Proceedings of the 17th Annual North American Waste-to-Energy Conference
NAWTEC17
May 18-20, 2009, Chantilly, Virginia, USA

NAWTEC17-2366

POTENTIAL FOR REDUCING THE CAPITAL COSTS OF WTE FACILITIES

Nickolas J. Themelis and Saman Reshadi

Earth Engineering Center, Columbia University, New York, NY 10027

ABSTRACT

The dominant waste-to-energy technology is combustion of "as-received" municipal solid wastes (MSW) on a moving grate. By far, the largest cost item in the operation of such plants is the repayment of the initial capital investment of $600 to $750 per annual metric ton of capacity which results in capital charges of $60-75 per ton of MSW processed. On the average, such plants generate about 650 kWh of electricity per metric ton of MSW combusted. Therefore, on the basis of 8,000 hours of operation per year (90% availability), the capital investment in WTE facilities ranges from $7,500 to $9,000 per kW of electric capacity. This number is three times higher than the present cost of installing coal-fired capacity (about $2,500 per kW). Of course, it is understood that WTE plants serve two purposes, environmental disposal of solid wastes and generation of electricity; in fact, most WTE plants would not exist if the fuel (i.e. the MSW) had to be paid for, as in the case of coal, instead of being a source of revenue, in the form of gate fees. However, the question remains as to why WTE plants are much more costly to build, per kWh of electricity generated, than coal-fired plants, even when the coal supply is lignite of calorific value close to that of MSW (about 10 MJ/kg). This study intends to examine the possible contributing causes, one by one, in the hope that the results may lead to the design of less costly WTE plants. Some of the factors to be examined are: Feed-stock handling; heat generation rate per unit volume of combustion chamber; heat transfer rate per unit area of boiler surfaces; % excess air and, therefore, volume of gas to be treated in Air Pollution per kW of electricity; differences in gas composition and high temperature corrosion in boiler that limit steam temperature and pressure and thus thermal efficiency; cost of APC (air pollution control) system because of the need to remove volatile metals and dioxin/furans from the process gas; and the handling of a relatively large amount of ash. In seeking the answers to the above questions, the study also compares the operational performance characteristics and engineering design of various existing WTE plants.

This study is at its very beginning and it is presented at NAWTEC 17 in the hope of generating useful discussion that may lead to significant improvements in the design of future WTE facilities. The WTEs built in the U.S. until 1995 were designed for efficient and environmentally benign disposal of MSW, with energy recovery being a secondary consideration. There have been three principal changes since then: (a) the capital cost of WTEs, per daily ton of capacity has doubled and in some cases nearly tripled, (b) energy recovery per unit of carbon dioxide emitted has become an important consideration, and (c) the price of

renewable electricity has increased appreciably. All these three factors point to the need for future WTEs to become more compact, less costly to build, and more energy-efficient.. It is believed that this can be done by combining developments that have already been tested and proven individually, such as shredding of the MSW, higher combustion rate per unit surface area of the grate, oxygen enrichment, flue gas recirculation and improved mixing in the combustion chamber, superior alloys used for superheaters, and steam reheating between the high-pressure and low-pressure sections of the steam turbine. For example, oxygen enrichment is practiced at the Arnoldstein, Austria, WTE where parts of the primary air stream are enriched between 23% and 31% oxygen; steam reheating has been proven at the Waste Fired Power Plant of AEB Amsterdam where electricity production for the grid has been increased to over 800 kWh per ton MSW.

INTRODUCTION

The tonnage of global post-recycling MSW in urban centers is estimated at about 1.2 billion metric tons. Of this amount, 0.2 billion are combusted in waste to energy (WTE) facilities, 0.2 billion are landfilled in modern regulation landfills, and 0.8 billion are disposed in traditional dumps without methane recovery, thus contributing over 3% of global CO2-emissions. Therefore, there is a lot of room for adding to the world's thermal treating capacity. This can be done either by means of the dominant technology of grate combustion (mass burn) with energy recovery or by means of more elaborate thermal treatment technologies, such as Refuse-Derived Fuel (RDF), Direct Smelting and Thermoselect Gasification process, and others that are still under development. In the case of "gasification" processes, that is partial combustion and production of "syngas" by the Thermoselect (oxygen enrichment) or the Plasco (thermal plasma) processes, the syngas product can be combusted in a gas turbine or engine operating at a higher thermal efficiency (e.g. 35-40%) than the steam turbine used in conventional waste-to-energy (WTE) facilities where the thermal efficiency may be as low as 20%. This advantage may compensate for the use of electricity to power the oxygen plant or the plasma torch. Another advantage of such energy-assisted processes is that they generate high enough temperatures to vitrify the ash product. Figure 1 illustrates the methods for energy production from municipal solid waste leading to electricity production. The mass-burn and RDF combustion technologies are the focus of this study.

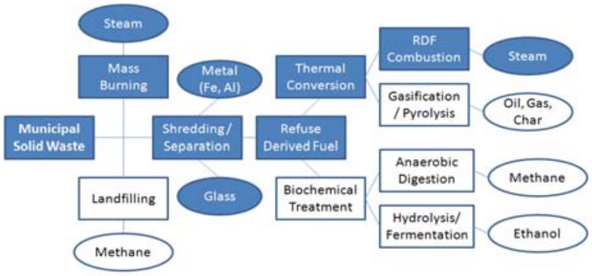

Fig. 1 Energy generation from MSW

Figure 2 shows how WTE technologies may be placed on a "technology" vs. "market" maturity plot (Navigant Consulting, 2004). The technology maturity axis indicates the potential for improving performance and reducing capital costs. Mass Burn technology has captured a larger fraction of the market than RDF; about 77% of the U.S. WTEs and nearly 90% of the global WTE industry are based on grate combustion of as received MSW. Also, the mass burn technology is judged to be at a lower technological level than RDF and thus there is more room for technological advancement.

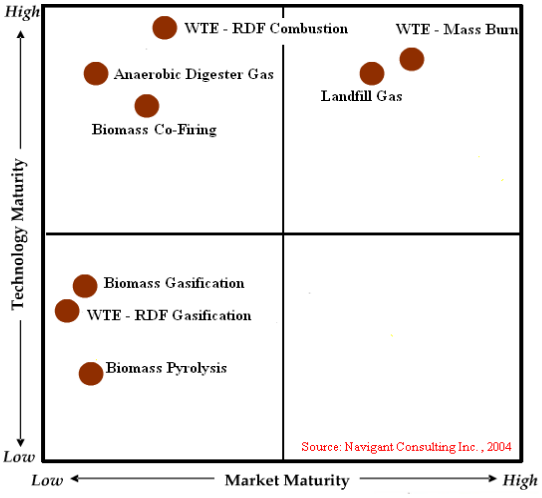

Fig. 2 Technology vs. market maturity of WTE technologies

Figure 3 shows the schematic diagrams of the principal WTE technologies used in the U.S., combustion of as-received MSW (mass-burn) and of shredded solid wastes (RDF-type), as practiced at the SEMASS boiler of Covanta Energy (Rochester, MA).

The feeding hopper of the mass-burn furnace is kept full of solid wastes. At the bottom of the hopper, a hydraulically operated ram feeder forces the solids onto the feed end of the grate. From there on, the bed of solids moves slowly towards the discharge end, due to gravity and the periodic motion of the grate bars. In many mass-burn furnaces, e.g. at the AEB Amsterdam WTE, the grate is a horizontal belt conveyer.

In the SEMASS furnace, the shredded feed falls freely through the hopper and enters the combustion chamber assisted by a high pressure air stream (Figure 3) that sweeps the feed into the space above the horizontal chain belt. The light particles in the feed are burned in suspension in the primary air; the heavier particles settle at the other end of the chamber and form a bed on the horizontal conveyer that moves the bed of solids slowly toward the feed end, instead of away from it as in the case of the mass-burn unit.

In both types of furnaces, the residence time of the moving bed on the grate or horizontal chain is about one hour.

The basic feedstock of waste-to-energy processes is MSW of typical calorific value of 10 MJ/kg, i.e., 2.8 MWh of thermal energy per ton. Whatever is done to change the MSW particle size (e.g., shredding of the MSW) or to increase its calorific value (e.g., drying and sorting of inorganic constituents), or to add auxiliary energy in the combustion furnace (e.g., oxygen enrichment) requires an investment of electrical energy that must be justified by increased energy production per ton of MSW, or by higher productivity per unit reactor volume and a more compact process that will decrease the capital investment in new WTE facilities.

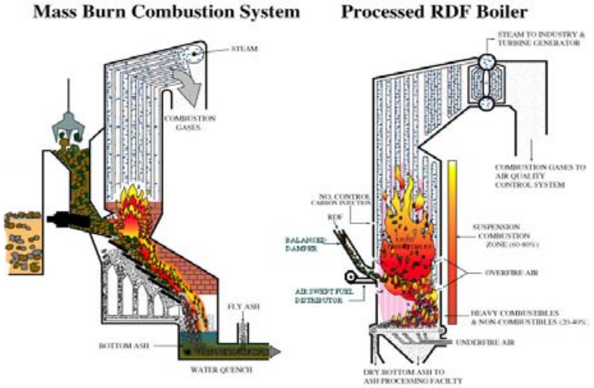

Fig. 3 Schematic diagrams of the mass-burn and SEMASS-type RDF combustion systems

Comparison of Mass-Burn to RDF WTE Facilities

The Mass-Burn (Stoker) Technology

The mass burn or stoker or WTE technology predominates globally, because it is the simplest method of all that have been devised up to this point. The MSW is combusted as received, without any fuel preparation, except of pulling out of very large and hazardous objects. The operators in the crane control room do not come into contact with MSW or MSW odors and can load up to 150 tons per hour into the hoppers that feed the furnaces. The stoker process is very effective in combusting the diverse materials encountered in MSW, as indicated by the high degree of combustion attained. This technology has been in use for nearly one hundred years and by now has reached a high state of development, in particular with respect to the capture and sequestration of undesirable emissions, such as chlorine, sulfur, carbon monoxide, particular matter, volatile metals and dioxins/furans.

The mass burn grate is 7-9 meters long and the average residence time of solids on the grate is about one hour. The grate width depends on the tonnage processed per day. Primary air flows upward through the grate and secondary air is injected through a series of tuyeres above the grate. The most efficient waste-to-energy (WTE) facilities are co-generators of electricity and district heating.

The RDF Combustion Technology

The Refuse Derived Fuel (RDF) WTE is the simplest possible technical advance over the dominant mass-burn process. Most RDF facilities in the U.S. were built with the idea that pre-shredding of the MSW would allow the subsequent separation and recycling of materials, such as metals and glass which have no calorific value, and also increase the capacity of the combustion unit. The RDF process consists of single-shredding of the MSW, sorting out some of the inorganic materials, and then combusting the resulting "RDF".

Various types of the RDF process are used in 12 U.S. facilities ranging in capacity from 360 to 2700 metric tons per day. In overall, the U.S. RDF plants treat about six million metric tons of MSW, i.e., 23% of the U.S total WTE capacity. The combustion technologies range from spreader stoker firing, semi-suspension firing like SEMASS, and circulating fluidized bed. Figure 4 shows the general flow-sheet of materials in the RDF process.

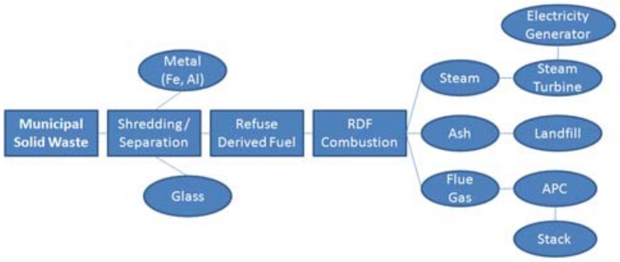

Fig. 4 Flow diagram of the RDF process

The simple equation below, computed for 750^{o}C discharge temperature of the ash exiting the combustion chamber, shows that, in contrast to moisture, the glass and metals contained in MSW take up little heat, because of their low specific heat:

$$\textbf{Heating value of mixed MSW} = 18.4 X_{comb} - 2.66 X_{H2O} - 0.63 X_{glass} - 0.54 X_{metal} \ \textbf{(MJ/kg)}$$

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

$$X_{comb} + X_{H2O} + X_{metal} + X_{glass} + \ldots = 1$$

Also, separation of the only valuable commodity in mixed MSW, metals, is not complete before combustion because of their commingling with other materials. An example of this is the SEMASS facility that pre-shreds nearly one million tons of MSW annually and recovers about 40,000 tons of metals; only one half of the contained metal is picked up by the electromagnetic separators that are located between the shredders and to furnaces; the other half is recovered from the bottom ash produced in the furnace.

One would expect that pre-shredding accelerates the rate of combustion of MSW particles. Figure 5 by Smoot and Smith shows that a coal particle of 1-cm thickness

(10,000 microns) requires about 0.28 hour for complete combustion in air, while a thinner particle, e.g. a sheet of paper can be combusted completely in a few seconds.

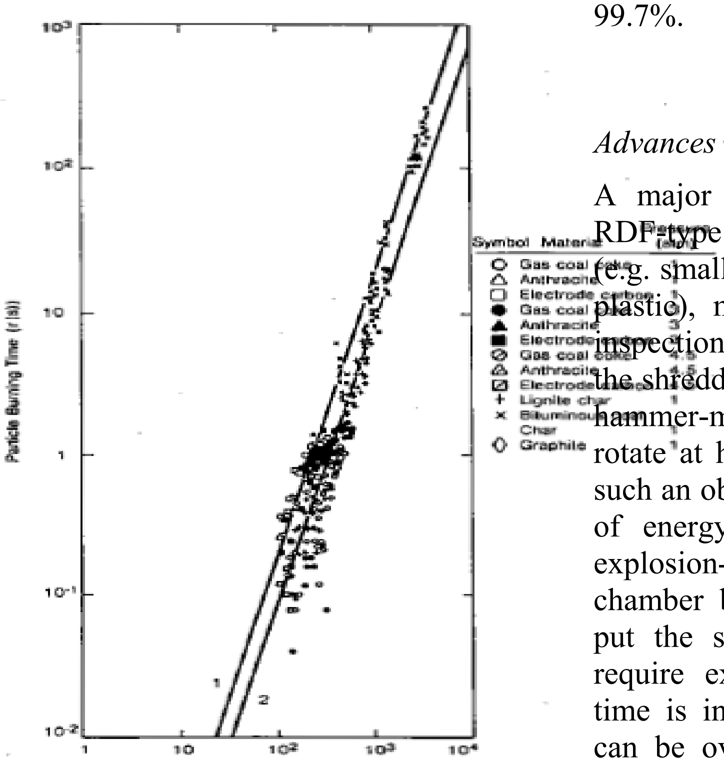

Fig. 5 Time required, in seconds, for complete combustion in air at 1000°C of various types of coal as a function of particle size, in microns (Schmoot et al)

Since the thickness of most waste materials, after the initial breakup of bags, books, etc. is below this size, it would be expected that within the allotted one-hour residence time in WTE combustion chambers there would be complete combustion of the organic materials in MSW. This is verified by the low concentration of carbon in the bottom-ash reported by ten WTE facilities that competed in the global WTERT competition in 2006 (Themelis 2007). Several of these plants reported about 1% carbon remaining in the bottom ash; the average of all ten plants was about 2% C. Combining these data with the known carbon concentration in a typical MSW (30%) and the typical ratio of dry bottom ash tonnage to MSW processed (<20%) leads to the conclusion that the fraction of carbon combusted in these ten WTE facilities ranged from 98.4-99.7%.

Advances in shredding technology

A major problem that is encountered in RDF-type plants is that explosive objects (e.g. small gas cylinders covered in paper or plastic), may pass undetected through the inspection of the incoming MSW. Nearly all the shredders used in U.S. RDF facilities are hammer-mills, in which giant hammers rotate at high speeds; when they encounter such an object it may explode releasing a lot of energy. Shredders are equipped with explosion-containment devices above the chamber but sometimes the explosion can put the shredder out of commission and require extensive repair. WTERT at this time is investigating whether this problem can be overcome in future SEMASS-type facilities by using the new generation of high torque, low speed (HTLS) shredders that are equipped with mechanisms that detect and divert large and hard objects thus avoid this major operating and maintenance problem. A simple design for integrating a shredder in a WTE facility will open the door for the pre-shredding of MSW, both in mass burn and in RDF-type facilities. This is the subject of another study undertaken by WTERT (www.wtert.org) this year and its progress is reported in another presentation at NAWTEC 17 (Fitzgerald et al).

Since not all of the ferrous content is recovered prior to combustion, SEMASS passes the bottom ash through magnetic separators, to recover ferrous metals, and then eddy-current separators, to recover non-ferrous metals. Energy Answers International, the company that built SEMASS, in future installations of this technology may eliminate the pre-combustion magnetic separation and capture all the ferrous metal after combustion, from the bottom ash. The SEMASS technology will then be the simplest possible manifestation of RDF technology, a simple shredding of the MSW before it is fed to the furnace.

The electricity used in the hammer-mill shredder of SEMASS is estimated to be about 25 kWh of electricity per ton of MSW. Therefore, the energy "investment" in shredding is relatively small for a unit that produces about 650 kWh of electricity per metric ton of MSW.

As noted earlier, from a reaction engineering point of view, shredding of the highly heterogeneous MSW to a more uniform particle size and composition should be beneficial: Heat and mass transfer rates increase with RDF's higher calorific value and smaller particle size; also, a certain degree of homogenization should facilitate the passage of primary air through the bed. Since the drying, volatilization, and combustion rates would be higher, the productivity of the RDF operation should be higher than for a mass-burn WTE of the same physical size.

On the downside, the fly ash carry-over of SEMASS is 45% of the total ash while that of the mass burn plants is less than 15%. However, this handicap can be overcome by providing a cyclone-type pass next to the combustion chamber, such as is standard addition to Circulating Fluid Boilers (CFBs) as well as some WTE facilities.

In general, WTE operators consider SEMASS and other RDF-type processes to be more difficult to operate than the mass burn technology. This is also indicated by the fact that twice as many people are engaged in an RDF plant than in a typical mass burn WTE of the same capacity. Therefore, in order to introduce shredding in the mass burn process, one would have to devise a relatively simple way of interposing shredders between the tipping floor and the furnace.

Comparison of an RDF-type plant with two mass-burn WTE facilities

In order to explore whether shredding can increase the rate of combustion of MSW per unit surface area of the grate, the authors compared the physical dimensions, rates of MSW feed, and air throughputs for the SEMASS RDF-type unit and two mass burn units. The results are shown in Table 1. It can be seen that the grate productivity of SEMASS is 96% greater than Brescia and 83% greater than that of the Union-County WTE. This is most likely due to the higher rate of combustion due to the pre-shredding of the feed and its partial combustion in suspension.

Table 1 also shows that the Brescia WTE uses a lower % excess air, which results in a substantially lower volume of combustion gas per ton of MSW processed. This is most likely due to the fact that Brescia re-circulates about 30% of the process gas back to the combustion chamber. One would expect that, because of its pre-shredding of the MSW, the SEMASS facility would have a higher oxygen utilization, and thus lower requirement of % excess air, than the Union County mass burn WTE (Covanta Energy). However, this is not the case: Both WTEs generate the same volume of process gas per ton of MSW combusted and thus use close to 100% excess air.

The argument may be made that this much excess air is needed in an existing plant order to cool the combustion gases to such a temperature that does not result in excessive corrosion of the superheater tubes. However, in future WTE plants, the temperature of the combustion gases can be decreased either by gas recirculation, or the Brescia WTE, or by increased heat transfer at the waterwall surface, as it is done in pulverized coal-fired power plants that operate at two to three times the heat transfer flux (0.10-0.20 MW/m^2) of WTE combustion chambers (0.05-0.06 MW/m^2).

Table 1. Comparison of two types of WTE Combustion plants (metric units)

	Mass-Burn Union County Stoker WTE, USA (1994)	Mass-Burn Brescia Stoker WTE, Italy (1998)	SEMASS semi-suspension combustion (1988)
Capacity, tons/day (per unit)	480	792	910
Heating value of fuel, MJ/kg	11	11.3	11.63
Process gas volume, Nm^3/hour	125300	135000	208500
Process gas volume/ton, dry Nm3	5653	4100	5500
Length of grate, m (L_g)	7.5	8	6
Width of grate & furnace, m (W)	7.8	12.8	10
Grate area, m^2 (L_g x W)	58.5	102.4	60
Grate productivity, tons/day/m^2	8.2	7.7	15.2
Heat generation rate, MW$_{th}$	55.5	94.2	111.4
Heat flux released on grate, MW/m^2	0.95	0.92	1.86
Length of furnace, m (L_f)	6.5	5	6
Furnace cross section, m^2 (L_f x W)	51	64	60
Velocity of gas in combustion chamber, m/s	2.7	2.3	3.8
Reynolds number in furnace (@ 900^{O}C)	100000	66000	130000
Furnace height, m (H)	19	22	30
Average gas residence time, s	7.0	9.5	7.9
Waterwall surface area, m^2	543	783	960
Heat flux at waterwall (50% load), MW/m^2	0.05	0.06	0.06

REFERENCES

Smoot L.D., and P.J. Smith, “Coal Combustion and Gasification”, Plenum Press, New York, 1985).

Themelis, N.J., “The Global WTE Industry”, Waste Management World, 2007 Review Issue, July-August 2007.