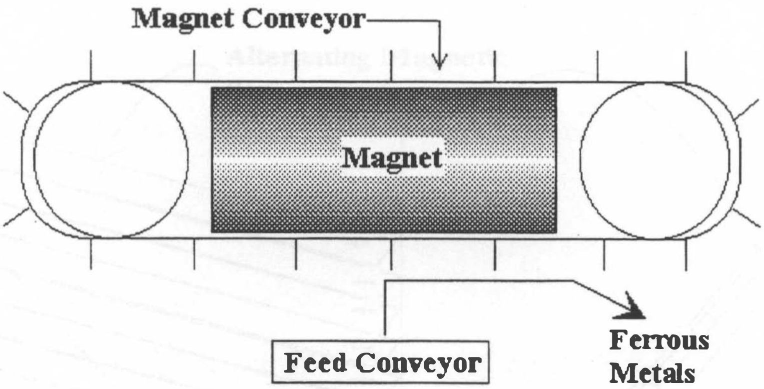

Figure 4 : Overhead Belt Magnet

6.1.5 Non-Ferrous Recovery

The recovery of non-ferrous metals is mainly important because of aluminum. Primary production of aluminum is highly energy-intensive. Therefore, a healthy recycling market has developed for this metal with fairly stable prices and a sizeable market. Non-ferrous metals recovery often is included only to recover aluminum to realize the cost benefits of this recycling. One of the most effective devices for achieving this aluminum separation is an eddy current separator (ECS). The actual recovery by the ECS is achieved by making use of Faraday's law of electromagnetic induction. In the presence of a varying magnetic field, a material will generate a voltage according to Faraday's law. If the material is a conductor, as non-ferrous metals are, this voltage will produce a current. This current, known as an eddy current, causes a magnetic field that is opposite the original magnetic field. This produces a magnetic force that can separate the conductors from the non-conductors. The magnets used can be permanent or electro-magnets, which has led to various designs of ECS's. Figure 5 shows a typical ECS from the front and the side. In this example, an inclined table has permanent magnets imbedded near a surface. The magnets are oriented at an angle and with alternating fields. This leads to the effect described previously that causes the separation of the non-ferrous metals from the rest of the stream. Other designs have been tested as well. ECS's have achieved recovery efficiencies of up to 98% (Tchobanoglous et al., 1993).

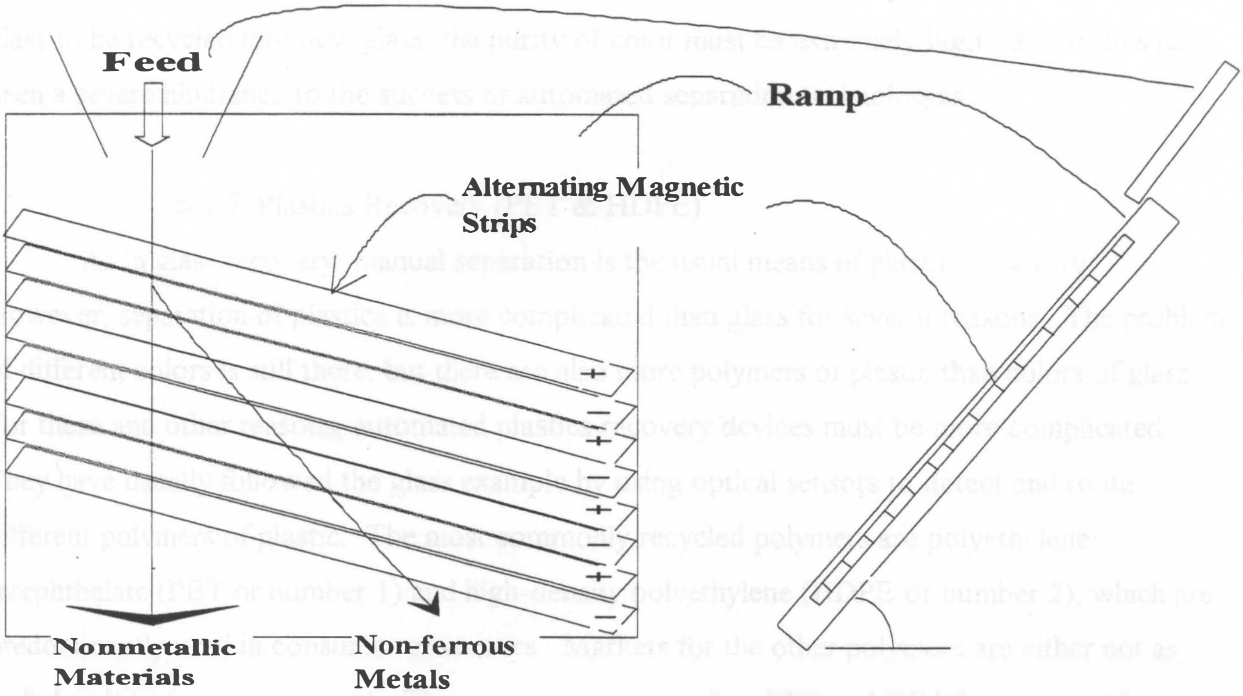

Figure 5 : Eddy Current Separator

6.1.6 Glass Recovery

Glass recovery is another unit operation that is set-up according to its planned purpose. If the MRF designer desires to separate glass according to color, then the layout will be different from a MRF where only mixed glass is desired. As expected, the color sorting of glass is much more difficult. In most MRF's, colored glass separation has not changed much over the years, as it still employs manual separation. Manual separation of colored glass entails a conveyor belt with mixed material moving past two lines of sorters, one on each side, who remove the desired colored glass bottle. The bottles are dropped into a collection area for further processing to ready the material for sale. This technique requires a large piece of glass, if not the whole bottle, if it is to be recovered. Since manual separation is expensive and inefficient, automated means of recovery have been investigated. The most extensively researched technique is optical separation. In this equipment, pieces of glass are fed past an optical sensor that detects the color. If the color matches the color being separated, a small air jet is activated to eject the piece from the feed stream. This results in different colored streams of glass, which are much higher in value than mixed glass. The purity of these streams is an extremely important issue. In order for glass to be recycled into new glass, the purity of color must be extremely high. So far, this has been a severe hindrance to the success of automated separation technologies.

6.1.7 Plastics Recovery (PET & HDPE)

As in glass recovery, manual separation is the usual means of plastics recovery. However, separation of plastics is more complicated than glass for several reasons. The problem of different colors is still there, but there are also more polymers of plastic than colors of glass. For these and other reasons, automated plastics recovery devices must be more complicated. They have usually followed the glass example by using optical sensors to detect and route different polymers of plastic. The most commonly recycled polymers are polyethylene terephthalate (PET or number 1) and high-density polyethylene (HDPE or number 2), which are predominantly used in consumer containers. Markets for the other polymers are either not as well developed or non-existent. The economics of recycling PET and HDPE, and possibly other polymers, would be improved by an efficient automated separation device. While several are on the market, none seems to enjoy mass success. Another polymer that deserves attention is polyvinyl chloride (PVC or number 3). If fed to a combustor, PVC can facilitate the formation of hydrochloric acid, dioxins, and furans, which must be removed by pollution control equipment. Removal of PVC before combustion would reduce emissions and prolong the life of the energy recovery facility. At least one company (Magnetic Separation Systems, Inc.) markets automated devices to remove PVC, either bottles or flakes, from a mixed stream.

6.1.8 Paper Recovery

The recovery of paper presents particular difficulties for MRF designers. Markets exist for certain grades of paper, but a high level of purity is required by purchasers for the more valuable grades. Often MRF's rely on manual labor to separate a dedicated paper collection to reduce contamination. Combining the collection of paper with other recyclables would decrease the costs of a waste management plan. The problem is that this combined collection would make it more difficult to ensure an acceptable level of purity in a recovered paper stream. Having efficient automated separation devices could alleviate some of this problem. Air classification devices could be used in this capacity if tuned to differentiate between the different densities of different grades of paper. As in glass and plastics recovery, optic technology has been applied to paper separation in limited capacity. The problems of paper recovery are discussed further in the next few sections as several different designs for MRF's are demonstrated.

6.2 Process Trains in MRF's

While most MRF's include some or all of the described unit operations, there are many variations possible in the arrangement of these operations. The eventual design of a MRF depends on many factors, not the least of which is economics. If a particular recyclable material has a good market and is separable, then the MRF is designed to recover this material. If the market for a material is not there, then it is a waste of money to add components to the MRF to recover it. In this analysis, MRF design must take into account the recovery of recyclables and the preparation of fuel. Combining these operations into one MRF helps ensure optimum performance. The level of preparation of the rest of the dry stream as fuel also determines some of the equipment needed in the MRF. If the fuel is to be densified, or pelletized, equipment must be added to do this. In the following MRF designs, this equipment is not shown, but it could easily be added as the last step in any MRF layout.

One way to distinguish between MRF designs is based on the level of technology present. High technology MRF's tend to focus on automated separation devices while low technology MRF's rely mainly on manual separation techniques. This difference in the level of technology affects the economics of MRF's in many ways. Not only are the capital and operating costs different, but the money generated by recovered recyclables will vary because of differences in the generation and purity of products. As important as economic considerations are, they should not be the highest priority of the MRF designer. The designer must know the feed to be processed and the materials that are to be recovered. If these two things are specified, the choice of the necessary pieces of equipment becomes clear. At that point, economics can help decide at what level of technology the MRF needs to operate.

For this study, the important difference between high and low tech MRF's is the resultant effect on the residue stream. The varying levels of recovery, inherent with differences in equipment, change the composition of the residue stream. This is especially true when handling the paper stream. If the paper is to be collected separately, as it is today, two MRF designs might be necessary: one for the paper stream and one for the rest of the dry stream. These different MRF's would likely result in performance differences that change the residue stream. If only one MRF is to be constructed, the separate collection of the paper stream might cause problems, especially for the high tech MRF. As the low tech MRF relies more on manual labor, this design would be more easily adapted to an entirely different feed stream. However, if the paper were collected with the rest of the dry stream, a high tech MRF would be the better choice as it is more suited to dealing with a feed stream with many different components. These differences become clear as several MRF designs are put forth in the following sections.

6.2.1 High Tech MRF Design for Dry Stream Processing

For a MRF to be labeled "high tech", it should include as much automated equipment as is technically feasible at the time of its construction. As of now this would mean magnetic separators, ECS's, optical glass and plastic sorters, and modern comminution and classification equipment. However, as stated previously, the purpose of a MRF is not to include as much modern equipment as possible, but to process and recover materials. That said, it is useful to examine the layout of a hypothetical high tech MRF to see what is possible. Two different high tech MRF designs are included in Figures 6 and 7. Figure 6 shows a high tech MRF that is not designed for paper recovery. This design would require a second MRF to process the separately collected paper stream. On the other hand, figure 7 shows a high tech MRF designed to process the entire dry stream. All of the designs are intended to recover the same recyclables as today and process the residue into a fuel. These figures show the processing order of the various unit operations with the connecting arrows denoting conveyor belts.

Figure 6 shows the layout of a high tech MRF designed for the recovery of ferrous and non-ferrous metals, glass, and plastics from the dry stream, but not paper. This MRF would be used if New York City continued to collect paper separately. The first unit operation in this MRF is the flail mill, which is used for de-bagging. The first materials to be separated are ferrous and non-ferrous metals. This is done with a magnetic separator and an ECS. Next, glass and plastics are recovered. Since this is a high tech MRF, automated equipment using optical sensors carry out the recovery. Glass recovery would remove flint, amber, and green glass. Plastics recovery could be set-up to recover PET and HDPE as is done today, or to include other polymers as economics and equipment dictate. Depending on the equipment selected, size reduction may be done before introduction into the next separation devices. If size reduction is not carried out before glass and plastics recovery, it is done after; and the output is sent to an air classifier for separation of the high-density materials. The lights from the air classifier are ready to be used as fuel. The heavies go through another round of metals recovery. This redundancy ensures optimum recovery of ferrous and non-ferrous metals, but may not be economically feasible for some MRF's. Finally, the remaining material is sent through a trommel to screen fine, non-combustible materials, such as glass and sand. The rest of the material is combined with the lights from the air classifier to produce a residue ready to be used as a fuel (RDF) or a coal substitute (CS).

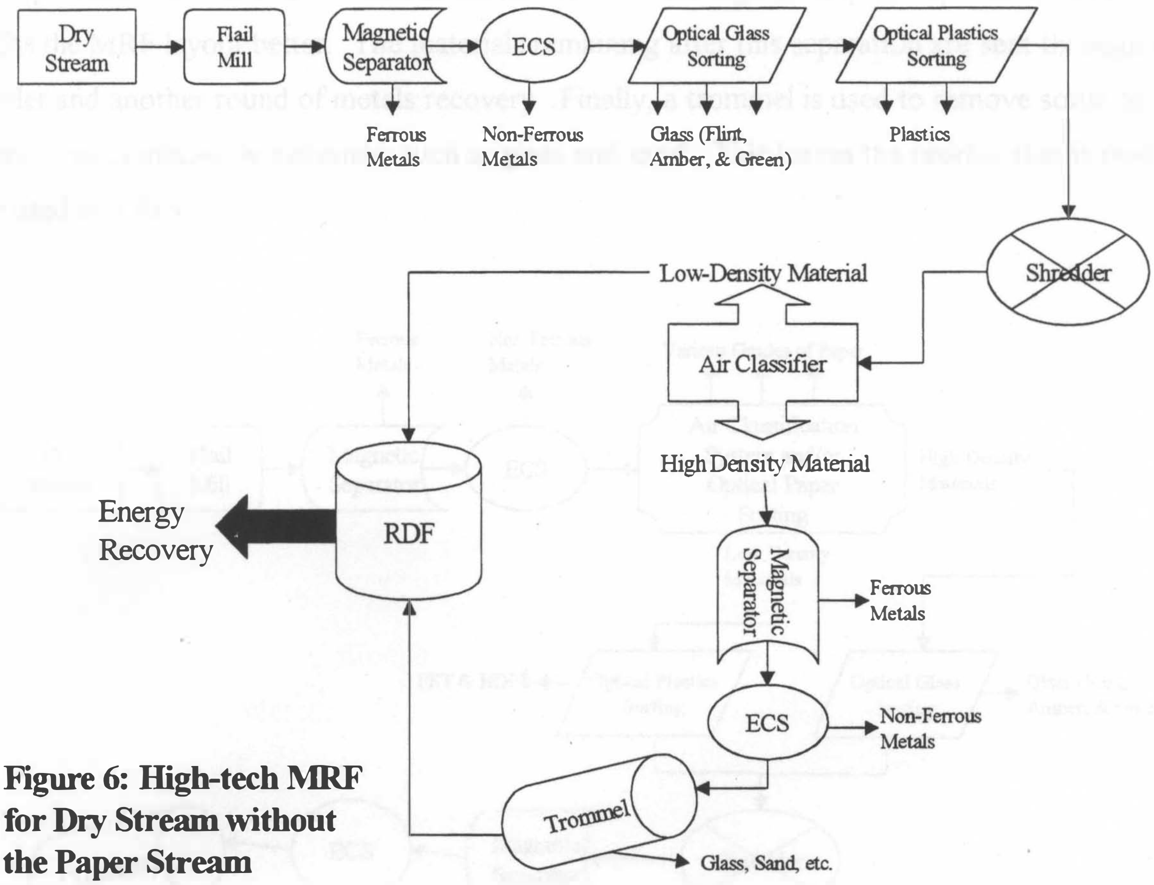

Figure 6: High-tech MRF for Dry Stream without the Paper Stream

Figure 7 is the layout of a high-tech MRF that is designed to process the entire dry stream. It begins just as Figure 6 did with a flail mill for de-bagging and an initial round of metals separation. At this point, MRF layout becomes product-specific. That is, the paper recovery system, which comes next, is designed with particular attention paid to the grades of paper that are to be recovered. Air classification devices, such as the air knife and the zig-zag air classifier, can be fine-tuned to separate paper grades based on density differences. Optical paper separation devices have also been developed, although these are relatively new devices that are still being proven. The selection, arrangement, and operational settings of these devices would all be determined by the grades of paper to be separated. After this paper recovery system, the MRF is very similar to that of Figure 6. Since the low density materials from the paper recovery system would contain most of the plastics, that stream is sent to the optical plastics sorting device. The high density materials, which would contain most of the glass, are diverted to the optical glass sorting device. This should help ensure the optimum efficiency of glass and plastics recovery. However, the two streams could be both sent through each of the optical devices if that fits the MRF layout better. The materials remaining after this separation are sent through a shredder and another round of metals recovery. Finally, a trommel is used to remove some of the fine, non-combustible materials, such as glass and sand. This leaves the residue that is ready to be used as a fuel.

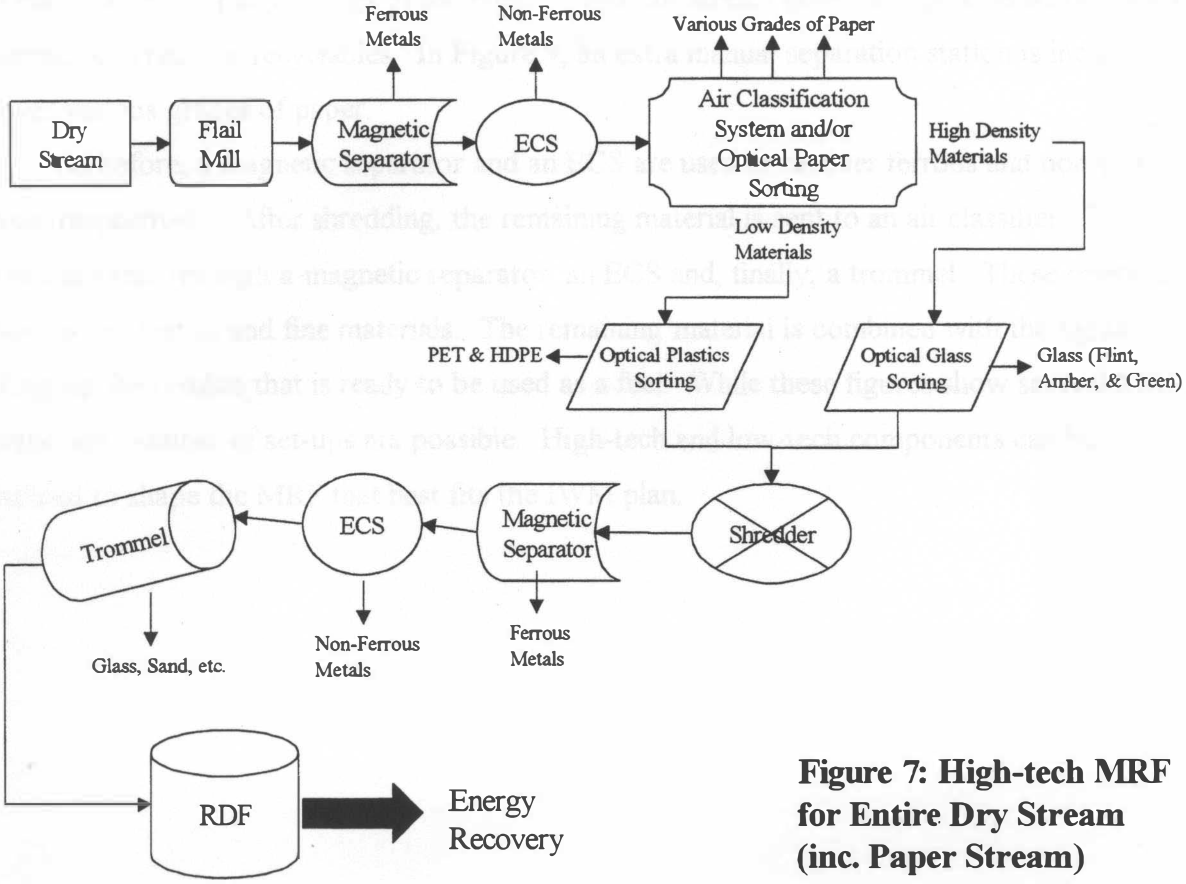

Figure 7: High-tech MRF for Entire Dry Stream (inc. Paper Stream)

6.2.2 Low Tech MRF Design for Dry Stream Processing

The "low-tech" MRF may include some of the unit operations present in the high tech version, but there would be a heavier reliance on manual sorting. This would be particularly true in the areas of glass, plastics, and paper separation. As in the high-tech MRF case, there would be differences in the design reflecting the status of the paper stream. Figure 8 shows a low-tech MRF that would handle the dry stream without the paper stream. This means there is separate collection of the paper stream, as is done presently in New York City. On the other hand, figure 9 shows a low-tech MRF for processing the entire dry stream. The connecting arrows again represent conveyor belts.

Because these two designs are so similar, they are explained together. Figure 8 is an example of a MRF that would process the dry stream minus the paper. Figure 9 shows the layout of a low-tech MRF that would process the dry stream with the paper. As in the other designs, a flail mill is used to open the bags of materials. Then, the stream goes through a series of manual separations to recover recyclables. In Figure 9, an extra manual separation station is included to recover various grades of paper.

As before, a magnetic separator and an ECS are used to recover ferrous and non-ferrous metals, respectively. After shredding, the remaining material is sent to an air classifier. The heavies are sent through a magnetic separator, an ECS and, finally, a trommel. These operations remove more metals and fine materials. The remaining material is combined with the lights making up the residue that is ready to be used as a fuel. While these figures show several MRF designs, any number of set-ups are possible. High-tech and low-tech components can be combined to shape the MRF that best fits the IWM plan.

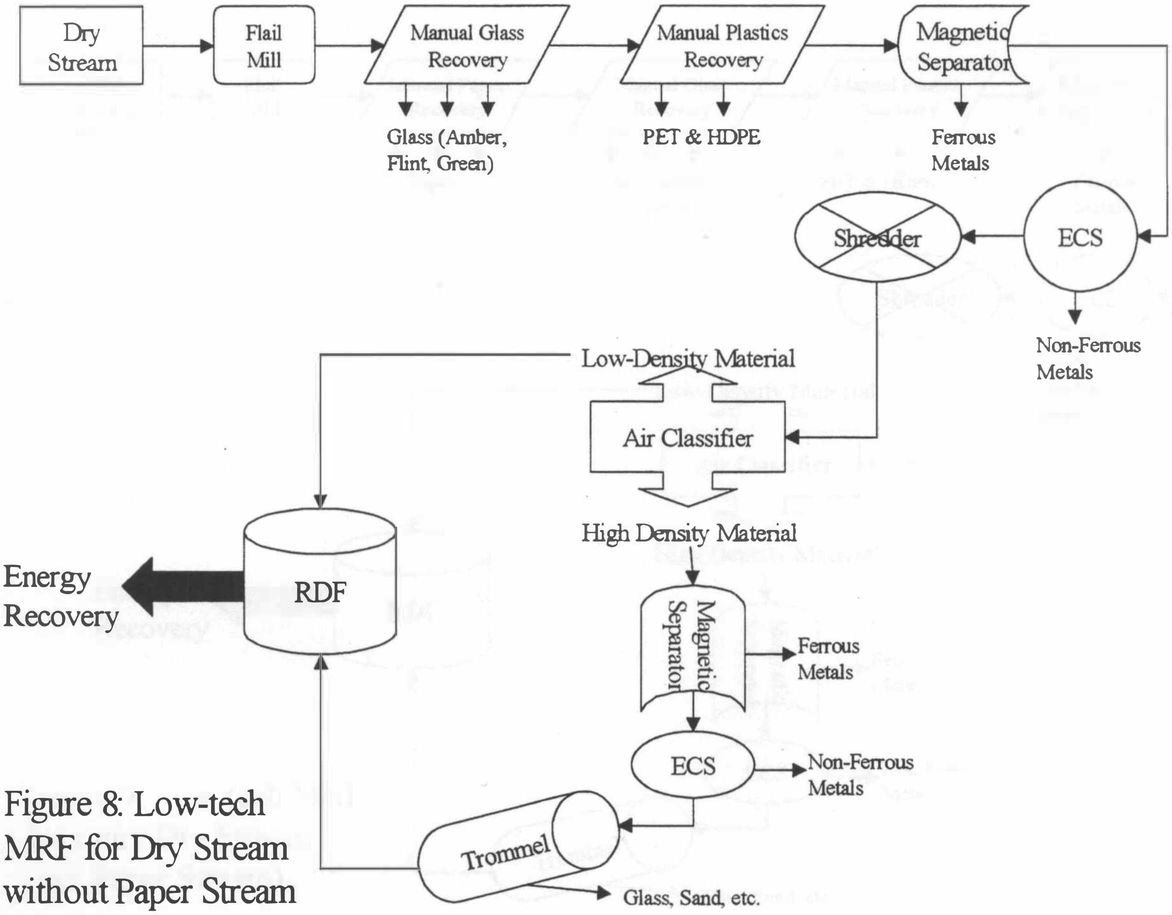

Figure 8: Low-tech MRF for Dry Stream without Paper Stream

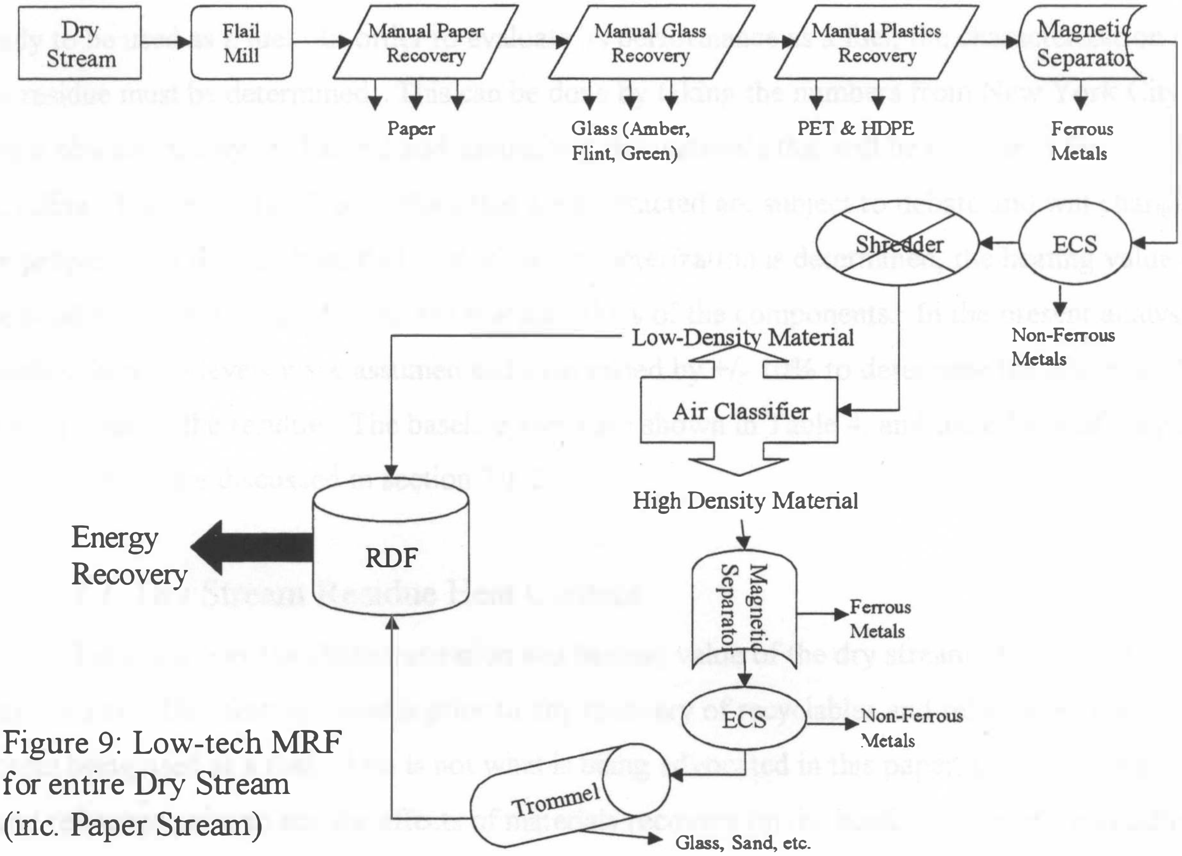

Figure 9: Low-tech MRF for entire Dry Stream (inc. Paper Stream)

6.2.3 MRF Design for Separate Paper Stream Processing

If there is separate collection of paper, as is done presently, an additional MRF might be required for the processing of this stream. The low tech MRF that was discussed in Figure 8 could also be used to process the paper stream. Since separation would be manual in a low tech MRF, the existing conveyor belts and recovery stations could be used for a paper stream. A high tech MRF for paper recovery would rely on differences in densities or optical properties to separate the various grades of paper. Air classification devices recover cardboard, office paper, etc., based on the different densities inherent in these types of paper. Optical devices similarly take advantage of differing optical properties. Obviously, an additional MRF significantly increases the cost of an IWM plan. Therefore, the handling of the paper stream is an important component that must be carefully considered when developing any plan.

7. Characteristics of the Residue Stream

After the dry stream has been processed in whatever MRF design is chosen, the residue is ready to be used as a fuel. In order to evaluate its performance as a fuel, the characterization of the residue must be determined. This can be done by taking the numbers from New York City's waste characterization in Table 2 and subtracting the materials that will be recovered for recycling. The amounts of recyclables that are subtracted are subject to debate and will change the properties of the resultant fuel. Once the characterization is determined, the heating value of the residue can be estimated using the heating values of the components. In the present analysis, baseline recovery levels were assumed and then varied by +/- 10% to determine the effect on the heating value of the residue. The baseline levels are shown in Table 4, and the effects of varying recovery levels are discussed in section 7.1.2.

7.1 Dry Stream Residue Heat Content

Table 3 shows the characterization and heating value of the dry stream of New York City's waste. This heating value is prior to any recovery of recyclables and reflects the entire dry stream being used as a fuel. This is not what is being advocated in this paper, but it serves as a good reference point to see the effects of materials recovery on the heating value of the residue. The second column corresponds to the values in the waste composition from Table 2. The weight in the residue stream is calculated by multiplying the percent composition by the rate of residential waste generation in New York City, i.e. 13000 tons per day (tpd) (New York CIty DOS, 1998). Heating values, in BTU/lb, are shown in the next column. In the last column, the heating value of each component of the dry stream is estimated in millions of BTU per day (MBTU/d). This number is calculated by multiplying the weight of a component in the dry stream by the corresponding heating value and converting units. The weights of all of the components are added, as are the Btu values and the totals are given below the columns. Finally, the total Btu value is divided by the total tonnage per day to arrive at the heating value per unit mass of the dry stream.

Table 3: Heating Value of NYC's Dry Stream Prior to Materials Recovery

Component of Dry Stream	**% in NYC Waste[1]**	**Weight[2] (tpd)**	**Heating Value[3] (BTU/lb)**	**BTU Value of Dry Stream (MBTU/d)**
Newspaper	9.2	1196	7974	19074
Cardboard	4.7	611	7043	8607
Other Paper	17.4	2262	6799	30759
All Paper	31.3			
Glass*	5.0	650	60	78
Ferrous Metals*	1.9	247	300	148
Metal, Tin Cans*	2.0	260	301	157
Non-Ferrous Metal	0.9	117	--	
Plastics	8.9	1157	14101	32630
(HDPE)	1.1			
(PET)	0.5			
Textiles	4.7	611	7960	9727
Rubber & Leather	0.2	26	9195	478
Wood	2.2	286	6640	3798
Fines	2.3	299	3669	2194
Other	2.3	299	3000	1794
		Total Weight of Dry Stream		Total BTU Value of Dry Stream
		8021 tpd		109443 MBTU/d
			Heating Value of Dry Stream	**6822 BTU/lb**

Columns may add up differently due to rounding.
* Heating value comes from labels and other attached substances.
[1] SCS Engineers, 1992.
[2] Weight is based on current generation levels of 13000 tons per day (tpd)
[3] Tchobanoglous et al., 1993.

7.1.1 Baseline Recovery of Recyclables

The heating value in Table 3 is not the heating value of the residue that this paper proposes to be used as a fuel. The residue is the material left after the recovery of paper, metals, and other recyclable materials. In order to estimate the heating value of the residue, recovery levels for the different recyclable materials must be assumed. These levels will depend MRF design and operation, feed material, and will vary for each recyclable material. In the following sections, the effects of changing these recovery levels are investigated, so the importance of the values of the baseline levels is somewhat mitigated. Typical recovery efficiencies of unit operations are used as baseline estimates. It is assumed that newspaper and cardboard are more easily recovered and recycled, so their percent recoveries are higher than that of other paper. Table 4 shows these baseline values and the resultant heating value of the residue. The table is very similar to Table 3 with the addition of the column for percent recovery, which is the percent of material that is recovered for recycling. The rest of the recyclables become part of the residue with the non-recyclables.

Table 4: Heating Value of Dry Stream Residue after Materials Recovery

Component of Residue Stream	% in NYC Waste[1]	Wt. of Comp.[2] (tpd)	% Recovery	Wt. in Residue (tpd)	Heating Value[3] (BTU/lb)	BTU Value of Residue (MBTU/d)
Newspaper	9.2	1196	70	538	7974	5722
Cardboard	4.7	611	70	275	7043	2582
Other Paper	17.4	2262	50	1018	6799	15379
Glass*	5.0	650	80	130	84	22
Ferrous Metals	1.9	247	85	37	300	22
Metal, Tin Cans*	2.0	260	85	39	301	23
Non-Ferrous Metal	0.9	117	85	18	--	
Plastics	8.9	1157		1032	14101	29110
(HDPE)	1.1	143	60			0
(PET)	0.5	65	60			0
Textiles	4.7	611		611	7960	9727
Rubber & Leather	0.2	26		26	9195	478
Wood	2.2	286		286	6640	3798
Misc. Fines	2.3	299	70	90	3669	658
Other	2.3	299		299	3000	1794
				Total Wt. of Residue 4241 tpd		Total BTU Value of Residue 69317 MBTU/d
				Heating Value of Residue		**8172 BTU/lb**

Columns may add up differently due to rounding.
* Heating value comes from labels and other attached substances.
[1] SCS Engineers, 1992.
[2] Weight is based on current generation levels of 13000 tons per day (tpd)
[3] Tchobanoglous et al., 1993.

Table 4 shows that the heating value of the residue of the dry stream, after the recovery of recyclable materials, is 8177 Btu/lb. However, it would be relatively easy in the MRF to separate the rest of the non-recyclable, high-density materials, such as glass, ceramics, and some metals. As shown in Table 4, these materials amount to about 5 % of the residue, so that their removal would increase the heating value of the dry stream residue to about 8600 Btu/lb. It should be noted that this value is in the range of lignitic and sub-bituminous coals that are used in some power plants in the US. Therefore, the use of this residue as a fuel reduces the need to dig up the Earth for non-renewable fossil fuels. Another way of expressing the value of this material as an energy resource is to state that on a daily basis the residue corresponds to half a million gallons of oil.

7.1.2 Effects of Varying Percent Recovery of Recyclables on Heating Value

Figures 11 through 15 show the effects of varying the recovery levels of recyclables. Each figure presents the heating value of the residue from 10% less than to 10% greater than baseline recovery. Figure 11 shows the effect of glass recovery, while Figure 12 shows paper, Figure 13 shows ferrous metals, Figure 14 shows PET and HDPE, and Figure 15 shows non-ferrous metals. It can be seen that higher recovery percentages translate into higher residue heating values for all materials, except PET and HDPE. All of the figures show a gradual, linear change of heating value as the recovery percentage changes. Above each graph are the numerical values at each level of recovery. The first row shows the percent recovery of the material, while the second shows the resultant heating value (HV) of the residue. The first value is the baseline, which is followed by the range of percent recoveries starting at ten percent below the baseline.

Table 5 is a summary of the heating values at the baseline and for +/- 10 % variation in recovery for each component, as well as the range from highest to lowest heating value for each component. The table shows that the variation of glass recovery has the greatest effect on residue heating value, while non-ferrous metals recovery has the least. Ten percent above and ten percent below baseline recovery of glass produce the highest and lowest heating value of the residue, respectively.

Table 5: Summary of Effects of Varying Percent Recovery on Heating Value

Component	**Heating Value of Residue (Btu/lb)**			
of Residue	At Baseline % Recovery	Baseline – 10% Rec.	Baseline + 10% Rec.	**Range**
Glass	8177	8059	8298	239
Paper	8177	8092	8278	186
Ferrous Metals	8177	8087	8268	182
PET and HDPE	8177	8205	8148	-57
Non-ferrous Metals	8177	8155	8198	43

7.2 Ultimate Analysis

The ultimate analysis of the entire dry stream and of the residue after materials recovery can be used to determine the approximate chemical formula. This is done by using the elemental chemical composition and relative amounts of each component to arrive at a composite formula. Table 6 shows the data and results of the calculation of the elemental analysis of the entire New York City dry stream. Table 8 presents the analysis for the residue stream after the recovery of recyclables at baseline levels. Arriving at the boxed formulae takes several steps, which are briefly described here and are discussed in more detail by Tchobanoglous, et al. (Tchobanoglous, et al., 1993). First, the composition table is created using data on the chemical break down of each component. Multiplying the weights of each component by the composition data and then summing across components yields the weight of each element in the stream. Atomic weights are then used to determine the number of moles of each present. Finally, an approximate chemical formula is ascertained by calculating mole ratios using $C_{6.0}$ the reference point since both cellulose and organic matter can be represented by organic compounds that contain variable six carbon atoms plus hydrogen and oxygen atoms. Sulfur and nitrogen are relatively minor constituents (Themelis, 2000). The final formulae are boxed at the bottom of each table.

Table 6: Ultimate Analysis of Dry Stream before Materials Recovery

Component of Waste Stream	**% in NYC[1]**	**Weight of Comp (tpd)**	**% by Weight[2]**				
			Carbon	*Hydrogen*	*Oxygen*	*Nitrogen*	*Sulfur*
Paper	26.6	3458	43.5	6.0	44.0	0.3	0.2
Cardboard	4.7	611	44.0	5.9	44.6	0.3	0.2
Plastics	8.9	1157	60.0	7.2	22.8	-	-
Textiles	4.7	611	55.0	6.6	31.2	4.6	0.2
Rubber & Leather	0.2	26.0	69.0	9.0	5.8	6.0	0.2
Wood	2.2	286	49.5	6.0	42.7	0.2	0.1
Glass	5.0	650	0.5	0.1	0.4	<0.1	-
Metals	4.8	624	4.5	0.6	4.3	<0.1	-
Other	4.6	598	26.3	3.0	2.0	0.5	0.2
		8021	3151	409	2413	46.1	10.6
Atomic Wt.(kg/kmol or lb/lbmol)			12.01	1.01	16.00	14.01	32.07
# of Moles			262	405	151	3.29	0.330
Molar Ratio		*C=6.0*	6.0	9.3	3.4	0.1	~0.0

Approximate Chemical Formula $C_{6.0}H_{9.3}O_{3.5}$

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[1] SCS Engineers, 1992

[2] Tchobanoglous et al., 1993

Table 7: Ultimate Analysis of Dry Stream Residue after Materials Recovery

Component of	**% in**	**Weight of**	**% by Weight[2]**				
Waste Stream	**NYC[1]**	**Comp (tpd)**	*Carbon*	*Hydrogen*	*Oxygen*	*Nitrogen*	*Sulfur*
Paper	11.4	1487	43.5	6.0	44.0	0.3	0.2
Cardboard	2.0	263	44.0	5.9	44.6	0.3	0.2
Plastics	7.9	1024	60.0	7.2	22.8	-	-
Textiles	4.7	611	55.0	6.6	31.2	4.6	0.2
Rubber & Leather	0.2	26	69.0	9.0	5.8	6.0	0.2
Wood	2.2	286	49.5	6.0	42.7	0.2	0.1
Glass	0.3	39	0.5	0.1	0.4	<0.1	-
Metals	0.2	31	4.5	0.6	4.3	<0.1	-
Other	4.6	598	26.3	3.0	2.0	0.5	0.2
		4365	2031	256	1333	38.5	5.95
Atomic Wt.(kg/kmol or lb/lbmol)			12.01	1.01	16.00	14.01	32.07
# of Moles			169	254	83.3	2.75	0.186
Molar Ratio		*C=6.0*	6.0	9.0	3.0	0.1	~0.0
Approximate Chemical Formula					$C_{6.0}H_{9.0}O_{2.9}$		

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[1] SCS Engineers, 1992.

[2] Tchobanoglous et al., 1993.

8. Experimental Test

In order to illustrate the feasibility of this approach, a sample was prepared along the lines of the treatment described in this paper. Several Columbia University students and some faculty were enlisted to separate the their waste into wet and dry streams. High density and recyclable materials were removed manually from the dry stream of the waste. The material left after this removal represented that which this study proposes to be sent to a WTE facility. Once the residue was collected, it was subjected to size reduction in a laboratory-size hammermill shredder. Thus, a sample was prepared that was comparable to what would be introduced into the combustion chamber of a WTE facility.

The shredding of the sample was conducted in a laboratory scale five (5) horsepower shredder from the Roto-Hoe® Company of Newbury, OH. It had blades that performed the function of the hammers in a hammermill shredder. The blades were three inches (3") long, one and one-half inches (1.5") wide, and one-eigth of an inch (1/8") thick. The shredder had three rods of these blades with seven blades each. The bottom screen, under the blades, had holes of three-quarters of an inch (1.75 cm) diameter. The motor was a Dayton® Premium Efficiency Severe Duty Motor. Its ratings were 3-phase, 5.0 horsepower, 1755 RPM, 230 V, 12.6 A. While this shredder was miniscule in comparison to the industrial-size shredder required for full-scale implementation of the scheme discussed in this paper, it was sufficient for the purposes of this demonstration. Since recyclables and other high density materials were removed, the 5.0 HP shredder was adequate to shred the remaining materials. It should be noted that in a full-scale version of this scheme, the shredder should be powerful enough to shred the small quantity of high-density materials that may not be sorted out by magnetic and other techniques.

Several things were made evident by this laboratory demonstration. One was that this portion of the waste stream did not give off any objectionable odors. This would alleviate one of the major concerns of neighbors of waste facilities. The shredded material was also of such a nature that its transport would be much easier than the transport of the entire waste stream, i.e. a mixture of wet and dry materials. This is especially appropriate given New York City's current plan to transport much of its residential waste to landfills outside New York state. The material left after shredding most closely resembled shredded paper and was very compressible. This further exhibited the advantages in terms of transport that this material has over the entire waste stream. Finally, the material was of such a nature that its combustion should be very easy and complete.

While this demonstration was on a small scale and included manual separation of high density and recyclable material, it did provide further evidence that the use of the dry stream residue by a WTE facility is feasible. The accidental occlusion of some recyclables, high-density wastes, and even some wet wastes should not provide any major problems to the scheme advocated in this paper. Shredders that are more powerful would be able to handle the high density materials. Also, it is expected that significant drying of the wet wastes would occur during the shredding due to the amount of heat produced by this process; this has ben the experience in the SEMASS plant referred to earlier. As previously stated, the persistence of wet waste even into the boiler would not significantly hamper combustion since the wet material would burn autogenously (Themelis, 2000). Therefore, there should not be any insurmountable obstacles on the technical side of this plan.

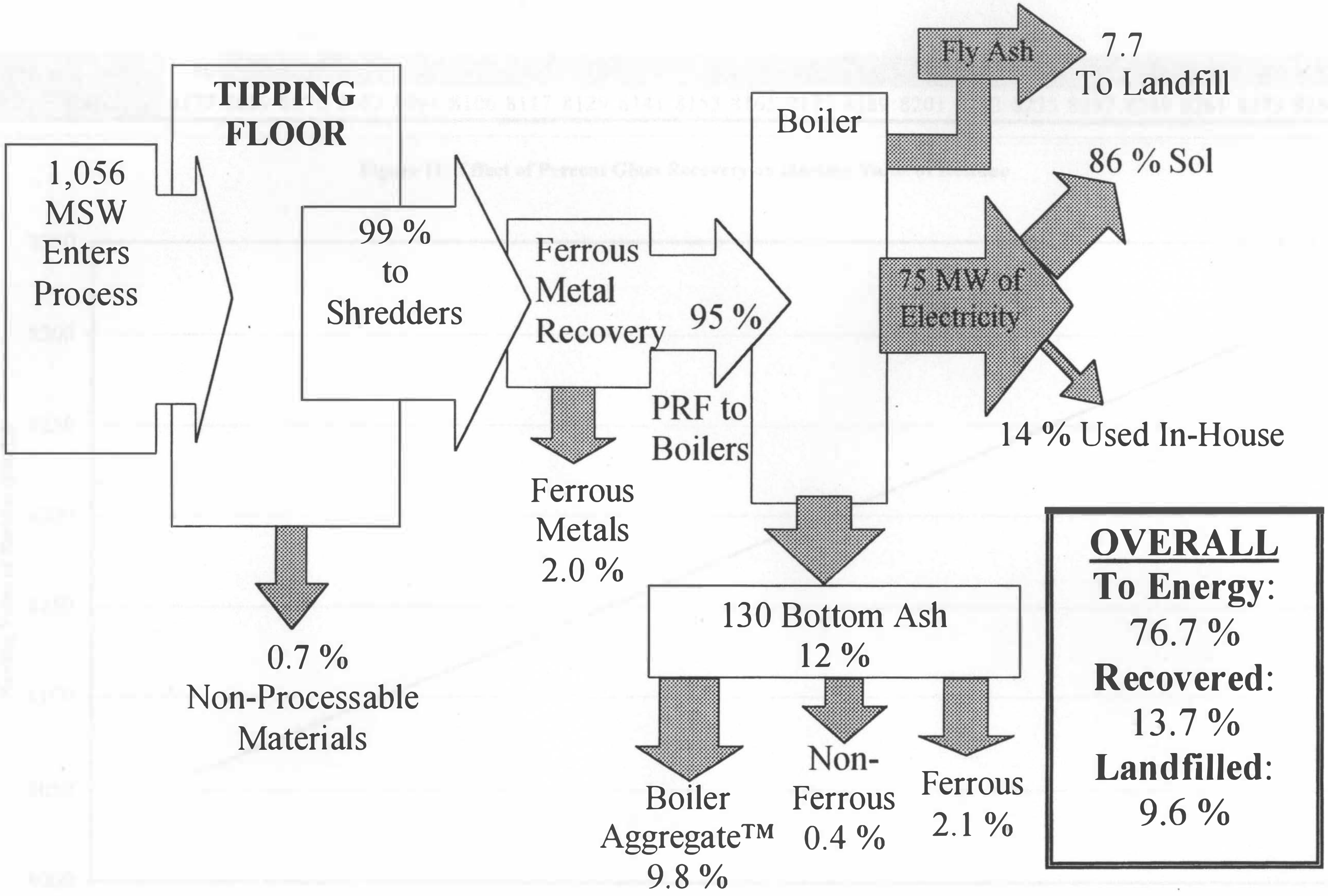
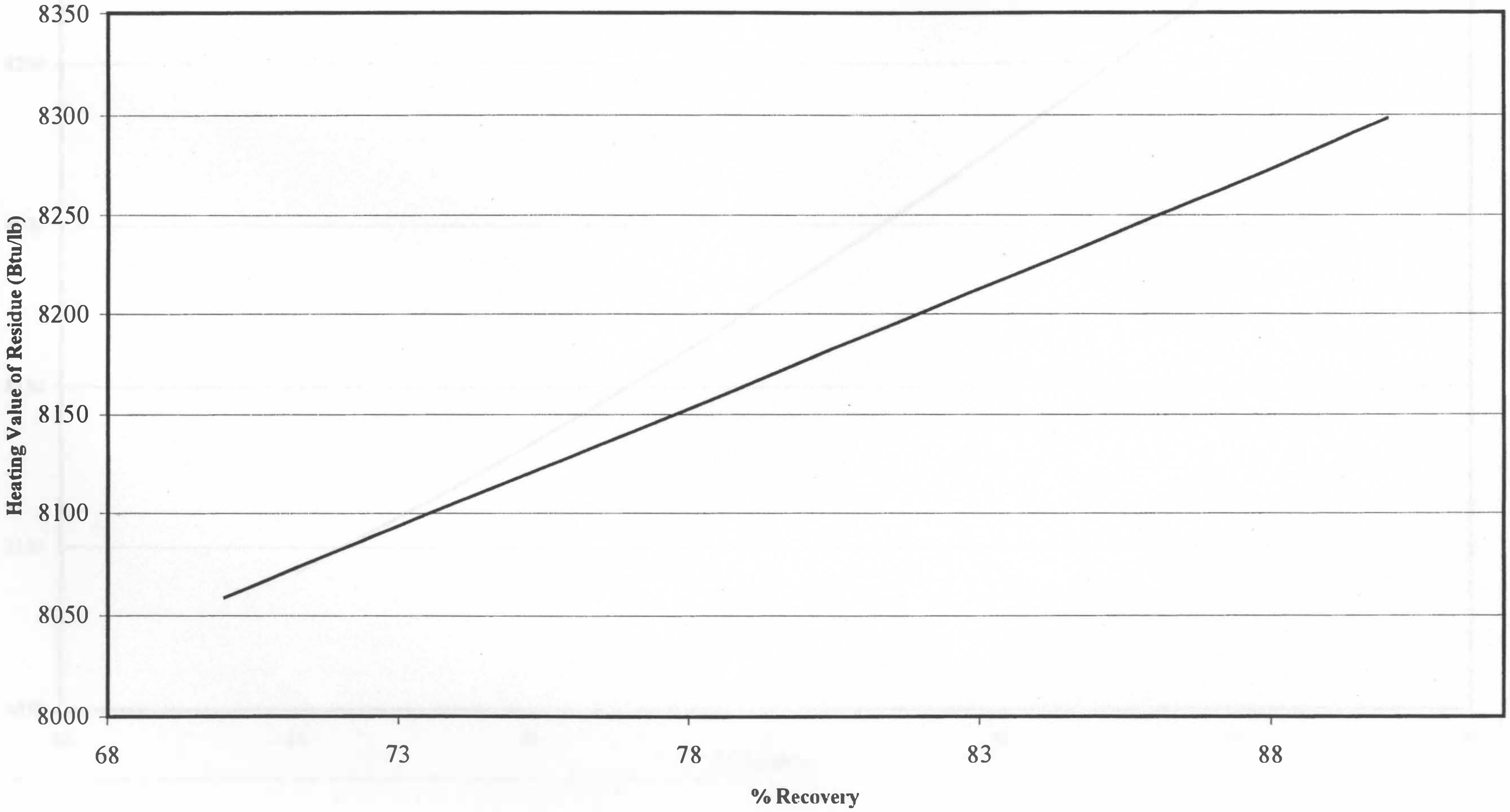


Figure 10: Flowsheet of SEMASS Facility; Rochester, MA

% Rec. of Glass:	80	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
Btu/lb of Residue:	8177	8059	8070	8082	8094	8106	8117	8129	8141	8153	8165	8177	8189	8201	8213	8225	8237	8249	8261	8273	8286	8298

Figure 11: Effect of Percent Glass Recovery on Heating Value of Residue



% Rec. of Paper:	55	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65
Btu/lb of Residue:	8177	8092	8100	8108	8116	8124	8133	8141	8150	8159	8168	8177	8186	8195	8205	8215	8225	8235	8246	8256	8267	8278

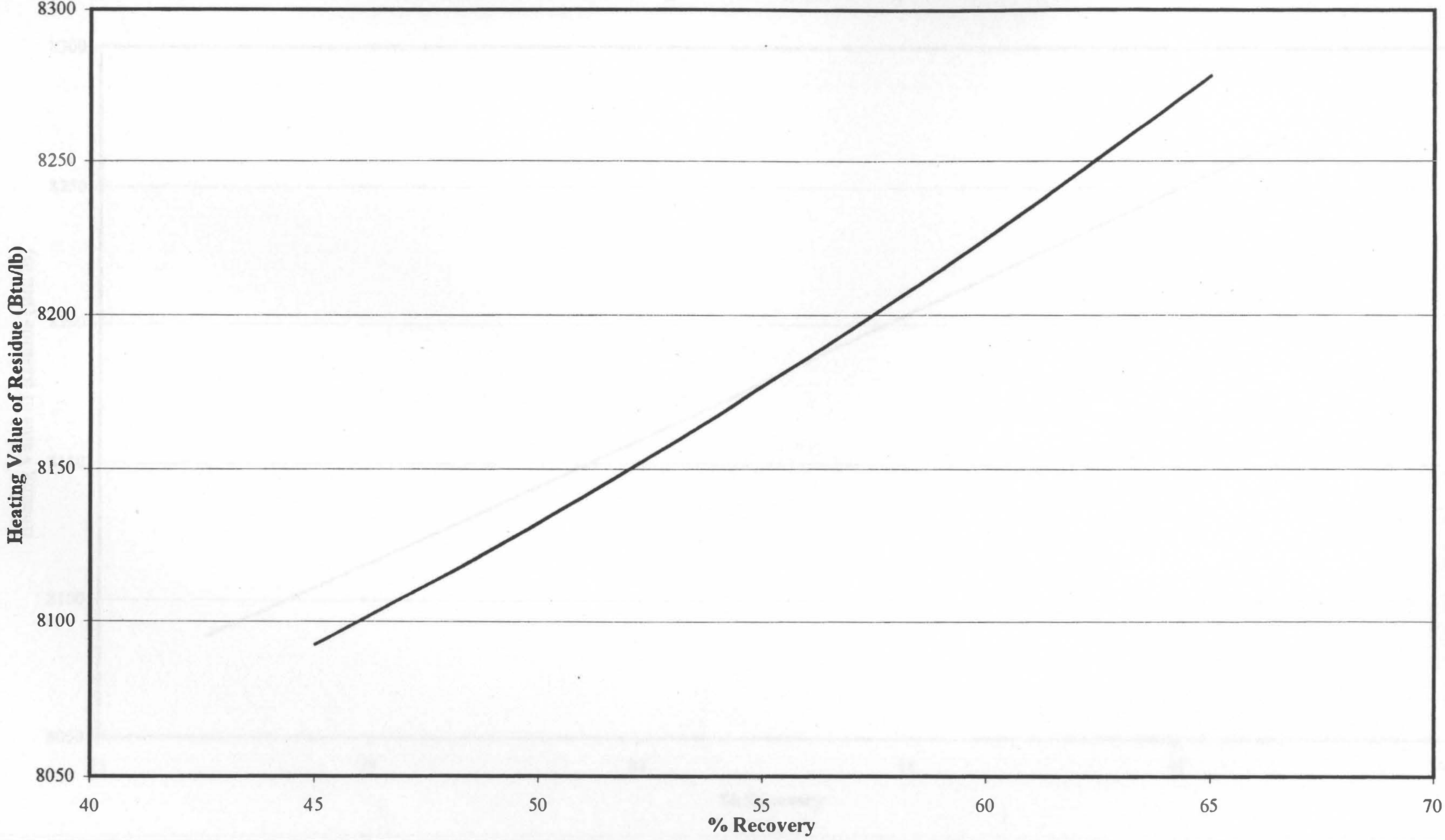
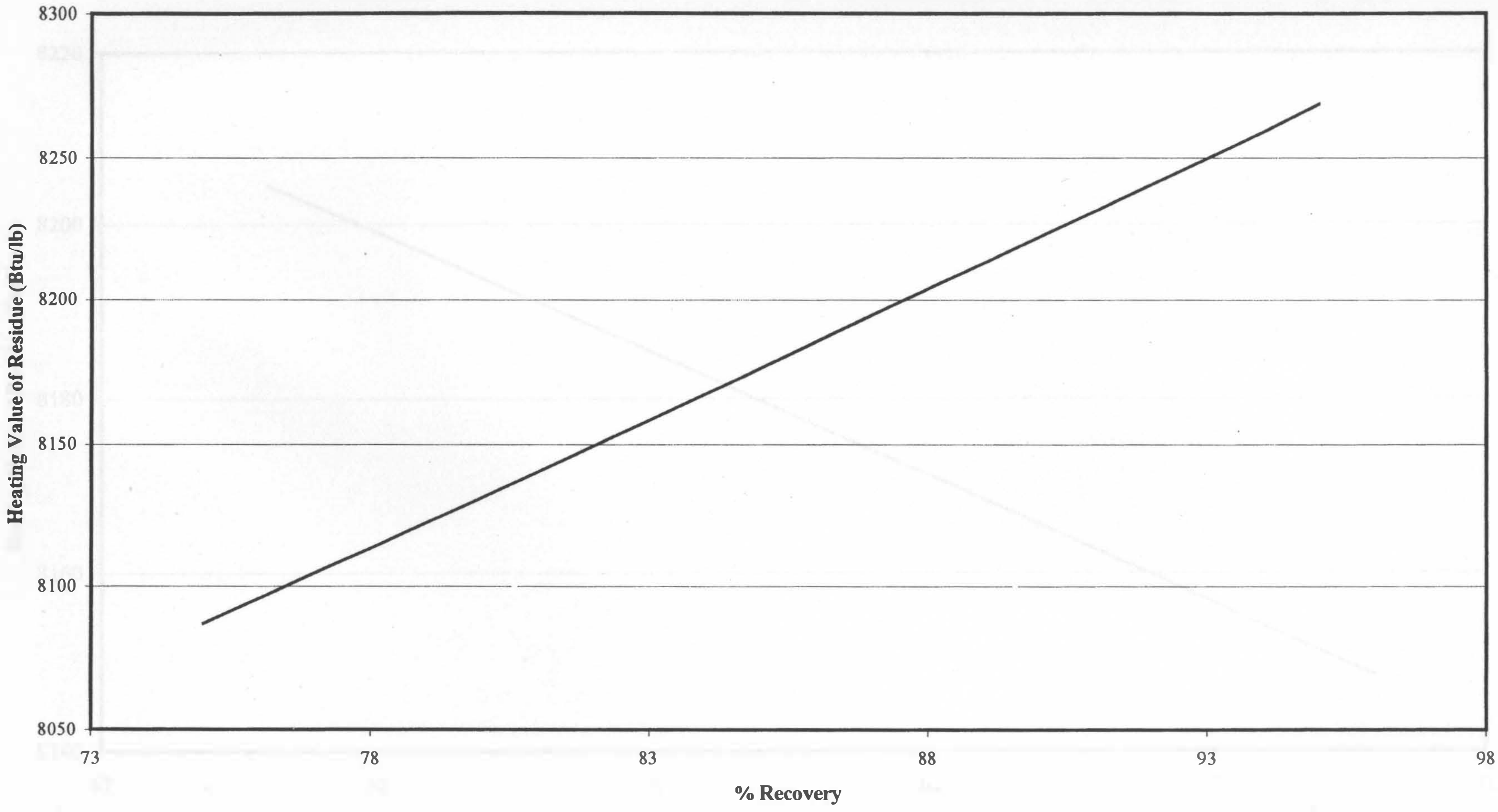


Figure 12: Effect of Percent Paper Recovery on Heating Value of Residue

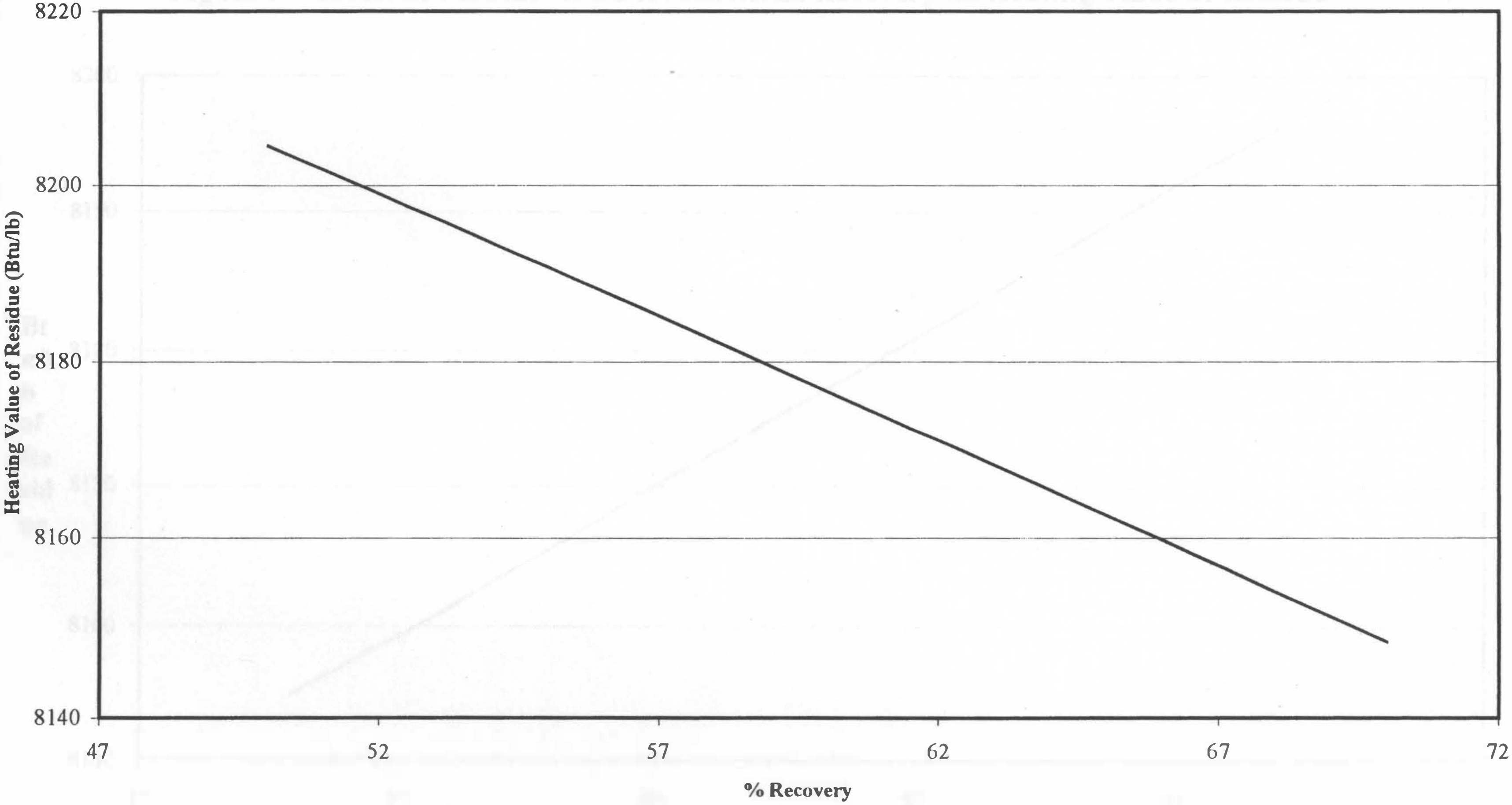
% Rec.-Ferrous:	85	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95
HV of Residue:	8177	8087	8096	8105	8114	8123	8132	8140	8150	8159	8168	8177	8186	8195	8204	8213	8222	8231	8241	8250	8259	8268

Figure 13: Effect of Percent Ferrous Metal Recovery on Heating Value of Residue



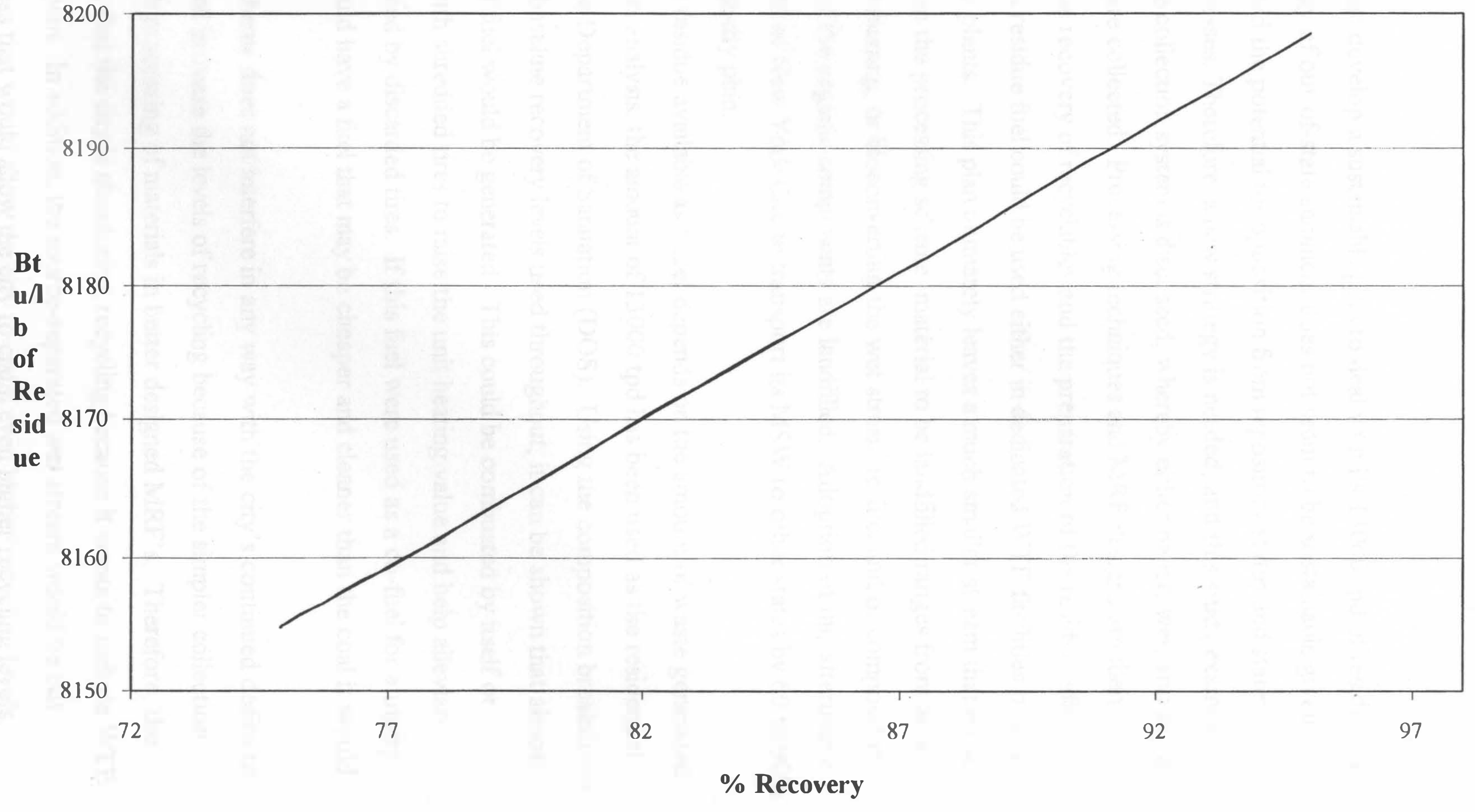
% Rec. of Plastic:	60	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
Btu/lb of Residue:	8177	8205	8202	8199	8196	8193	8191	8188	8185	8182	8179	8177	8174	8171	8168	8165	8163	8160	8157	8154	8151	8148

Figure 14: Effect of Percent PET and HDPE Recovery on Heating Value of Residue



% Recovery:	85	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95
Btu/lb Residue:	8177	8155	8157	8159	8161	8164	8166	8168	8170	8172	8174	8177	8179	8181	8183	8185	8188	8190	8192	8194	8196	8198

Figure 15: Effect of Percent Non-Ferrous Metal Recovery on Heating Value of Residue



9. Conclusions

New York City must develop a sustainable plan to deal with its 13000 tpd of residential waste. The present strategy of out-of-state shipment does not seem to be sustainable given its over-reliance on landfills and the potential for opposition from repository states and states through which the waste passes. Therefore, a new strategy is needed, and this study examines one option. An alternative collection system is discussed, whereby either paper, wet, and dry or only wet and dry streams are collected. Processing techniques and MRF designs are then suggested that allow for the recovery of recyclables and the preparation of the residue, after recycling, into a fuel. This residue fuel could be used either in dedicated WTE facilities or as a co-fuel in coal-fired power plants. This plan ultimately leaves a much smaller stream that must be landfilled. Depending on the processing scheme, material to be landfilled ranges from about 10% (for composting, combusting, or bioconverting the wet stream to fuel and/or compost) to 40% of the waste stream, if the organic components are landfilled. Adoption of this alternative plan would reduce the need of New York City to transport its MSW to other states by 60 to 90%, as compared to the current city plan.

The amount of the residue available as a fuel depends on the amount of waste generated in New York City. For this analysis, the amount of 13000 tpd has been used as the residential waste load collected by the Department of Sanitation (DOS). Using the composition breakdown shown in Table 2 and the baseline recovery levels used throughout, it can be shown that almost 4400 tons per day (tpd) of fuel would be generated. This could be combusted by itself or possibly even combined with shredded tires to raise the unit heating value and help alleviate some of the problems caused by discarded tires. If this fuel were used as a co-fuel for a utility plant, the power plant would have a fuel that may be cheaper and cleaner than the coal it would replace.

This processing scheme does not interfere in any way with the city's continued desire to recycle. In fact, it may well increase the levels of recycling because of the simpler collection system and more thorough processing of materials in better designed MRF's. Therefore, the public could not complain that the city is abandoning recycling because it wants to include WTE in its waste management plan. In addition, the source-separated wet stream would be put through a treatment process that would allow the city to claim even higher recycling levels.

This study is an example of integrated waste management (IWM). This philosophy states that several different waste management techniques must be combined to develop a plan that fits the municipality's needs. New York City has utilized several aspects of IWM: source reduction, recycling, minor forays into composting, and landfilling. It should continue its efforts in the first two but should not ignore the benefits that WTE could bring. The plan discussed here presents a rational means of including WTE that continues or even expands recycling efforts. It also reduces the city's and the state's reliance on other states. Ultimately, if the city wants to develop a sustainable plan for its waste and establish itself as a leader in MSW management, it must come up with a plan that will process a significant amount of its waste locally. The processing scheme examined in this study is one step toward realizing this goal.

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