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Energy recovery from New York City solid wastes

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Abstract

The principal means for integrated management of municipal solid wastes (MSW) are recovery of materials (recycling), recovery of energy, bioconversion to fuel and compost, and landfilling of the remaining residues. This study examined the recovery of energy by pre-processing the combustible components of MSW and using them as a fuel in a properly designed combustion reactor and thermoelectric plant to generate electricity and process steam. Despite the heterogeneity of materials in MSW, the mean hydrocarbon structure can be approximated by the organic compound $C_6H_{10}O_4$. A formula is derived that allows the prediction of the heating value of MSW as a function of moisture and glass/metal content and compares well with experimentally derived values. The performance of a leading Waste-to-Energy plant in the U.S. that processes about 0.9 million tons of MSW per year and produces a net 620 kWh/ton is examined. The results of this study indicate that energy recovery from MSW can reduce considerably the amount of land consigned annually to landfilling and also decrease to a small extent dependence on fossil fuels.

Keywords – municipal solid waste; energy recovery; combustion; incineration; ash; emissions; pre-processing; WTE

1. Introduction

Economic development and prosperity are accompanied by the generation of large amounts of wastes that must be re-used in some way or disposed in landfills. The generation of wastes can be reduced to some extent by improved design of products and packaging materials and by increasing intensity of service per unit mass of material used. However, even after such measures are taken, there will remain a large amount of solid wastes to be dealt with.

Solid wastes can be classified in various classes. The broadest classification is in municipal (residential and commercial), industrial, construction and demolition wastes. The municipal solid wastes (MSW) are the most non-homogeneous since they consist of the residues of nearly all materials used by humanity: Food and other organic wastes, papers, plastics, fabrics, leather, metals, glass and miscellaneous other inorganic materials. Everything wears out gradually or abruptly and then ends up either in MSW or is discarded in land or water. The annual generation of MSW in the U.S. is about 0.7 metric tons (0.8 short tons) per capita.

Processing or disposal of MSW require what is called Integrated Waste Management (IWM): Separating the MSW into a number of streams each of which is then subjected to the most appropriate method of resource recovery. The separation of MSW components can take place at the source, i.e. households or businesses or at Materials Recovery Facilities (MRFs) where manual and electromechanical methods are used. There are four principal methods for resource recovery or disposal of MSW:

- **Recovery of materials:** Recovered paper, plastic, rubber, fiber, metal, and glass can be re-used to produce similar materials.
- **Recovery of energy:** Recoverable energy is stored in chemical form in all MSW materials that contain hydrocarbons; this includes everything except metals, glasses, and other inorganic materials (ceramics, plaster, etc.). By combusting such wastes, electricity and steam can be generated.
- **Bioconversion:** The natural organic components of MSW (food and plant wastes, paper, etc.) can be composted aerobically (i.e., in the presence of oxygen) to carbon dioxide, water, and a compost product that can be used as soil conditioner. On the other hand, anaerobic digestion or fermentation produces methane or alcohol and a compost product; this method provides an alternate route for recovering some of the chemical energy stored in the hydrocarbon fraction of MSW.
- **Landfilling:** Any fraction of the MSW that is not or cannot be subjected to any of the above three methods, plus any residuals from these processes (e.g., ash from combustion) must be disposed in properly designed landfills.

The objective of this study was to examine the recovery of energy by sorting and pre-processing the combustible components of MSW and then using them as a fuel in a properly designed combustion vessel, similar to those used for generating electricity in fuel-fired power plants. Energy recovery from MSW can reduce the amounts of fossil fuels that are extracted from the Earth to provide power and heat. It can also reduce the amount of land needed for MSW disposal and undesirable emissions from landfills to air and water.

This paper is part of a continuing joint study conducted by the Earth Engineering Center and the Center for Urban Research and Policy of Columbia University on alternatives for MSW management in New York City.

2. Disposal of MSW to landfills

Table 1 is based on data provided by the Council of Environmental Quality (1997) and shows that all four methods of managing MSW are used in the U.S. It is interesting to note that in the period of 1980-1996, the fractions of MSW recycled or combusted nearly doubled; also, the fraction of composted materials (consisting mostly of yard wastes) increased to 5.4% of the total MSW. However, landfilling remains the major means of disposition of wastes in the U.S. For example, New York City currently recycles about 20% of its MSW (0.6 million short tons) as paper, metal, glass and plastics; the remainder is landfilled at “tipping” fees that have tripled in the last few decades to the current fee of about $72/ ton for out-of-state disposal.

Table 1. U.S. Municipal Solid Waste Trends (Council for Environmental Quality, 1997)

	1980	1990	1996

	10^6 tons*	%	10^6 tons*	%	10^6 tons*	%
Gross discards	151.64		205.21		209.66	
Recycling	14.52	9.6	29.38	14.3	46.01	21.9
Composting	<0.5	0.0	4.2	2.0	11.32	5.4
Combustion	13.7	9.0	31.9	15.5	36.09	17.2
Landfilling	123.42	81.4	139.73	68.1	116.24	55.4

*in short tons; for metric tons, multiply by 1.1.

To illustrate the "for ever" use for land for landfilling, it is interesting to examine the case of the city of Halifax, Canada (Halifax, 2000) that has acquired the reputation of a very advanced waste management system. They practice "wet" and "dry" separation at the household level, recycling of usable materials, composting of part of the "wet" fraction, and controlled pre-composting of the remainder of the MSW, prior to disposal in a state-of-the-art landfill. Halifax is a community of about three hundred thousand people generating 250000 tons of MSW per year. Their recycling and composting activities result in only 60%(150000 tons/yr.) of the total MSW going to the landfill. The planned lifetime of this modern 80-acre landfill is twenty years; thus amounting to the use of about 16200 square meters (4 acres) per year. For the same land to population ratio, the corresponding annual land requirements of New York (population: 8 million) for a modern landfill are calculated to be 430000 square meters (107 acres) per year.

If the enlightened waste management of Halifax were to be applied universally, the land consigned annually to landfilling by the six billion population of the planet would amount to a swath of land 320 km long and 1 km wide. Unfortunately, the waste management practice in most places is much behind Halifax and the land area covered by primitive landfilling, or simply by discarding wastes to the environment, much greater than the 320 square kilometers of the above calculation. It is evident that better methods for dealing with solid wastes should be part of the ABC of the global effort for sustainable development.

3. Composition of MSW

The MSW composition varies amongst communities, and even within one community from year to year, but the differences is not substantial. Table 2 compares the major components in the "typical" U.S. composition of MSW (Tchobanoglous, 1993; EPA, 1997) with the composition of the New York City waste stream (SCS Engineers, 1992).

Table 2. Comparison of MSW components (% weight)

	"TYPICAL" U.S. MSW (1)	(2)	NEW YORK CITY MSW (3)
Paper	34.0	33.7	26.6
Cardboard	6.0	5.5	4.7

Plastics	7.0	9.1	8.9
Textiles	2.0	3.6	4.7
Rubber, Leather, “Other”	1.0	2.9	0.2
Wood	2.0	7.2	2.2
Yard Wastes	2.0	14.0	4.1
Food Wastes (mixed)	9.0	9.0	12.7
Glass and metals	17.5	13.1	16.4*

(1) Tchobanoglous, et al. ,1993. (2) EPA 530-S-97-015. 1997; (3) SCS Engineers, 1992.
*On assumption that 2/3 of weight of NYC "bulk items" is metal

The MSW composition used in this study is based on the New York citywide data of an extensive characterization study conducted in 1990 for the NYC Department of Sanitation (SCS Engineers, 1992). Table 3 shows the corresponding daily tonnage of each waste material, computed by using these data and the 1998 rate of MSW generation of 11800 tons per day (Department of Sanitation, NYC, 1998).

Table 3. Composition of New York City MSW

WASTE COMPONENT	% WEIGHT*	tons/day **
“Dry” Stream Combustibles	*51.9*	*6121*
Paper	31.3	3691
Corrugated Cardboard	4.7	554
Newspapers	9.2	1085
All other paper	17.4	2052
Plastics	8.9	1049
HDPE (clear & color)	1.1	134
Films and Bags	4.8	568
PET	0.5	58
Polypropylene, polystyrene	0.9	108
PVC	0.1	14
All other plastics	1.4	167
Other dry combustibles	11.7	1380
Wood	2.2	259
Textiles	4.7	554
Rubber & Leather	0.2	24
Fines	2.3	271
Other	2.3	272
“Wet” Stream Combustibles	***28.0***	***3302***
Food Waste	12.7	1498
Grass/Leaves	3.4	400
Brush/Prunings/Stumps	0.7	83
Disposable Diapers	3.4	401
Miscellaneous Organics	7.8	920

“Dry” Non-combustibles	***9.8***	***1156***
Glass	5.0	590
Clear Glass Containers	2.9	342
All other glass	2.1	248
Aluminum	0.9	106
Ferrous Metal	3.9	460
Other materials	***10.3***	***1215***
Hazardous Waste	0.4	47
Bulk Items (appliances, furniture, etc)	9.9	1168

* Adapted From: SCS Engineers, 1992 ** At current rate of generation of 11800 metric tons/day

Table 3 shows that the major constituent of MSW is paper. Other low-moisture combustible materials are plastics, textiles, rubber, leather, and wood. These materials can be called “dry combustibles”, in distinction to the “wet combustibles” of food, plant and other wastes that contain 50-70% water. The third category shown in Table 3 is “dry non-combustibles”, i.e. metal, glass and other inorganic compounds that have no heating value. 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 metal scrap, or wood scraps that are either recyclable or combustible.

4. Division of MSW into “dry” and “wet” materials

MSW can be classified into “dry” and “wet” materials, on the basis of their moisture content. The unpleasant odors and liquids associated with “garbage” are due to the putrescible organic components of food and plant wastes in the “wet” stream. These materials are less than 30% of the total MSW; yet they contaminate and complicate the transport and processing of the rest of the MSW. Therefore, it is generally preferable to separate the “wet and “dry” components at the source. This is already done at some forward-looking communities in Canada (Guelph, 2000; Halifax, 2000), Europe and Australia. However, it is interesting to note that the citizens of New York City were also separating “wet” from “dry” in the first part of the 20th century and recovered useful products from both streams. However, this system was made uneconomic by the creation of the giant Fresh Kills landfill on Staten Island.

From the perspective of energy recovery (Table 3), the “dry” fraction can be divided into combustible materials, such as paper, plastics, and wood; and non-combustible or “inert” materials, such as metal and glass. There are three options for handling the “wet” fraction: combustion, aerobic or anaerobic bioconversion and landfilling. Table 4 (after Tchobanoglous et al, 1993) shows the "proximate analysis" composition of various types of combustible waste materials, i.e. % moisture, volatile matter (principally hydrocarbons), fixed carbon, and non-combustible, non-volatile “ash”. The experimentally determined heats of combustion of each waste material are also shown.

Table 4: 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
“Wet” Combustibles					
Wood	20.0	68.1	11.3	0.6	15445
Yard Wastes	60.0	30.0	9.5	0.5	6050
Food Wastes	70.0	21.4	3.6	5.0	5350
“Dry” and “Wet”	21	52	7	20	11630

***** Adapted from data in Tchobanoglous et al., 1993.

Table 4 shows that 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. 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 cannot generate much electricity.

5. Thermal energy in MSW components

In this study, the chemical thermodynamics of the MSW combustion reaction were modeled by representing the composite combustible MSW by an established hydrocarbon compound. On the basis of the composition data for the “typical” U.S. MSW by Tchobanoglous (1993), and the atomic weights of the respective elements, Themelis and Kim (2000) calculated the molecular formula corresponding to each of the combustible components of MSW:

Mixed paper: $C_6H_{9.6}O_{4.6}N_{0.036}\,S_{0.01}$

Mixed plastics: $C_6H_{8.6}O_{1.7}$

Mixed food wastes: $C_6H_{9.6}O_{3.5}N_{0.28}\,S_{0.2}$

Yard wastes: $C_6H_{9.2}O_{3.8}N_{0.01}\,S_{0..04}$

They also showed that the hydrocarbon formula $C_6H_{10}O_4$ most closely approximated the mix of organic wastes in MSW. This molecular formula corresponds to that of at least ten organic compounds, such as adipic acid, ethylene glycol diacetate, and others. The heat of formation of most of these $C_6H_{10}O_4$ compounds mentioned earlier 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:

$$C_6H_{10}O_4 + 6.5O_2 = 6CO_2 + 5H_2O \qquad (1)$$

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).

Similarly, if the MSW combustibles are simulated by the less oxidized compound $C_6H_{10}O_3$, the combustion reaction is

$$C_6H_{10}O_3 + 7O_2 = 6CO_2 + 5H_2O \qquad (2)$$

and the "theoretical" heat generated 23000 kJ/kg (9900 BTU/lb.). A computation by Brady (2000) of the molecular formula of NYC wastes resulted in the hypothetical compound $C_6H_{9.3}O_{3.5}$ that lies between the above two organic compounds (Table 5).

__________ **Table 5: Ultimate Analysis of Dry Stream before Materials Recovery**

Component of Waste Stream	**% in NYC***	**Weight of Comp. (tpd)**	**% by Weight****				
			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	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	11
		Atomic Weight (kg/kmol)	12.01	1.01	16.00	14.01	32.07
		# of moles	262	405	151	3.29	0.33
Molar Ratio		*C=6*	6.0	9.3	3.5	0.1	~0.0

Approximate Chemical Formula $C_6H_{9.3}O_{3.5}$

6. Effect of moisture and inert materials on available heating value

Let us now examine how the inclusion of moisture and non-combustible materials in the MSW affects the available heat in Waste-To-Energy (WTE) plants that produce electricity and steam. To quantify these effects, it is assumed that the WTE plant provides steam to a standard power plant and that the exhaust gases leave the boiler at 120°C and 135 kPa (20psi). Accordingly, the amount of heat wasted per kg of water in the feed, as water vapor in the exhaust gases, is calculated to be 2636 kJ/kg.

The non-combustible materials in the feed, mainly glass and metals, will end up mostly in the bottom ash. If it is assumed that the ash leaves the grate at about 700°C and a reasonable value for the specific heat of ash, the corresponding heat loss to inorganic materials fed with the combustibles is estimated to be as follows:

- Glass and other siliceous materials: 628 kJ/kg (270 BTU/lb.)
- Iron: 420 kJ/kg
- Aluminum: 1134 kJ/kg

Considering that the iron/aluminum ratio in MSW is about 4 (Table 3), the mean heat loss per kg of metal is estimated to be 544 kJ/kg (234 BTU/lb.). Accordingly, the effects of non-combustibles on the heating value of RDF can be expressed as follows:

$$\textbf{Heating value of mixed MSW} = (\text{heating value of combustibles})^* X_{comb} - (\text{heat loss due to water in feed})^* X_{H2O} - (\text{heat loss due to glass in feed})^* X_{glass} - (\text{heat loss due to metal in feed})^* X_{metal} \quad (3)$$

and substituting numerical values for heating value of Equation 1 and the above heat loss gives,

$$\textbf{Heating value of mixed MSW} = 18400X_{comb} - 2636X_{H2O} - 628X_{glass} - 544X_{metal} \quad \text{kJ/kg} \quad (4)$$

where X_{comb}, X_{H2O}, etc. are the fractions of combustible matter, water, etc. in the RDF.

From the point of view of combustion efficiency and maximization of energy recovery per ton of MSW, it is clear that it would be preferable to separate wet putrescible materials. This will increase the heating value of the material being burned and therefore will generate more energy per ton of waste burned. Separation of non-combustibles in the waste (glass and metals) will also increase heating value and energy generation per ton. However, the prime function of waste combustion facilities is waste disposal. The removal of specific materials before combustion requires either collection of separate streams at the source, or separation at the combustion facility before burning. Either of these processes increases the collection, transportation and processing costs with relatively little change in the energy generation per ton of original waste. Thus, although heating value is increased, the net cost of energy production from solid wastes increases.

Table 6 shows that the experimentally determined 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 1. Also, this value is in the range of lignitic and sub-bituminous coals that are still used in many power plants. Therefore, using the “dry combustible” MSW as a fuel can reduce, by as much as ton per ton, the need for mining coal. Another way of expressing the value of MSW as an energy resource is by stating that the 1.15×10^5 GJ/day of heat contained in the NYC dry combustibles correspond to about 3.05 million liters (806400 gallons) of No.2 fuel oil per day.

It is also of interest to compare the experimentally determined heating values of Table 6 with the projection of Equation (4) for the effects of moisture and inert on the heating value of RDF. Table 6 shows that when the dry non-combustibles are included, the combined stream consists of 84.1% combustibles, 7.8% metal and 8.1% glass and the experimental heating value is 15817 kJ/kg (6800 BTU/lb). This value is in close agreement with the value of 15400 kJ/kg (6620 BTU/lb.) projected by Equation 4. Also, if we assume that the "wet" fraction contains 50% water, when the wet fraction is commingled with the dry fraction, the composition of the entire stream becomes: Combustibles: 67.5%; glass and metal: 10.9%; moisture: 15.6%. Table 6 shows that the experimentally determined heating value of this mixed stream is 12332 kJ/kg, in comparison to the 12000 kJ/kg projected by Equation 4.

To put this last number into perspective, it should be noted that a typical large-scale power plant uses approximately 11000 kJ to produce 1 kWh; therefore, combusting one ton of the "dry" and "wet" mix should generate about 1000 kWh. However, the best WTE plants produce about 650 kWh per ton of mixed MSW (EAC, 1999). The same WTE plants fueled only by the "dry" combustible fraction would produce about 1000 kWh/ton (650* 18470/12000).

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Figure 1. Comparison of experimental heating values of various waste materials

Figure 1 shows the effect of moisture on the heating value of MSW. The bold line represents the heating value calculated from Equations 1 and 4 (i.e. assuming that the composition of organic matter in MSW can be represented by the molecular formula $C_6H_{10}O_4$). It can be seen that this line is fairly representative of the heating value of several waste materials reported in that literature as well as of the New York City MSW (Table 6). Of course, 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 only papers where cellulose ($C_6H_{10}O_5$) is the prevalent compound. Figure 1 shows the projected heating values of various $C_6H_{10}O_x$ compounds.

Table 6. Heating Value of Various Components of NYC MSW

Component of MSW Dry Stream	% in NYC Waste[1]	Weight[2] (Tons/day)	Heating Value[3] (MJ/ton)	Heating Value of Component (GJ/day)
Combustibles:				
Paper:	31.3			
Newspaper	9.2	1087	18548	20162
Cardboard	4.7	555	16382	9092
Other Paper	17.4	2056	15814	32514
Plastics (HDPE: 1.1%; PET: 0.5%)	8.9	1052	32800	34506
Textiles	4.7	555	17445	9682
Rubber & Leather	0.2	24	21387	513

Wood	2.2	260	15445	4016
Fines	2.3	272	8534	2321
Other	2.3	273	6978	1905
Total Dry combustibles	**51.9**	**6134**	**18470**	**114711**
Non-combustibles				
Metal	4.8	567		
Glass	5.0	591		
Total Non-combustibles	**9.8**	**1158**		
Total Dry Stream	*61.7*	*7292*	*15817*	*115338*
Total Wet Stream				
Including Food & yard waste, All other “wet”	*28.0*	*3309*	*4652*	*15393*
Total Wet+Dry[4]	***89.7***	***10601***	***12332***	***130731***

[1] SCS Engineers, 1990

[2] Weight is based on current NYC generation levels of 13000 short tons per day (stpd)

[3] Tchobanoglous, 1993

[4] In addition to these materials, NYC handles 1287 short tons per day of bulk items (appliances, furniture, etc.) and 52 tons of hazardous wastes.

7. Combustion techniques for energy recovery

7.1 Mass Burn WTE plants

When people discuss the pros and cons of “incineration” of MSW, they are usually influenced by the results of past practice when there was no or little concern about the environment and the emission controls rudimentary or non-existent. For instance, between 1910 and 1968 there were approximately 17000 apartment/house incinerators operating in New York City; in the same period 32 municipal incinerators were constructed in NYC and combusted a total of about 73 million tons (81 million short tons) of MSW (Walsh et al, 2000).

More recently, “mass burning” incinerators were provided with emission control systems but many were not used for energy recovery. Today, mass burning of MSW with power generation, in Waste to Energy (WTE) plants is practiced widely in the U.S. and other developed countries and does not requires pre-processing of the waste, apart from manual removal of bulky items like “white goods”. The rest of the waste is charged to the furnace by means of a mechanical “claw” that deposits full garbage bag and other items at the feed end of a metal grate that moves the waste materials slowly through the combustion chamber. Because of the large size of the items deposited on the grate mechanism, the rates of mass transfer and chemical reaction with the oxidizing gas are relatively slow. Because of the low rate of oxidation, a very large combustion chamber and grate are required and the intensity of combustion (rate of heat generation per unit volume) is correspondingly low. Therefore, the temperatures generated in the combustion chamber are in the order of 900°C and the ash does not reach the point of fusion or semi-fusion. There have been improvements over the years in combustion efficiency and pollution control of mass burn WTE plants but has this technology been surpassed by newer ones that are discussed in the following sections.

7.2 Fluidized-Bed WTE Plants

Combusting of MSW in fluidized bed reactors is used extensively in Japan. This method requires shredding (to –5 cm) and removing inert materials like glass and metals from the feed to the fluid bed reactor. The remainder is fed on top of a fluidized bed of sand or limestone. Combustion under these conditions is more efficient and results in even temperatures and higher energy recovery, lower amounts of non-oxidized materials leaving the combustion chamber, and less excess air than mass burn plants. Fluidized-bed combustors operate at temperatures in the range of 830 – 910^{o}C and can use additional fuel as required so that they can burn materials with very high moisture content. Because of the lower uniform temperatures, "slagging" and corrosion problems in the furnace are kept to a minimum. On the other hand, lower temperatures result in the high NO_x levels and thus an additional dry lime scrubber is required in addition to the limestone fed into the bed. Fluidized beds also have a potential for solid agglomeration in the bed, if salts are present in feed, and may provide insufficient residence times for fine particles. The non-uniformity and fluctuation of heating values in feed is compensated by the large total mass of inert solids in bed.

7.3 Refuse Derived Fuel (RDF)

The term refuse-derived fuel (RDF) is used to describe MSW that has been processed sufficiently to produce a fairly uniform fuel that is ready for combustion either in WTE plants or as complementary fuel in conventional thermoelectric plants. The processing generally entails separation of inert materials, size reduction, and densifying (e.g., pelletizing). This allows for the removal of both recyclables and hazardous materials. The densified material is more easily transported, stored, and combusted than raw MSW. RDF can be produced on a small scale at several locations and then transported and used in a large WTE plant where the efficiencies of scale allow for effective emission controls. Also, the processing of MSW to RDF can include the addition of calcium compounds that after combustion they reduce HCl emissions. Lakeland Electric in Florida 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).

The first attempt to co-fire processed MSW and coal in a utility boiler was in St. Louis, in 1970. A demonstration was organized to co-fire prepared MSW and coal in suspension-fired utility boilers (Horner & Shifrin, Inc., 1970). Their study concluded that this technology was feasible and recommended a combination of 10% prepared MSW to 90% coal. The success of the demonstration project led the Union Electric Company to go ahead with full-scale plans at its Merramec power plant. However, this project failed due to several factors, such as community opposition to a transfer facility, financial constraints, and inadequate supply of waste. Apparently, none of these reasons reflected a problem with the technical aspects of the project (Harrison, 1980).

Another test was carried out in South Dakota under the supervision of Argonne National Laboratory (ANL), National Renewable Energy Laboratory (NREL), and Otter Tail Power Company in 1992. This test combined 12% of RDF and 88% coal prior to introduction into 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 RDF to coal, due to increased moisture. Emissions were about the same, except for some metal emissions, which increased slightly. All ash samples from this test passed the EPA's toxicity characteristic leaching procedure (TCLP) tests. A thorough analysis of this test is available in a report by ANL (Ohlsson, 1994).

The biggest problem faced by the use of RDF as a coal substitute is that many power plants are equipped with antiquated emission control equipment that does not meet emission standards even with respect to coal combustion.

In general, RDF allows greater resource recovery, and higher combustion and boiler efficiencies at the expense of decreased landfill and higher initial and operating costs, due to the extensive processing which occurs in the usual RDF processes. Furthermore, experience has shown that the combination of coal with a significant percentage of RDF in existing power station boilers has received little acceptance from the power industry.

8. A state-of-art WTE plant

The SEMASS facility at Rochester, Massachusetts is a good example of a state-of-art WTE plant. It was designed by Energy Answers Corporation (EAC, Albany, NY) and is presently operated by American Ref-Fuel. The feed material consists of the entire (i.e., wet + dry) MSW stream. The facility takes in waste by covered rail car and truck from 50 communities in a 65-mile radius, including the entire Cape Cod area and Martha's Vineyard. The plant consists of three parallel combustion units and processes over one million short tons per year. The first two units were built in 1989 and Unit 3 in 1994. At this time, the SEMASS combustion chamber and its products are the subject of an in-depth study by Columbia University and the results will be published in the near future.

8.1 Pre-processing of MSW

Waste brought to plant is dumped on a tipping floor (Figure 2). The waste is loaded onto conveyors that pass inspectors who look for bulk waste that could jam the shredders, or for 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 –6 inch size coarse RDF. 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 closed building. This material is called "processed refuse fuel" (PRF) and apparently can be stored in a storage building for long periods. Because some of the moisture has evaporated during shredding and storage, any moisture left is distributed and absorbed throughout the PRF; therefore the PRF does not have the acrid smell of garbage and does not attract rats or flies.

__________See all figures at the end of paper

Figure 2. Materials Flow Sheet of WTE Facility; (SEMASS, Rochester, MA)

8.2 Combustion chamber

The PRF is conveyed to bins and from there is ejected through inclined chutes into the three combustion chambers. The feed rate of PRF into the boilers is adjusted by means of automated temperature controls. The PRF contains a lot of small, light particles that with the help of deflectors at the bottom of the chutes and high-velocity air jets are dispersed in the hot gases and are subjected to flash combustion. The bottom of the combustion chamber consists of a moving grate that collects inert materials and heavy combustibles after they are blown into the boiler. These materials settle on the end of the grate away from the feed end and gradually move towards the feed end. The grate speed is variable but generally a residence time of about one-hour is provided. An upward airflow through the grate provides for completing combustion, during the first two thirds of the travel, and for partial cooling of the ash towards the end of the travel. This counter-current heat exchange mode allows good heat recovery and eliminates the need for quenching the bottom ash with water. The temperatures reached in the middle of moving bed are high and the discharged "bottom" ash, collected by the authors and examined in the laboratory, is semi-fused, unlike the powdery ash of mass-burn plants. During visits of the SEMASS plant by the authors, it was observed that the temperatures within the combustion chamber were much higher than for mass-burn plants. It was not possible to look into the combustion chamber with the naked eye, much as is the case in copper smelting and other high temperature reactors.

8.3 Other operating aspects

At the end of the grate, the ash "clinker" falls onto a conveyor belt that transports it to the ash processing section of the plant. Ferrous metals that were not recovered before combustion and also non-ferrous metals are recovered from this ash by means of magnetic and eddy current separators, respectively. EAC has used the resulting granular aggregate as a substitute for crushed stone in concrete and asphalt applications and is presently using it as a government-mandated daily landfill cover.

The fly ash collected in the fiber bag filters contains most of the heavy metals that were present in the waste and is landfilled. EAC uses a patented stabilization system to bind heavy metals so that they do not leach out during various tests performed on the ash.

The SEMASS boilers are of the water-wall type without refractory linings. The superheated steam is used for the generation of electricity. The three units of the SEMASS plant process about 910000 metric tons per year and produce up to 720 kWh of electricity per ton of MSW, of which about 100 kWh/ton are used to run the plant and the remainder are sold to the local utility.

The gas handling plant of the SEMASS Combustion Unit 3(built in 1994) is more advanced than the earlier two units. 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. After the combustion gases leave the boiler they pass through water and air heat recuperators. Then they enter a "dry scrubber" chamber where a lime slurry is injected to neutralize acid gases and trap any chlorides and dioxins/furans that may have either persisted the high temperature atmosphere in the combustion chamber, or re-formed during the cooling stage of the gas. Finally, fiber fabric filter captures fine particles before the gases are discharged through the stack.

On the basis of reported operating data (Figure 2), the EAC system at the SEMASS facility, converts approximately 76.7% of the incoming waste into energy, recovers 4.5% 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. The combustion and power generations are continuous except for planned maintenance shutdowns. The fuel preparation stage (shredding and magnetic separation) operates only two shifts and the ash processing one shift each day.

8.4 Gas Emissions

The most contentious issue in discussions of energy recovery from solid wastes is that of emissions to the atmosphere. Emissions of mercury, hydrochloric acid, and dioxins have been the most worrisome problems in the past. However, in modern WTEs such as the SEMASS No. 3 plant, they have been reduced to very low levels by means of reduction of the precursors in the feed, better combustion practices, and much improved gas control systems that include advanced dry-scrubbing and filter bag technologies. In particular, the problem of mercury emissions in the U.S. has subsided as this metal has been replaced by other metals in household batteries and by digital technology in thermometers, and by separate collection of fluorescent lights.

Table 7 compares air emission levels for the SEMASS No. 3 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 in modern WTE facilities are substantially lower than those expected by the EPA.

All of the air emissions associated with in incinerators of the past 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 earlier, both sulfur dioxide and carbon monoxide emissions were lower than in coal-fired tests. Hydrochloric acid and particulate increased, but only slightly, and dioxins and furans were well below federal and state regulated levels (Ohlsson, 1994).

Table 7: Emissions from WTE Facilities Compared to EPA Standards

Emission	EPA Standard[1]	SEMASS[2]	Herschkowitz, 1987 European standards
Particulate (g/dscm)	0.0228	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: grain/dry standard cubic foot; 1 gr/dscf = 2.28 g/dscm

* ppmdv: parts per million dry volume

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

The standards and data are reported for 7% O_2, dry basis, and standard conditions.

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

[2] EAC, average of 1994-1998. Boiler No.3 [3] Studley, 1997.

As noted earlier, in the SEMASS plant, the high temperature combustion results in destruction of any dioxins/furans in the PRF; also dry scrubbing and then collecting fine particles by means of fabric filters combats the formation of these compounds after the boiler.

It is also interest to note that the undesirable chloride ions enter the waste stream principally in the form of chlorinated organic compounds like PVC. Yet this material constitutes only 0.1% of the total waste stream and could easily be replaced by other materials in all current applications, as was done for the halide compounds that threatened the ozone layer, if a higher priority is assigned by EPA to recovering energy from MSW.

8.5 Use or Disposal of Ash

Companies and 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). The post-treatment of ash produced by the low temperature combustion chambers such as fluidized beds usually involves vitrification at high temperatures in order to immobilize the metals. The main aim of ash treatment is to prevent the toxic constituents of the ash, especially dioxins, furans and heavy metals, from escaping into the environment after disposal. Solidification by means of vitrification or the application of various chemicals is further means of decreasing the chances of leaching metals. Phosphate has been shown to stabilize heavy metals in dusts that result from the vitrification of incinerator ash (Eighmy et. al., 1998). Treatment of ash is a much more mature technology than re-use.

The bottom ash produced in the SEMASS plant resembles clinker ash and, after mechanical separation of ferrous and non-ferrous metals, has a relatively high specific gravity (typically 2.25) and as per SEMASS reports contains less than 2% carbon and less than 1% fines. The toxicity characteristics leaching test (TCLP, Wiles, 1997) based on the EPA standard has shown that the metals in bottom ash are not leachable.

Comprehensive assessments of the re-use of ash from WTE plants are presented in the papers by Wiles (Wiles, 1995) and Chang (1998).

9. Life cycle assessment of energy recovery

A critical analysis and comparison of the life-cycle environmental impacts of recycling, incineration and landfilling by Dennison (1996), based on the major North American studies of the subject showed that recycling of used materials is superior to either incineration or landfilling, as one might reasonably expect. However, it also showed that combustion is preferable to landfilling and offered the advantage of 28 MJ less of energy used per ton of material processed than landfilling. Of course, interstate transport of MSW, as planned by NYC, will increase considerably the energy usage per ton of MSW.

Of equal importance was the finding that, for the 10 major air pollutants categories considered, combustion resulted in lower emissions than landfilling, with the exception of higher generation of carbon dioxide in the combustion process. However, when the generation of carbon dioxide is associated with the production of useful energy, e.g. 620 kWh/ton in the SEMASS process, one should subtract the "avoided" amount of carbon dioxide that would be produced anyway in a conventional power plant.

A more recent study by Eschenroeder (1998) indicated that, for modern landfills equipped with methane collection systems (70-year post-closure period), the time-integrated effect of green house gases emitted is 45 times greater than when the MSW is combusted.

10. Conclusions

This paper is part of a continuing joint study between Columbia University's schools of engineering and Public Affairs that entails an examination of both technology and policy constraints. The joint study recognizes that waste minimization by means of better design of products and packaging is highly desirable. Also the best means way of managing municipal solid wastes is by recovering recyclable materials. However, even when the best available technology is applied for collecting, sorting and processing, there remains a large fraction of wastes that cannot be recycled. It is then advisable, both from the economic and environmental viewpoints, to recover energy from the combustible fraction of MSW instead of consigning it to landfills.

It was shown that the formula $C_6H_{10}O_4$ is fairly representative of the organic mix in a typical MSW and that the calculated thermochemical heat of combustion of this compound is in good agreement with experimentally determined values for mixed organic materials. On this basis, a formula was derived that projects the heating value of MSW as a function of moisture and glass/metal content. The calculated and experimental heating values of the "dry combustible" fraction of MSW is in the range of lignitic and sub-bituminous coals that are still used in many power plants. Thus, using the "dry combustible" MSW as a fuel can reduce, by as much as ton per ton, the need for mining fossil fuels. For example, the usable energy in the New York City MSW is equivalent to nearly three million liters of fuel oil per day.

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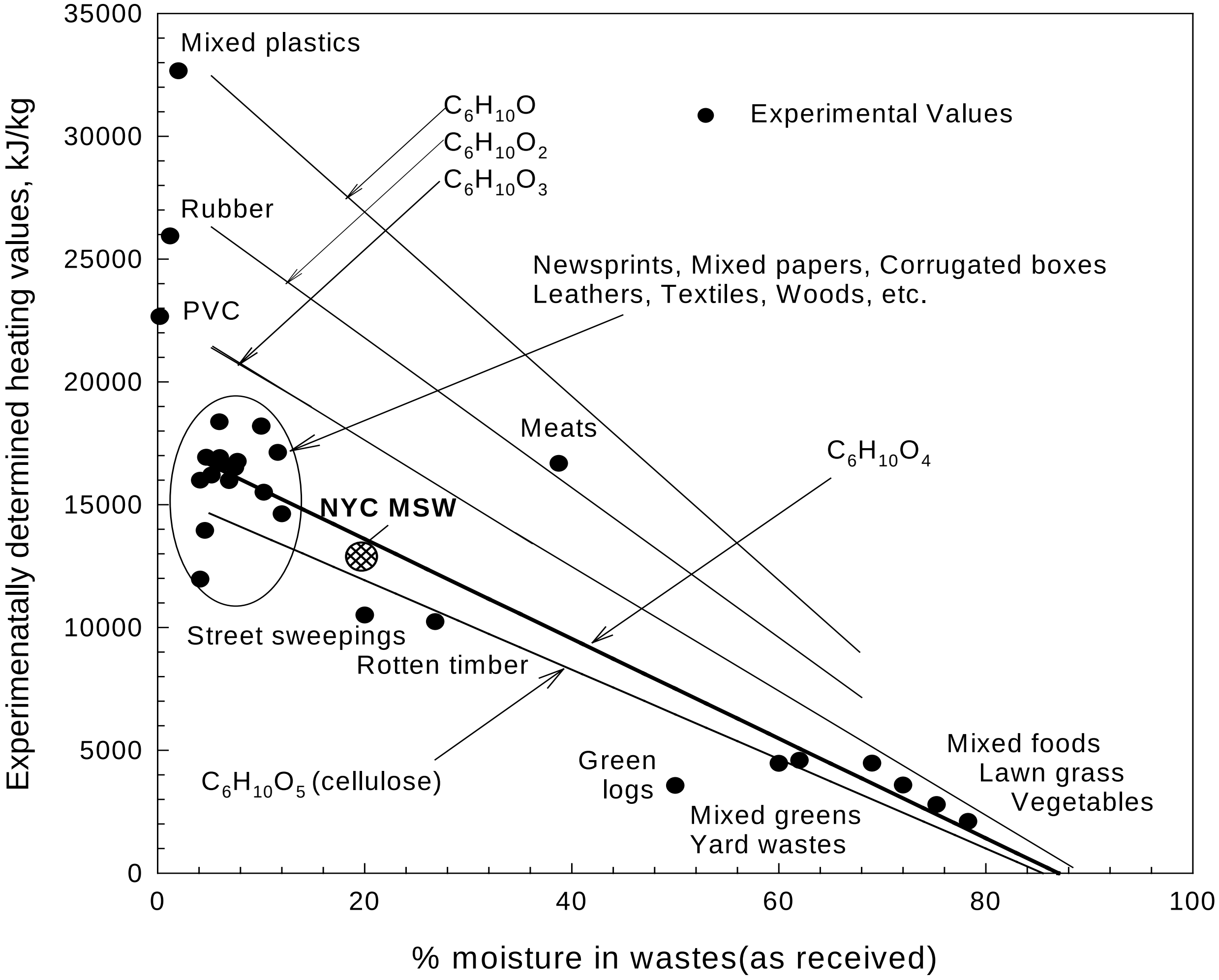

Figure1. Comparison of experimental heating values of various waste materials (Hollander, Tchobanoglous,1980). Lines show thermochemical values for respective $C_6H_{10}O_x$ materials.

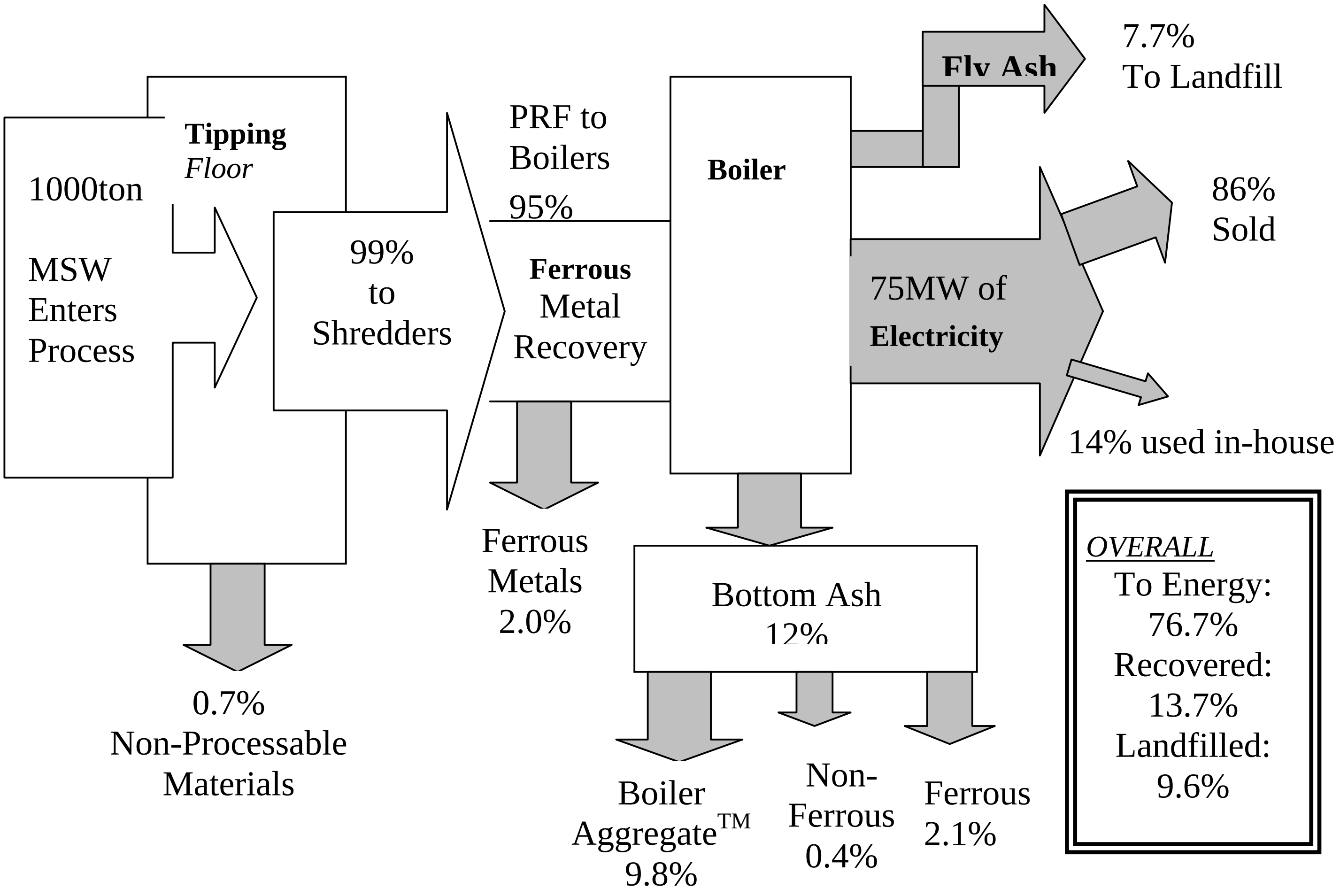

Figure 2. Flow sheet of WTE Facility; SEMASS Rochester, MA