

INTEGRATED MANAGEMENT OF SOLID WASTES FOR NEW YORK CITY

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ABSTRACT

This report presents the results of a study that examined alternatives to landfilling the municipal solid wastes (MSW) of New York City. Detailed characterization of the wastes led to their classification, according to materials properties and inherent value, to “recyclable”, “compostable”, “combustible”, and “landfillable”. The results showed that the present rates of recycling (16.6%) and combustion (12.4%) in New York City can be increased by

a) implementing an automated, modern Materials Recovery Facility (MRF) that separates the blue bag stream to “recyclables” and “combustibles”, and b) combusting the non-recyclable materials in a Waste-to-Energy (WTE) facility. Combustion of wastes to produce electricity is environmentally much preferable to landfilling. An advanced technology for combustion is that used in a modern Waste-to-Energy plant (SEMASS, Massachusetts) that processes 0.9 million metric tons of MSW per year, generates a net of 610 kWh per metric ton of MSW, recovers ferrous and non-ferrous metals, and has lower emissions than many coal-fired power plants.

INTRODUCTION

Economic development is accompanied by greatly increased use of materials and generation of wastes. Solid wastes are classified into municipal (residential and commercial), industrial, and construction and demolition wastes. Because of high population densities and scarcity of land, integrated management of solid wastes is specially needed in urban centers located in coastal areas or islands, such as New York City. Integrated waste management requires that MSW be separated into a number of streams, which can then be subjected to the most appropriate method of resource recovery. Separation can take place either at the source, i.e. households or businesses, or at Materials Recovery Facilities (MRFs). The principal means for managing the various streams of MSW are:

- **Recovery of materials:** Paper, plastics, metals, and glass can be recycled to produce similar materials.
- **Recovery of energy:** Recoverable energy is stored in chemical form in all MSW materials that contain natural or man-made organic carbon. The combustion of organic compounds in Waste-to-Energy plants generates electricity and steam.
- **Biochemical or thermal conversion:** The natural organic components of MSW (food and plant wastes, paper, etc.) can be composted *aerobically* (i.e., in the presence of air) to generate carbon dioxide, water, and a

compost product that can be used as soil conditioner. *Anaerobic* digestion produces methane and a compost product; this method provides an alternate route for recovering some of the chemical energy stored in the organic fraction of MSW. Pyrolytic processes subject MSW to high temperature decomposition and reforming to generate a gaseous fuel.

- **Landfilling:** The fraction of MSW that cannot be subjected to materials or energy recovery, plus the residuals from recycling or combustion (e.g., ash, non-usable glass, etc.) must be disposed in properly designed landfills.

The annual rate of MSW generation in the U.S. has been estimated at about 200 million tons, i.e. about 0.8 tons per capita. The Council for Environmental Quality (1997) reported that, in 1996, 22% of the collected MSW was recycled (paper, plastics, metals, glass), 5.4% composted, 17.2% combusted and 55.4% landfilled. Landfilling remains the principal mode of MSW disposal in the U.S. although it is being phased out in countries like France and Japan that place a high value on land use and environmental quality.

Table 1, in a later section of this report, shows the composition of the New York City waste stream (SCS Engineers, 1992). The largest constituent of MSW is paper. Other low-moisture combustibles are plastics, textiles, rubber, leather, and wood. These materials can be called “dry combustibles”, in distinction to the “wet combustibles” of food and plant wastes that contain 50-70% water. The “non-combustible” constituents of MSW are metal, glass and other inorganic materials. Hazardous wastes, such as paints, oils, and chemicals constitute only 0.4% of the total waste stream and must be handled separately. Large items such as appliances and furniture can be broken down to recyclable metals or combustible wood scrap.

2. MSW MANAGEMENT IN NEW YORK CITY

In the second part of the 20th century, New York City (NYC) disposed most of its solid wastes in the giant (about 20 million square meters) Fresh Kills landfill in Staten Island. However, Fresh Kills was finally closed in 2001 (re-opened temporarily after the September 11 attack on the World Trade Towers). At present, New York City, with a population of 8 million, generates about 12,000 metric tons per working day of residential wastes (collected by the City) and nearly an equal amount of commercial and institutional wastes, collected by private contractors. This paper addresses the municipal solid wastes collected by the Department of Sanitation (DOS) of NYC in three streams, separated at the household level: Recyclable paper (“clear” bags), recyclable “metal-glass-plastics” (MGP, “blue” bags) and all other wastes (“black” bags). The four million metric tons of “black” bag MSW collected annually by NYC are disposed as follows (Figure 1):

- a) **Recycling:** In recent years, NYC has mounted a campaign to increase recycling to the present level of about 700,000 metric tons. The paper stream consists of mixed paper, newspapers, magazines, and corrugated cardboard and represents about 65% of the recyclables collected by NYC. Most of this stream is used in paper recycling plants in Staten Island (Visy Paper) and elsewhere. The residue from the paper stream (12-15% of the paper stream) consists of plastics (mostly from plastic bags and some unusable paper).

Although this material is combustible and has a relatively high heating value, after compacting into 0.7- ton bales, it is send to landfills.

The MGP stream also goes to a sorting operation where steel cans (about 8%), iron and steel parts (18%), aluminum cans and foil (1%) are sorted out, manually and mechanically (e.g. by use of electromagnets). A small fraction of recyclable plastics (5%; mixed color HDPE, natural HDPE, PET) and clear glass (4%) are also recovered. The residues of the MGP stream (consist of a large amount of broken glass mixed with small particles of plastic, metal and dirt (about 40% of the stream) and plastic bags (about 10% of the MGP stream). The glass residue is used as "day cover" in landfills. The plastic residue is baled and sent to landfills. The sorting, baling, and further treatment or disposal of the various products of the paper and MGP streams are contracted by the City to several private companies.

- b) **Waste-to-energy:** About 500,000 tons of "black bag" waste go to two Waste-to-Energy plants, one in New Jersey (Essex County WTE) and the other in New York (Hempstead WTE).
- c) **Landfilling:** The remaining 2.8 million metric tons of "black bag" waste are transported, mostly by truck (Figure 2), to Pennsylvania, Virginia, and New Jersey (Figure 3).

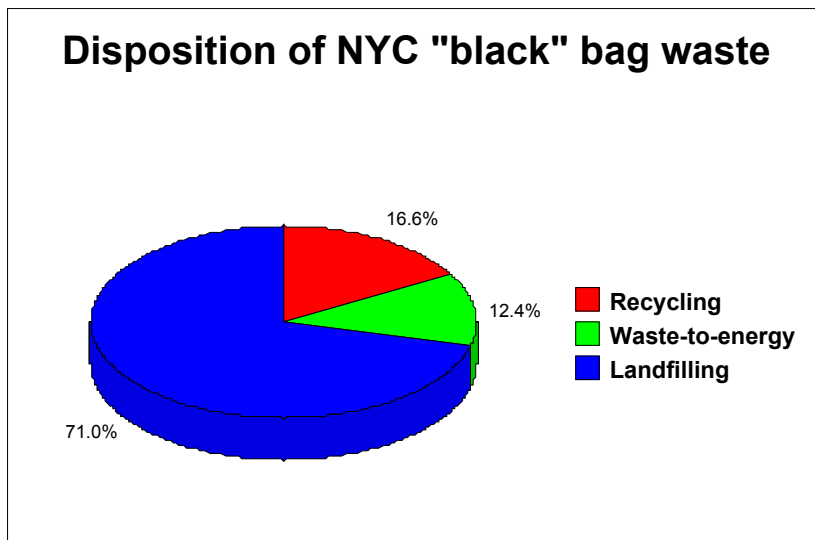


Figure 1. Disposition of solid wastes collected by NYC

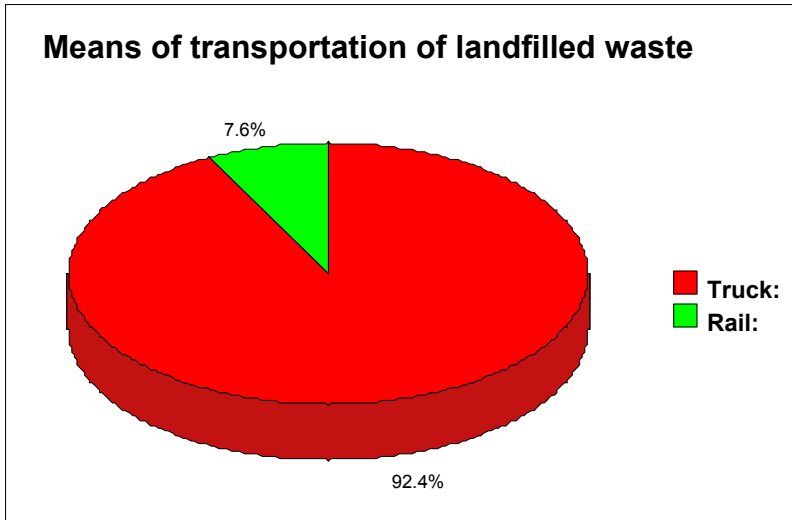


Figure 2. Means of transportation of NYC “black” bag waste

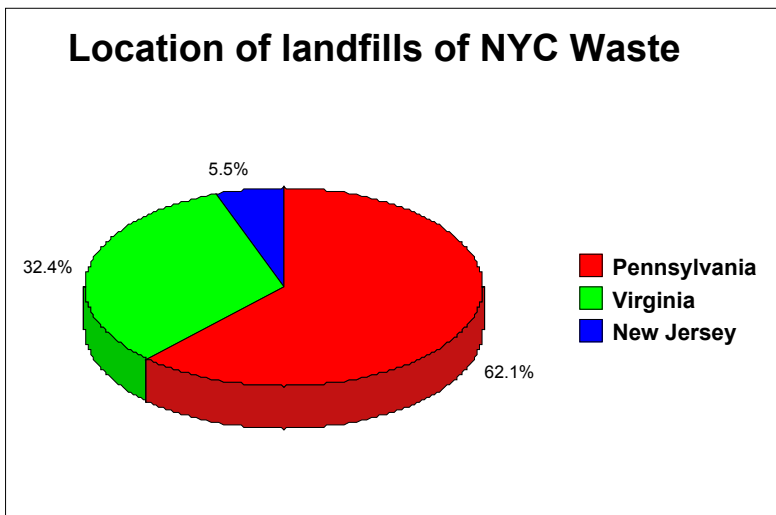


Figure 3. Distribution of landfills of NYC MSW

3. OUT-OF-STATE TRANSPORTATION OF MSW

Prior to closing Fresh Kills, the NYC DOS trucks traveled relatively short distances within the City to unload at marine transfer terminals from where the waste was transported by barges to the Fresh Kills landfill in Staten Island. Presently, six of the thirteen transfer stations are located outside New York City and the DOS trucks must travel distances up to 60 kilometers to unload. It has been estimated that as many as one thousand trucks cross to New Jersey each working day over the existing two bridges and two tunnels (Columbia Earth Institute 2002, Fresh Kills report). At the New

Jersey transfer stations, the NYC waste is loaded onto 20-ton tractor trailers that transport it to landfills in Pennsylvania, Virginia, and New Jersey. The total distance traveled daily by the NYC DOS 10-ton trucks crossing to NJ is estimated at 64,000 kilometers per working day. The distance traveled by the 20-ton trucks (average of 480 kilometers per round trip) is estimated at 216,000 kilometers each day. Wang et al (2000) have determined fuel consumption for various types of heavy trucks. On the basis of the above data, the fuel consumption for transporting NYC MSW to other states by truck for landfilling is estimated at 40 million liters per year (about ten million gallons; Columbia Earth Institute 2002).

4. IDEAL DISPOSITION OF NYC MSW MATERIALS ACCORDING TO PROPERTIES AND INHERENT VALUE

As noted earlier, MSW consists of many materials with entirely different properties. Under ideal circumstances of sorting, processing, and recycling, these materials should go to different destinations. For example, metals and glass are not combustible or compostable; therefore, “recycling” would be the most appropriate route for such materials. Most of the collected paper and some plastics (e.g., PET and PE) are readily sorted out and recycled: Visy Paper on Staten Island (300,000 tons per year) is an example of a modern, efficient plant that operates fully on recycled feedstock. The non-recyclable paper, plastics and fibers contain useful energy; therefore, they constitute a fuel that can be burnt in a properly designed combustion chamber to generate steam and then electric energy. Finally, the only materials to be landfilled properly should be inorganic compounds such as non-recyclable glass and ashes from the Waste-to-Energy power plants.

Table 1 shows how the NYC MSW may be classified under the four categories of “recyclable”, “combustible”, “compostable”, and “landfillable”. The ideal disposition of Table 1 is not easily realizable because of social, economic and market factors. For example, New York City citizens are already asked to separate three streams: Paper (“clear bag”), plastic, metal and glass (PMG; in “blue bags”) and trash (“black bags”). However, despite an intensive campaign by the Recycling Bureau of NYC-DOS, the recycling rates of some areas of NYC are lower than others; that is one reason why the present rate of city-wide recycling is less than one half of the projected maximum (Table 1).

Table 1 also shows that the maximum “compostable” fraction is 19%. However, separating and composting the “wet” fraction will require the development of a regional market for nearly 0.5 million tons of compost product. In the absence of a “wet-dry” system of collection, the compostable fraction will remain commingled with the other materials in the black bag stream. Therefore, the two alternatives for the black bag stream are combustion or landfilling. Table 1 shows that ideally, only about 6% of the NYC MSW needs to be landfilled, vs. the present 71%.

5. GENERATION OF ELECTRICITY BY COMBUSTION OF MSW

Most MSW materials contain chemical energy that is released during combustion. For example, plastics contain the same heating value, kilogram per

kilogram, as fuel oil. Table 3 shows the "proximate analysis" of the combustible materials and also their experimentally determined heats of combustion.

Table 1. Classification of NYC MSW by most appropriate method of disposal
(in thousands of short tons/year; numbers in parenthesis show the assumed maximum % recyclable for each material; Themelis et al 2002)

	Collected Short tons	% of total MSW	Recyclable short tons	Combustible short tons	Compost-able short tons	Landfill-able short tons
Cardboard (90%)	229	5.1%	206	23		2
Newsprint (90%)	446	9.9%	401	43		5
All other paper (50%)	869	19.2%	434	414		41
Plastic bags/film (50%)	252	5.6%	126	126		13
All other plastics (50%)	193	4.3%	97	96		10
Wood, textiles, leather, rubber (20%)	608	13.4%	122	486		49
Food and plant wastes (0%)	879	19.4%			879	88
Disposable diapers (0%)	178	3.9%		178		18
Miscellan. Organics (0%)	409	9.0%		409		41
Glass (90%)	234	5.2%	210			24
Aluminum scrap (100%)	42	0.9%	42			
Ferrous scrap (100%)	185	4.1%	185			
Total:	4,524	100.0%	1,823	1,775	879	291
Fraction of NYC MSW	100.0%		40.3%	39.2%	19.4%	6.4%

**Landfillable is assumed to consist of 10% ash from all combustible streams and 10% of non-recyclable glass.*

5.1 Chemical Representation of Combustible Fraction of MSW

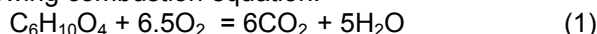
Wood has nearly the same heating value per unit mass as paper, while yard and food wastes contain less energy because of their high moisture content (Table 3). For example, food wastes contain about 70% moisture and their calorific value is only 5350 kJ/kg (2300 BTU/lb). Thus, high-moisture food wastes contain enough heat to burn "autogenously" (i.e. without fuel addition) but do not generate much electricity. In Table 3, the combustibles in the MSW are divided into "dry" materials that contain relatively low moisture and "wet" materials, such as food and plant wastes, that contain over 50% water.

Table 2. Proximate Analysis of Components of MSW (% weight)*

	Moisture	Volatile Matter	Fixed Carbon	Non-Combustible	kJ/kg As collected
“Dry” Combustibles					
Paper	10.2	75.9	8.4	5.4	15814
Cardboard	5.2	77.5	12.3	5.0	16380
Mixed Plastics	2.0	95.8	2.0	2.0	32800
Textiles	10.0	66.0	17.5	6.5	17445
Rubber	1.2	83.9	4.9	9.9	25330
Leather	10.0	68.5	12.5	9.0	18515
Wood	20.0	68.1	11.3	0.6	15445
NYC mix of “dry” combustibles**					18470
“Wet” Combustibles					
Yard Wastes	60.0	30.0	9.5	0.5	6050
Food Wastes	70.0	21.4	3.6	5.0	5350
NYC mixed “dry” and “wet”	21	52	7	20	11630

* Tchobanoglous et al., 1993; Brady 2000

Themelis et al (2002) showed that the molecular formula $C_6H_{10}O_4$ closely approximated the mix of organic wastes in the NYC MSW. This formula corresponds to that of several organic compounds, whose heat of formation is about -962 kJ/mol (Roinen, 1999). Representing the NYC dry stream by the $C_6H_{10}O_4$ formula results in the following combustion equation:



This reaction is highly exothermic and at the combustion temperature of 1000°C generates about 27000 kJ/mol. Since the molecular weight of $C_6H_{10}O_4$ is 146, the “theoretical” heat of reaction (i.e. in the absence of inert or moisture) per unit mass of MSW is calculated to be 18400 kJ/kg (7900 BTU/lb).

5.2 Effect of Moisture and Inert Materials on Heating Value of MSW

Obviously, moisture in the MSW decreases the available heat for combustion in Waste-to-Energy (WTE) plants that produce electricity and steam. The amount of heat wasted per kg of water in the feed, in the form of water vapor in the exhaust gases, has been calculated at 2636 kJ/kg. A similar calculation for the effects of glass and metals on the heating value of mixed MSW resulted in the following equation (Themelis et al 2002):

Heating value of mixed MSW=

$$= 18400X_{\text{comb}} - 2636X_{\text{H}_2\text{O}} - 628X_{\text{glass}} - 544X_{\text{metal}} \quad \text{kJ/kg} \quad (3)$$

where X_{comb} , $X_{\text{H}_2\text{O}}$, etc. are the fractions of combustible matter, water, etc. in the feed material.

Table 2 showed that the heating value of the “dry” stream, after separation of the “wet” and the non-combustible fractions, amounts to 18470 kJ/kg. This value is fairly close to the thermochemical value calculated on the basis of Equation 3 and also in the range of lignitic and sub-bituminous coals.

Figure 4 (Themelis et al 2002) shows the effect of moisture on the heating value of MSW. The bold line represents the heating value calculated from Equation 3. It is fairly representative of the heating value of several waste materials reported in the literature, as well as of the New York City MSW (Table 2). Wastes consisting mostly of plastics cannot be represented by $C_6H_{10}O_4$ but by lower oxygen organic materials that have higher heating values. The opposite is true for wastes that contain a lot of paper where cellulose ($C_6H_{10}O_5$) is the prevalent compound.

6. ELECTRIC ENERGY FROM MSW

6.1 Moving Bed Combustion: “Mass Burning”

“Mass burning” is the dominant WTE technology in the U.S., Japan, and other developed countries. Trucks carrying MSW empty their load into a large totally enclosed chamber. An overhead

“claw” crane scoops material and deposits it at the feed end of a moving metal grate, or set of slowly rotating cylinders, that slowly convey the waste materials through the combustion chamber. Many WTE operators favor the “mass burning” process because it does not require pre-processing of the feed and is a relatively simple operation. However, the rates of heat, mass transfer, and combustion of the large bags deposited on the grate are relatively low and a large combustion chamber is required. The temperatures generated in the combustion chamber are in the order of 900°C.

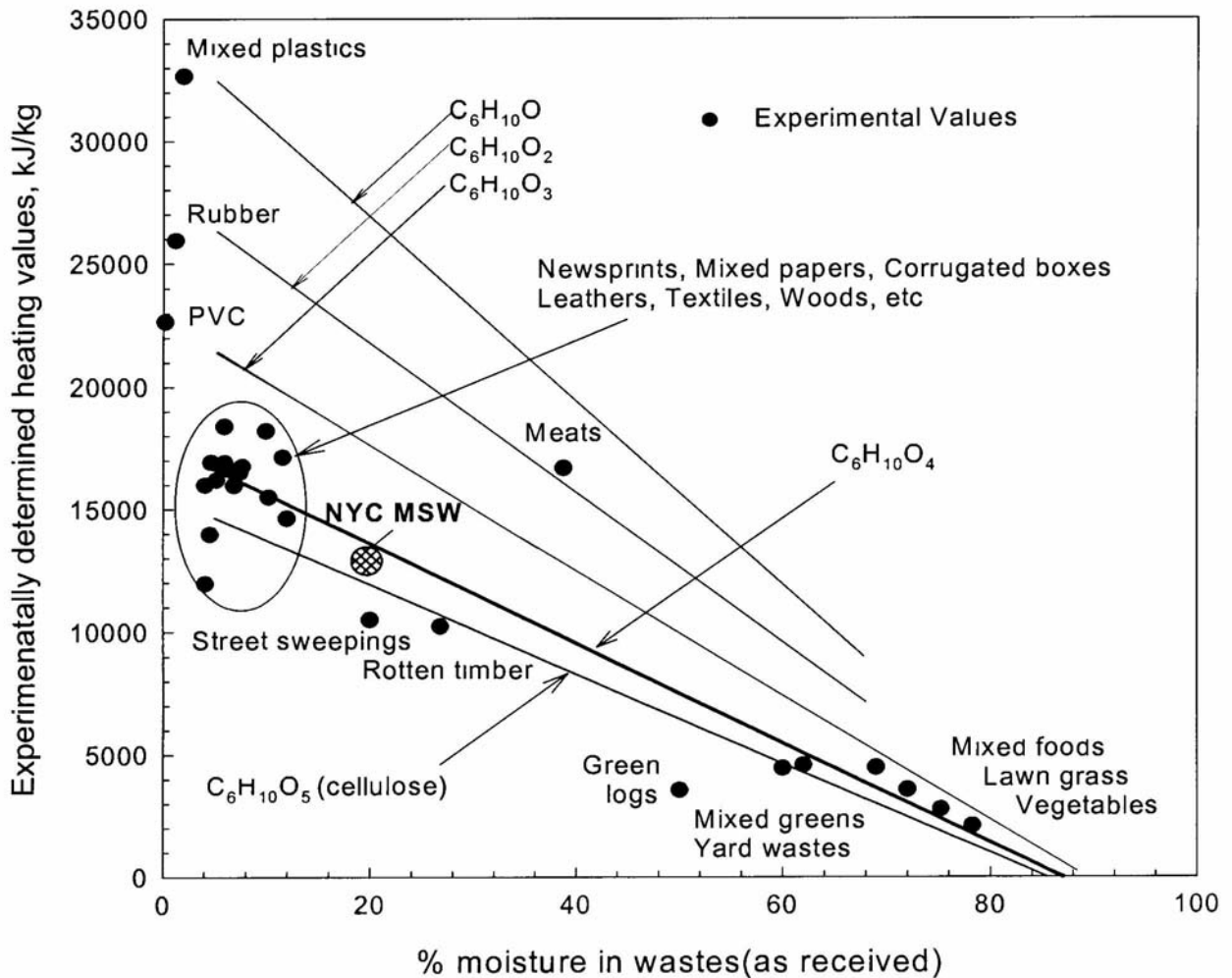


Figure 4. Effect of moisture on heating value of MSW materials (points are heating values reported in the literature; solid lines show thermochemical values for various organic compounds; Themelis and Kim 2002)

6.2 Combined Flash and Moving Bed Combustion: The SEMASS WTE Plant

The EAC process was developed by Energy Answers Corporation (EAC 1999) and was implemented at the SEMASS WTE at Rochester, MA that is presently operated by American Ref-fuel (www.ref-fuel.com/locations/semass.htm). MSW is transported to this plant by covered railcar and truck from about 40 communities in a 65-mile radius, including the entire Cape Cod area, Martha’s Vineyard, and Nantucket. The plant consists of three parallel combustion units that process about 2,700 metric tons per day. The first two units were built in 1989 and Unit 3 in 1994. An average of 720 kWh of electricity is produced per metric ton of MSW, of which 110 kWh are used to operate the plant and 610 are sold to the local utility. The flow diagram for one of the three SEMASS units is shown in Figure 5.

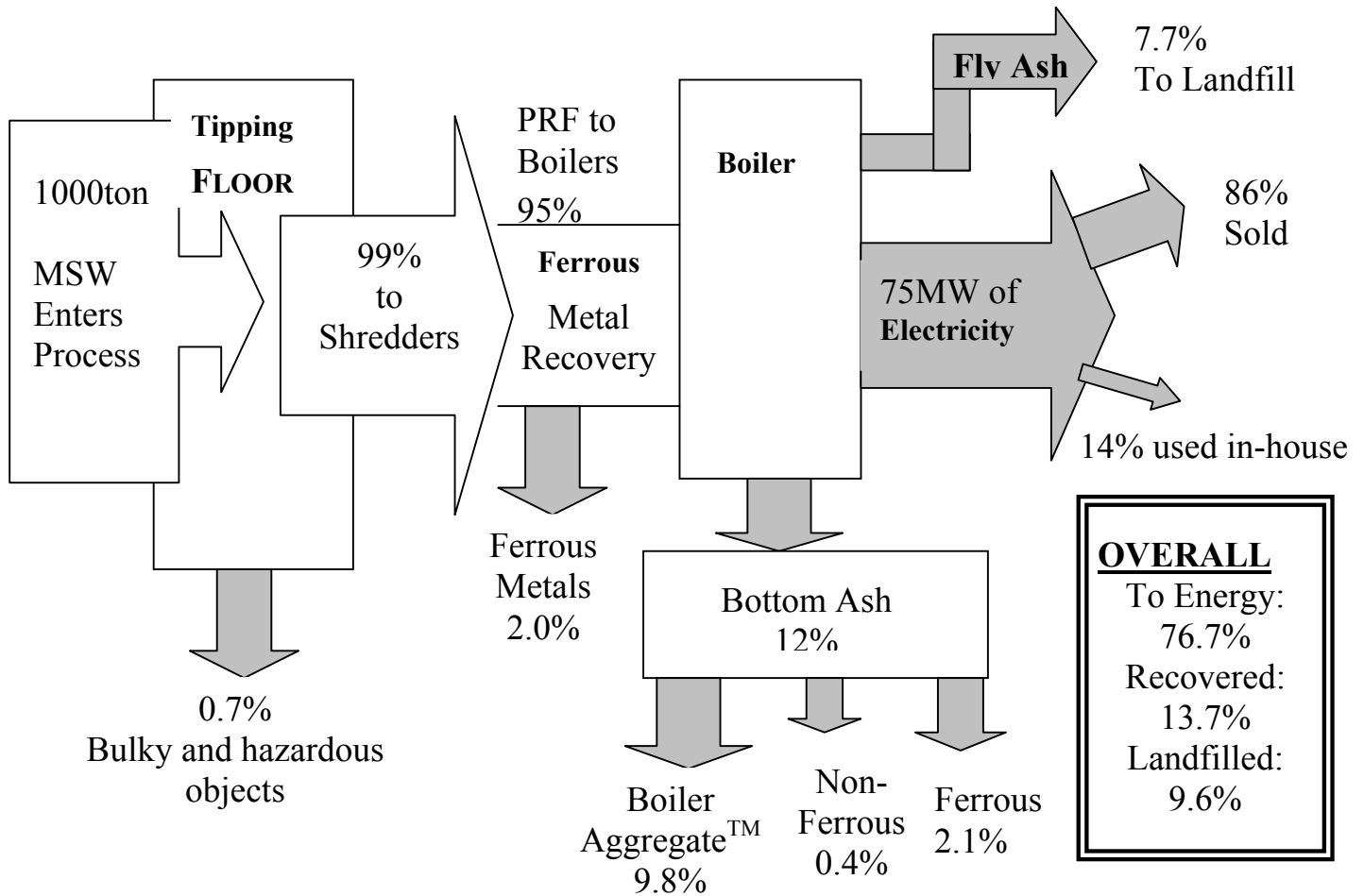


Figure 5. Process flow diagram of one of the three SEMASS WTE units

The feed material of SEMASS consists of the entire (i.e., “wet” + “dry”) MSW stream. Waste brought to plant is dumped on a tipping floor. Front end loaders load the MSW onto conveyors that pass by inspectors who look for bulk or hazardous waste; these items constitute about 1.6% of the incoming material. The waste is then shredded in one of two large hammermill shredders that produce a blended material of minus 6-inch size. The shredded material is conveyed under overhead belt magnets for the first round of ferrous metal recovery and is then stored in bays in a storage building. This material is called “processed refuse fuel” and can be stored for long periods, as it is fairly dry and is not malodorous as bulk MSW.

When this material is fed by conveyor belt through inclined chutes into the combustion chamber, deflectors at the bottom of the chutes and high-velocity air jets, disperse the lighter particles in the hot gas where they are subjected to flash combustion. The heavier particles settle on the far end of a moving grate that is located at the bottom of the combustion chamber. Air is injected from below through the grate and completes combustion of the carbon content of the bed on the grate as it moves slowly towards the front wall of the combustion chamber. The estimated residence time of material on the bed is about one hour. At the front end, the ash is discharged into a bin below the grate.

The SEMASS reactor combines flash and moving bed combustion. The temperatures reached in the combustion chamber and on the moving grate are at least 100°C higher than in mass burning. Also, the discharged “bottom” ash, examined by the authors in the laboratory, is semi-fused, unlike the flaky and powdery ash of mass-burning plants. Additional ferrous metals and also non-ferrous metals are recovered from this ash by means of magnetic and eddy current separators, respectively. The ash meets the EPA non-toxic criteria (TCLP test) and can be used as landfill cover and other beneficial uses.

The gas handling plant of the SEMASS Combustion Unit 3 (built in 1994) is more advanced than the first two units (built in 1989). Potential air contaminants are controlled by a variety of means. A solution of urea in water is injected continuously into the furnace to control the level of nitrogen oxides. The combustion gases pass through water and air heat recuperators and then enter a “dry scrubber” chamber where injected lime slurry neutralizes acid gases and reacts with halides and also with dioxins/furans that may have persisted in the high temperature atmosphere in the combustion chamber, or re-formed during the cooling stage of the gas. Activated carbon is also injected in the process gas to collect mercury and other volatile contaminants. Finally, fiber fabric filters capture most of the fine particles before the gases are discharged through the stack. The fly ash collected in the fiber bag filters contains most of the heavy metals that were present in the MSW and is disposed in a monofill landfill.

The SEMASS plant recovers 4.5% of the feed MSW as ferrous and non-ferrous metal, and disposes 7.7% as fly ash to the nearby backup landfill. The bottom ash, after metal recovery, represents about 10% of the feed and can be used as road fill or in other beneficial uses.

6.3 Gas Emissions from WTE Power Plants

The most contentious issue regarding energy recovery from solid wastes is that of emissions to the atmosphere. Emissions of particulate matter (PM), mercury, hydrochloric acid, and dioxins have been the most worrisome problems in the past. However, by the end of the 20th century, emissions in modern WTEs were reduced to extremely low levels by means of reduction of the precursors in the feed (e.g. mercury-containing products), better combustion practice, and greatly improved gas control systems that include dry-scrubbing, activated carbon injection and filter bag collection systems.

For example, Walsh et al have reported (Walsh 2000) that during the 20th century there were thousands of residential incinerators in NYC and thirty two municipal incinerators. In total they emitted about 0.8 million tons of particulate matter, i.e. nearly 1% of the MSW incinerated. In comparison, the SEMASS emission of 0.0045 grams of PM per cubic meter of stack gas corresponds to less than 0.003% of the MSW processed in this WTE plant. Table 3 compares all other air emissions of the SEMASS No. 3 unit with the current EPA standards (Themelis et al 2002).

Table 3. Comparison of 1999 Emissions from SEMASS No. 3 Unit with EPA standards

Emission	EPA Standard ¹	SEMASS ²
Particulate (gr/dscf)	0.010	0.002
Sulfur Dioxide*	30	16.06
Hydrogen Chloride*	25	3.6
Nitrogen Oxides*	150	141
Carbon Monoxide*	150	56.3
Cadmium**	20	1.24
Lead**	200	30.03
Mercury**	80	5.09
Dioxins/Furans (ng/dscm)	30	0.86

gr/dscf: grains/dry standard cubic foot; 1 gr/dscf=2.28 g/dry standard cubic meter;

** ppm_{dv}: parts per million dry volume*

*** μg /dscm: microgram per dry standard cubic meter; ng: nanogram*

¹*The standards and data are reported for 7% O₂, dry basis, and standard conditions.*

²*EAC, average of 1994-1998. Boiler No.3*

6.4 Decrease in mercury emissions in the nineties

As the most prominent pollutant of the volatile heavy metals, mercury is a good indicator of the drastic decrease of U.S. WTE emissions in the nineties. A study by the National Renewable Energy Laboratory (NREL 1993) reported that the 1989 emissions of all U.S. WTEs amounted to 81.8 tons of mercury. By the mid-nineties, the total emissions from WTE plants in the U.S. had been reduced to 26.9 tons of mercury (EPA 1997). Table 4 shows the mercury emissions from several mass-burning plants in New York and New Jersey and from the SEMASS facility (Themelis and Gregory 2002). The last column brings all data to the common metric of kilograms of mercury emitted per one million metric tons of MASW processed. If one applies the average value of 60 kg of mercury per million metric tons of MSW (Table 4) to the 33 million metric tons (36 million short tons) of MSW combusted in the U.S. (Berenyi, 1998), the mercury emissions from U.S. WTE plants in 1999 are estimated to be about 2 tons, i.e. thirteen times smaller than the EPA 1995 estimate and nearly forty times lower than the 1989 WTE emissions. In contrast, the mercury emissions from all U.S. coal-fired power plants are about 43 metric tons per year (EWG 2001). The rapid decrease in mercury emissions from WTE facilities is illustrated in Figure 6.

Table 4. 1999 Mercury emissions from Waste-to-Energy plants

Facility	Gas control system (all use carbon injection)	MSW combusted, short tons per year	Annual micrograms of mercury per dry standard cubic meter	Mercury emissions Kg/y	Kilograms of mercury per million metric tons of MSW
Camden, NJ	ESP	451,000	25.1	51.3	125
Essex, NJ	ESP	985,000	31.8	73.5	82
Gloucester, NJ	Fabric filters	210,000	38.0	6.8	36
Union, NJ	Fabric filters	562,000	2.2	14.5	28
Warren, NJ	Fabric filters	160,000	2.4	1.8	12
New Jersey total		2,368,000		148	69
Onondaga, NY	Fabric filters	330,000	8.1	15.3	52
Hempstead, NY	Fabric filters	700,000	NA	NA	
Niagara Falls, NY	Fabric filters	800,000	NA	NA	
New York total		1,826,000			
SEMASS, MA	Fabric filters	1,000,000	5.1	33.0	37

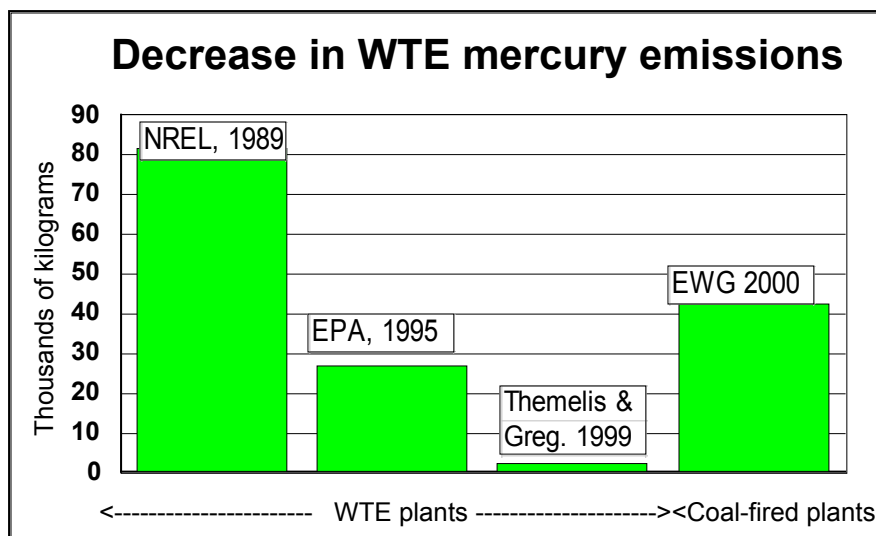


Figure 6. Decrease in mercury emissions of U.S. WTE plants in the last decade of the 20th century

6.5 Decrease in Dioxin Emissions from WTE Plants

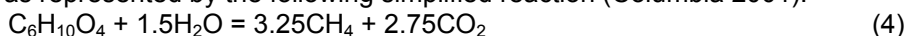
Another environmental concern regarding WTE plants in the past has been the emission of dioxins. In the case of the SEMASS WTE plant, the dioxin concentration of 0.86 nanograms per dry standard cubic meter of gas (Table 11) corresponds to only 4.5 grams per year, i.e. 4.5 grams per million tons of MSW. If all the U.S. WTE plants (33 million metric tons of MSW) were doing as well, the total WTE emissions would amount to 162 grams per year. However the Onondaga WTE reported (Jan.-Feb 2000, www.ocrra.org) an average dioxin concentration of 2.78 nanograms per dscm. This number is three times higher than at SEMASS and if it applied to the entire WTE industry, the annual emissions would amount to 480 grams, or about one pound per year.

A preliminary report by EPA (1998) estimated that as of 1995, the dioxin emissions of municipal waste incinerators were in the range of 492-2,460 grams and represented 40% of the tabulated emissions. However, the review panel of this report (EPA Review 1998) noted that “estimates for dioxin emissions from landfill fires and backyard trash burning suggest that these sources may release more dioxins to the air than do most of the sources EPA included in (their estimate)”. The review panel also commented that “25,000 grams of TEQ dioxin may be found in pentachlorophenol (PCP) used for wood treatment. This amount is over eight times greater than EPA’s (total 1995) estimate”. Another observation by the review panel of the EPA report was that “EPA estimates that there are 25,000,000 residential wood combustion sources in the United States, yet none have been tested for dioxin emissions.”

In summary, the implementation of Activated Carbon Injection in WTE plants has helped to decrease both mercury and dioxin emissions. The dioxin emissions are specially low in flash-moving bed combustion, such as is used at the SEMASS WTE, that generates higher temperatures within the combustion chamber. At the present time, the dioxin emissions from the entire U.S. WTE industry are of the order of one pound per year.

7. GAS EMISSIONS FROM LANDFILLS

The anaerobic decomposition of MSW in landfills leads to the generation of methane and carbon dioxide as represented by the following simplified reaction (Columbia 2001):



The gas produced by this reaction contains about 54 percent methane and 46 percent carbon dioxide. If it is assumed that the biodegradable component of MSW represents 25% of the MSW stream, the maximum amount of natural gas that can be produced from the NYC black-bag stream is calculated from the above equation to be about 130 standard m³/metric ton. However, as the organic molecule chains become shorter, they become more stable and the rate of biodegradation decreases. Franklin (1995)

reported that the maximum capacity of landfilled MSW to produce methane is 62 standard m³ of CH₄ per ton of MSW. The actual capture of methane gas generated in landfills in the U.S. has been estimated at about 66 percent (Dennison, 1996), i.e. at 62*.66= 41 m³/metric ton landfilled. This last number is in good agreement with the compilation of landfill data by Berenyi (1999) that showed the total capture of LFG gas from U.S. landfills in 1999 to be 778 million scfd; for the 106 million of metric tons landfilled annually in the U.S., this corresponds to a capture of 75.6 m³ of LFG per metric ton, i.e. about 38 m³ of CH₄. Accordingly, for each metric ton of MSW landfilled, the carbon loss to the atmosphere is calculated to be 21 (62-41) m³ in the form of CH₄, i.e. about 11 kilograms of carbon. Since methane is 21 times more potent as a greenhouse gas than CO₂, the methane loss from landfills corresponds to about 230 kilograms of carbon equivalent. The carbon emissions in the form of carbon dioxide, both from captured and non-captured LFG amount to another 30 kilograms of carbon bringing the total emissions of carbon from landfilling to 260 kilograms per metric ton of MSW.

In comparison, the total carbon emissions from the combustion of the MSW amount to about 247 kilograms of carbon. However, the electricity produced in the combustion process reduces the need for coal consumption by about 250 kilograms of coal per ton of MSW. Therefore, the net effect is that landfilling increases carbon emissions to the atmosphere by nearly 230 kilograms of carbon equivalent per metric ton of MSW. It should also be noted that if the entire 62 m³ of CH₄ per ton of MSW were to be recovered, the contained heating value would amount to 1940 MJ per ton MSW, i.e. only 20 percent of the heating value of combusted MSW (11630 MJ/ton, Table 2).

8. CONCLUSIONS

With respect to the estimated 60% of NYC MSW that is not recyclable under any circumstances, the only viable technologies are Waste-to-Energy or landfilling. The Columbia Earth Institute report (Columbia 2002) found that WTE is environmentally preferable on several counts:

- a) WTE generates a net of 610 kWh per metric ton of MSW. This reduces the U.S. dependence on coal mining (about 0.25 tons of coal less per ton of MSW combusted) or on oil imports (45 gallons of oil less per ton of MSW). At this time, 33 million metric tons of MSW are combusted annually in U.S. WTE plants to generate about 20 billion kWh per year. This is equivalent to a saving of about 1.6 billion gallons of fuel oil per year.
- b) The gas emissions from landfills contain methane (natural gas), a gas that is 21 times more potent as a greenhouse gas than carbon dioxide. Thus, including the advantage of electricity production from the combusted MSW, the landfill greenhouse gas emissions are much greater than for WTE. With regard to other emissions, such as mercury and dioxins, this report documents the great progress that the U.S. WTE industry has made in this sector towards the end of the 20th century. Currently, modern WTE plants are equipped with advanced gas control systems, such as dry scrubbing, activated carbon injection and bag filters that are superior to the gas handling systems of most coal-fired power plants.
- c) In modern landfills, during the life of the landfill and for a mandated period after that, the generated aqueous effluents are collected and treated chemically. However, reactions within the landfill can continue for decades and centuries after closure. Thus there is potential for future contamination of adjacent waters.
- d) WTE recovers ferrous and non-ferrous metals, thus conserving natural resources.
- e) Landfilling practically condemns for any future use a large amount of land per ton of MSW disposed. A rough estimate for the direct use of land is one acre for every 33,000 metric tons of MSW. This figure corresponds to an annual "consumption" of about 90 acres per year for the NYC MSW that is presently transported to out of state landfills. Of course, a much larger surface area is required between landfills and inhabited areas or parks.

In recognition of the above factors, other developed nations, like France, Germany and Japan, have phased out landfills, except for the disposal of inorganic materials (e.g. ash) that cannot be recycled or combusted. From an economic point of view, landfilling is at present less costly in the U.S. because land is inexpensive. However, "tipping" fees depend on current environmental regulations and also on the distance over which MSW must be transported. For New York City, in the last few decades tipping fees have increased manifold to the present rate of \$70/ton. They are bound to increase further as landfills come under further public and state scrutiny and as NYC MSW may have to be transported further and further away. On the other hand, if the City's plan encourages private firms to build new WTE plants in

the states of New York or New Jersey, tipping fees can be negotiated and guaranteed for a long period of time.

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