

Technical and Economic Analysis of Pre-Shredding Municipal Solid Wastes Prior to Disposal

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Earth Engineering Center



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EXECUTIVE SUMMARY

Sustainable waste management of post-recycling municipal solid wastes (MSW) is an important component in the 'green' movement toward a cleaner, environmentally-conscious society. Waste-to-Energy (WTE) power plants have potential to significantly reduce the amount of landfilled refuse while producing a carbon neutral form of heat and power, However, ; the average capital investment for a new WTE facility ranges from \$7,500 to \$9,000 per installed kW of capacity, nearly three times that of coal fire power plants. There exists a need to considerably reduce the cost of such facilities in order to bring them into the mainstream of solid waste management. This report examines how size-reduction and homogenization of the raw MSW stream can potentially improve WTE operating characteristics while decreasing capital investments.

Chemical rate and heat transfer theories indicate that the productivity of a moving grate WTE boiler should be enhanced by means of pre-shredding the MSW, thus reducing the average particle size, homogenizing the feed, and increasing its bulk density by an estimated 30%. Smaller particle sizes enhance reaction kinetics and flame propagation speed, due to the higher surface to volume ratio, and thus lower the amount of combustion air needed to meet the required combustion rates. Minimizing the primary combustion air supply rate lowers the total amount of flue gases and can result in decreased costs of the Air Pollution Control system. Smaller and more homogeneous particles increase bed mixing coefficients and reduce retention time required for complete combustion. The benefits realized through the pre-processing of MSW by means of modern shredding equipment were evaluated quantitatively both for the traditional High-Speed, Low-torque (HSLT) hammermills and the new generation of LSHT shear shredders. The shearing mechanism utilized in these low rpm devices produce a more uniform particle distribution at a lower energy cost per ton MSW processed than hammermills of the same capacity.

The integration of size reduction systems into the typical flow sheet of WTE facilities has been hindered by the high frequency of fires, explosions, and ejected material from hammermill grinders. The low shaft speed of the shear shredders has reduced the occurrence of fires and explosions while nearly eliminating ejected materials, allowing for safer and more reliable adaptation into new and existing WTE facilities.

The most important criterion in the adoption of pre-shredding MSW for grate combustion will require that economic and energy benefits of pre-shredding be clearly greater than the conventional operation of combusting as received MSW. At an average WTE electrical production of 650 kWh per metric ton of MSW processed, the required 3-11 kWh/ton for LSHT devices is less than 2% and should be more than accounted for by improved combustion efficiency in the WTE plant. The addition of a shredding system in a medium sized WTE plant will increase the O&M from current costs by roughly 10%, not including the benefit of lower maintenance due to improved distribution of thermal stresses on the grate and in the boiler. Finally, for the capital cost of a new WTE facility in the range of \$8000 per kW of capacity, the initial investment in shredding and fuel handling equipment will increase capital costs by about 2% from current values. It should be determined on a case-by-case basis whether the addition of pre-shredding equipment may increase capacity and decrease maintenance sufficiently to cover capital and operational costs as well as lower overall cost of operating the facility.

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Introduction

MSW Production

Municipal solid waste (MSW) is generated in staggeringly large quantities in the United States of America. According to a recent survey 'The State of Garbage in America' conducted in collaboration between BioCycle and the Earth Engineering Center (EEC) at Columbia University, Americans produced an estimated 413 million tons of MSW in the year of 2008. If one year of our waste was piled one story high (3 m) it would occupy an area greater than 60,000 standard football fields! Such large volumes of waste indicate that however we choose to handle our waste it will have a significant impact on our society both economically and, more importantly, environmentally. Making matters more severe is the fact that the annual per capita trash production has increased from 1.3 tons/person in 2006 to 1.38 tons/person in 2008, a 6% increase in only two years.

As global population continues to grow and developing countries' economies expand towards that of developed nations, the world will continue to see large increases in global MSW production and subsequently the need to handle and store/dispose/reuse this material responsibly. This seemingly ever increasing mass of garbage must be handled in an environmentally intelligent manner such that amount of energy and material recovered is maximized while costs and negative externalities are minimized. As society adjusts to the ideas of less packaging and lower consumerism and consumption it is important that we limit the amount of material that ends up as 'waste' in landfills or dumps. The waste that does end up in a landfill must be accounted for and properly treated to limit its negative interaction with the natural environment.

The goal of moving towards a sustainable society means that in all aspects of our daily lives we must strive to diverge from our current linear outlook on major natural resources. Linear, in this context, is referring to our use of resources; materials are extracted from the earth, manipulated and intermingled into a useful product and then disposed of into what we have been treating as a bottomless storage pit. The concept of mimicking nature's ecological cycle of taking the waste of one process and utilizing it as

feedstock for another is growing in popularity in present society and holds great potential for easing our dependence on non-renewable resources. Industrial ecology can be adopted in many aspects of human civilization, especially integrated waste management to drastically lower our reliance on raw natural material and energy resources.

MSW should not be considered 'waste' in the literal context as it contains a great deal of recoverable materials and imbedded energy. A more appropriate way to classify it would be as a heterogeneous stream of commonly used materials that no longer has significant value to the original user. The potential to recover over 50% of the materials found in MSW is demonstrated in many European countries that have begun to phase out landfills as an acceptable method for waste disposal. Figure 2 demonstrates that it is possible to recover nearly half of the MSW stream and utilize the balance as fuel in WTE power plants. If this strategy were to be adopted in the U.S. nearly 200 million tons of MSW with a heating value in the range of 6000 kJ/kg could be converted via incineration into roughly 90 billion kWh annually.

MSW Disposal

The most common form of waste disposal in the U.S. is to pile it up in a location that has been deemed invaluable enough to be sacrificed to a dump. As can be seen below in Figure 1, roughly two thirds of all waste produced in the U.S. is currently disposed of in landfills. In contrast to North Americas waste management statistics, all but a few nations in the European Union (EU) have higher material and energy recover and lower landfilling rates than those of the U.S. The most basic explanation for the larger landfilling rates in the U.S. is one of economics; the amount of available land at low costs is sufficiently large enough that alternative waste management techniques have difficulties competing. Unlike North America the majority of European countries do not have the option to continue to dispose of waste in landfills and are beginning to look towards other more integrated and sustainable waste management plans.

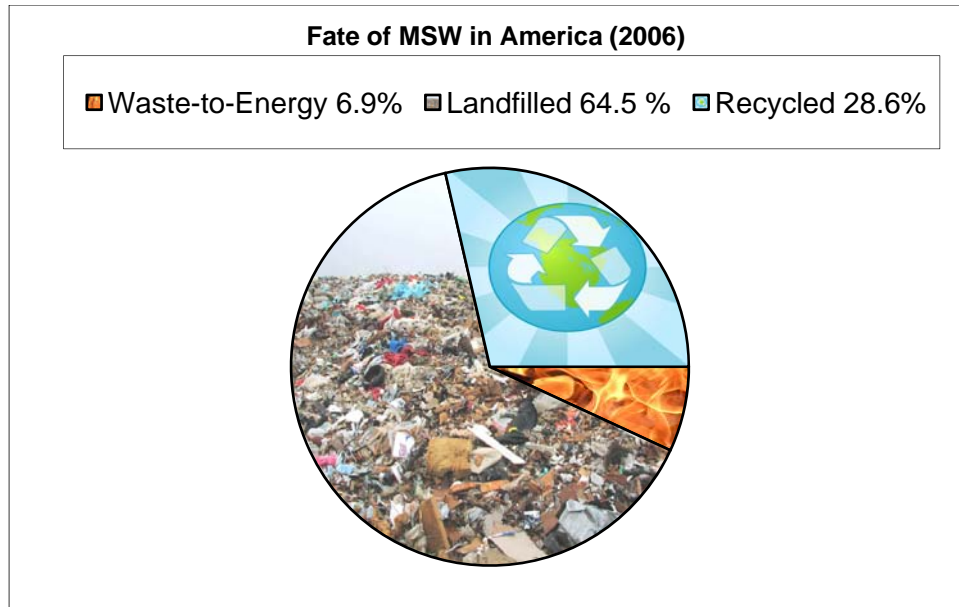


Figure 1: Fate of MSW in America

In 1999 the EU initiated a landfill directive with the objective to significantly reduce negative environmental impacts, particularly pollution of surface water, soil and air, including green house gasses (GHG) from the landfilling of waste. The directive aims to reduce the amount of biodegradable waste landfilled to 50% of 1996 values by 2013. Waste-to-Energy has been, and continues to be, a major player in this directive to avert waste from landfills. The far right side of Figure 2 is a good representation of the possible distribution of waste management techniques when landfills are considered the last resort, more than half of the E.U. landfills under 50% of their total waste, with Denmark and the Netherlands leading the way each landfilling less than 10%. There are currently over 400 WTE plants in Europe with an estimated 100 more plants to be installed in the next decade in order to meet the landfill directive.

European countries are undoubtedly leading the way in solid waste management with their strong support of energy recovery via incineration and high recycling rates. This increase in popularity and acceptance of WTE will hopefully spur a similar movement in North America. In the past decade there has been no new incineration plants constructed in the United States, if this technology is to become widely accepted as a renewable energy source and sustainable waste management practice it will be

necessary for American engineers to ‘piggy back’ on the developments being made in Europe as well as focus more energy and funding for development in our own country.

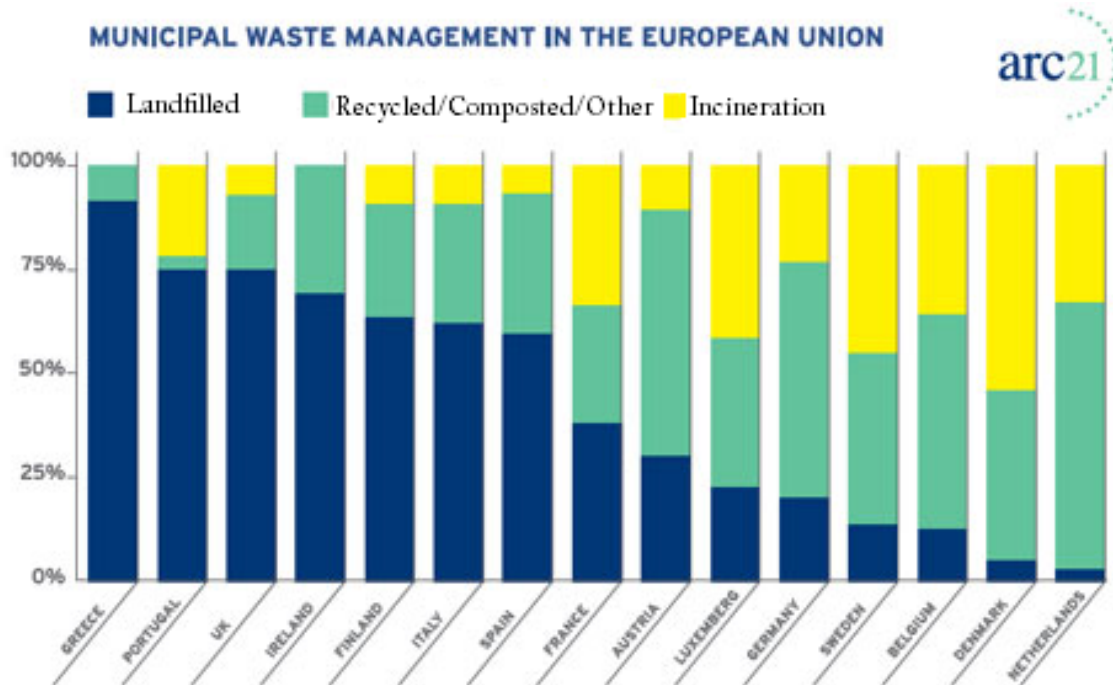


Figure 2: European Union Waste Management [ARC21]

The fraction of MSW that is landfilled in the U.S. has decreased over the past two decades from 84% in 1989 to 65% in 2006. This decrease in landfill rates is primarily a result of increased recycling or diversion rates, which have increased from 8% to 28% in the same time period. The WTE rates show an interesting trend with a relatively sharp increase in 1990 followed by a slow but steady decline. Waste Incineration in the mid 80’s and early 90’s acquired a negative reputation as being a dirty and pollution intensive method of disposing waste. The majority of existing North American WTE plants became operational between 1980 and 1996 with little activity to date. The reason that these plants have a negative stereotype about them is because they were not built to meet current EPA emissions standards for dioxins, particulate matter, VOC’s, SO_x and NO_x. In order to meet environmental and health standards these systems have been upgraded to include electrostatic precipitators (ESP), baghouse filters, SO_x and NO_x scrubbers that

can now bring them well below the EPA standards, often producing emission gasses that are cleaner than that emitted from a coal fired power plant.

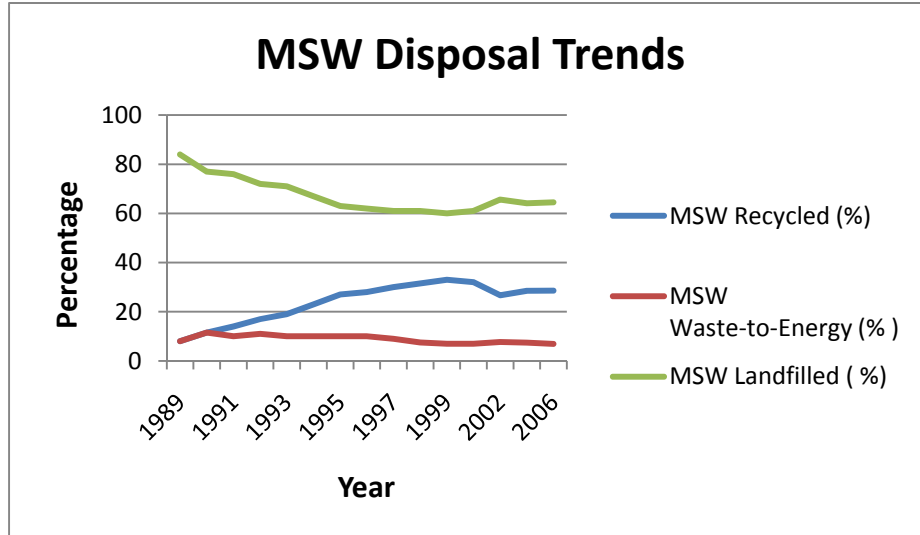


Figure 3: MSW Disposal Trends in the U.S.

The decline in the fraction of MSW processed via incineration is a result of the stagnant national WTE capacity coupled with the significant increase in MSW production. The current limiting factor on creating new WTE projects is most often related to capital and operating costs that cannot compete with landfilling in the absence of some external financial motivation. Facilities that combust waste for energy recovery have proven to be an environmentally acceptable method of handling large amounts of MSW, however the 103 WTE operations do not have enough capacity to make an appreciable dent on the amount of MSW that is annually wasted in landfills. There is a growing need to bring down the capital cost of new WTE projects such that tipping fees can compete with landfills without the need for government incentives or subsidies. Yet as has been demonstrated in Europe, regulations of what can and cannot be sent to a landfill has been a successful method to increase WTE use and wean communities off cheap and environmentally dangerous landfill use.

1. Waste-to-Energy

History of Incineration

The first waste incinerator was developed in Nottingham, England in 1874 and dubbed ‘The Destructor’, the purpose of this creation was to reduce and sanitize waste that had been accumulating in the streets. Little interest was focused in energy or material recovery. These early incinerators were not designed to generate heat or electricity other than that required to run the plant itself. The idea of reducing the volume of waste via combustion dates back beyond that of the 19th century incinerators when waste was burnt in open pits or piles solely for volume reduction or sanitary purposes. It was not long after the first incinerators were developed that it became apparent that heat and electricity could be harvested from the chemical energy present in refuse.

In 1905 American mechanical engineer Joseph G. Branch set out to design a high temperature refuse incinerator that was capable of reducing the waste and producing both steam and electricity for municipalities. At this time Europe had shown great success in implementing incinerators all across the continent and as Mr. Branch put it in 1906 “today incineration here [America] is not as far advanced as it was thirty years ago in England. We are still working with low temperature furnaces, using natural draft and operating the plant with cheap labor” [Valenti] The U.S. municipalities would soon attempt to catch up to the idea of incinerating waste in areas where land disposal was not feasible. This 30 year lag in WTE adoption still exist today and is an indicator to the lack of innovation in waste management in the United States. In the early 1900’s Manhattan had two incinerators, one beneath the Williamsburg Bridge in the lower east side and the other on the Hudson River. The Williamsburg plant was capable of processing 175 tons of refuse per day generating 180 kW electricity, but would be shut down 5 years after coming online due to competing electricity production via fossil fuels.

These plants lost popularity in the United States after the Williamsburg plant shut down until the post WWII era. Incineration saw a large increase in use between 1945 and 1960, in which 269 incinerators were built with essentially no concern for environmental protection. These incinerators had minimal flue gas control, with abatement techniques limited to a screen designed to trap live embers and water to cool the exhaust gasses to

avoid thermal damages. Electrostatic precipitators and bag house filters did not become popular in WTE plants until the 80's when they were required to meet the clean air act set out by the EPA. Flue gas cleaning technologies have made impressive improvements in the past decades in the newer European facilities and are capable of reducing NO_x, SO_x, dioxins and particulate to well below EPA regulated standards. This early use of dirty incineration has had a lasting effect on the general public's opinion towards a clean renewable source of energy and waste management.

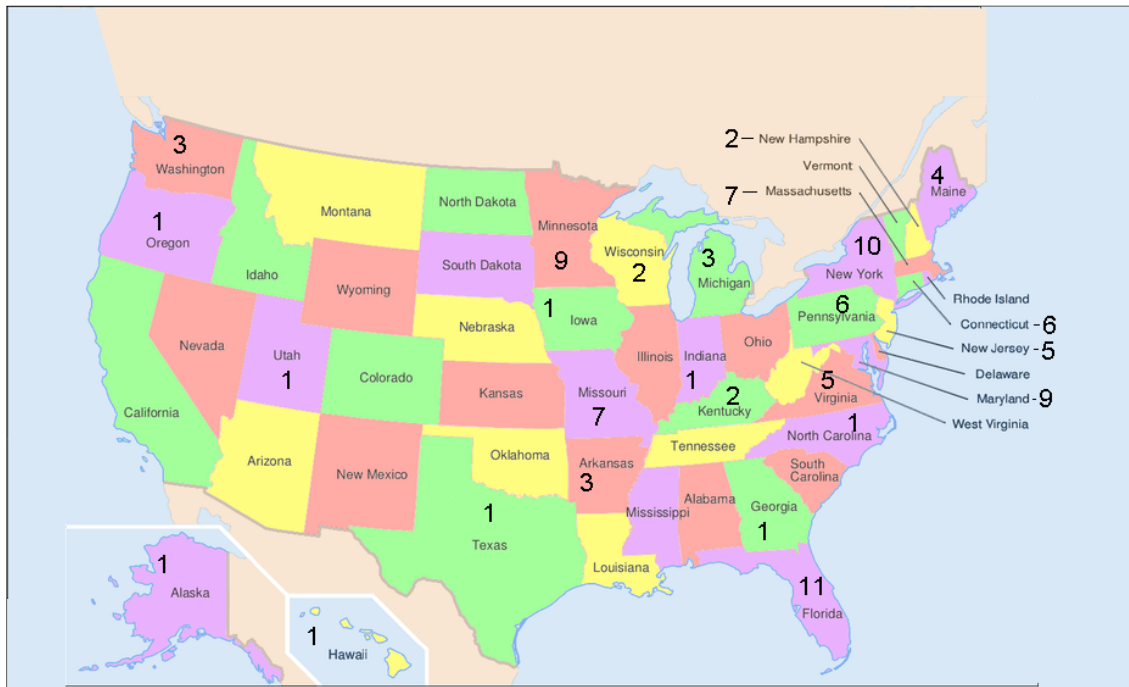


Figure 4: WTE locations in the U.S.

WTE plants have previously been concentrated in areas where landfilling is not an economical option, in locations such as the north east where excess land is difficult and expensive to acquire. Figure 4 gives a visual representation of the location and concentration of WTE plants across America. It is clearly evident that WTE has not yet become popular in the westerly states, however due to its growing acceptance as a form of renewable energy the use of WTE as a waste management practice may follow in the footsteps of the E.U. as it attempted to do a century ago. The message to be taken from this figure is that current WTE plants are concentrated in areas with high population density and limited open space for landfilling; these constraints naturally increase the cost of landfilling enough that WTE is an economically sound alternative.

One of the reasons that there have not been any new WTE facilities constructed in the U.S. for several years is the very high capital cost of new plants. It is believed that one way of increasing the specific productivity of such plants, and thus reducing their size and capital cost, may be by pre-shredding of the MSW, thus homogenizing and increasing the density of the feed to the grate. This study evaluates the potential benefits that pre-shredding may have on MSW management, both by means of combustion with energy recovery and of landfilling in regulation landfills.

Most of the present WTE facilities are based on the combustion of “as received” MSW, commonly referred to as “mass burn” or “stoker” combustion. Refuse Derived Fuel (RDF) is a less widely used form of MSW in WTE facilities. In the U.S., an estimated 6 million tons of MSW are used as the fuel of RDF WTE facilities, i.e. 23% of the total MSW combusted in the U.S. Refuse derived fuel is MSW that has undergone mechanical treatment to remove non-combustibles, with shredding being the first step in the process. In RDF plants, shredding is followed by sorting and recovery of non-combustible materials such as glass, ferrous and non-ferrous metals. However, the recovery of non-ferrous and ferrous materials can also be carried out at the back end of incineration process, via separation from the bottom ash by-product as is currently practiced in many WTE plants. This leads one to believe that shredding of MSW is not only viable for RDF burning facilities but also for the mass burn plants.

The major concern with shredding MSW for mass burn facilities is that the capital and operating costs required for shredding MSW may not be recovered by the improved efficiency. This perception is reinforced by the fact that RDF facilities are as costly to build as mass burn plants and also require about twice the personnel complement of mass burn facilities of the same capacity. Therefore, the question arises: Has shredding technology progressed sufficiently in the last fifteen years since the design of the last WTEs in the U.S. to the point that shredding can be now implemented more economically and safely due to advances in public education and collection programs.

Facility and Operations

Waste-to-Energy plants are typically in operation over 80% of the time generating a continuous supply of electricity and steam. In order for a plant to continuously operate at optimum capacity it is required that the facility have an appreciable amount of onsite storage space for MSW. Storage pits are generally sized such that they can supply the boilers enough fuel to run for a minimum of three days at normal capacity. The reason for this 3 day minimum is a result of waste collection service typically being in operation only 5 days per week with the need to handle holidays that can keep the waste collection inactive for three full days. Operating capacity for WTE plants ranges from 500- 3000 tons per day, requiring that the storage pit be large enough to store nearly 10,000 tons of MSW for high throughput operations.

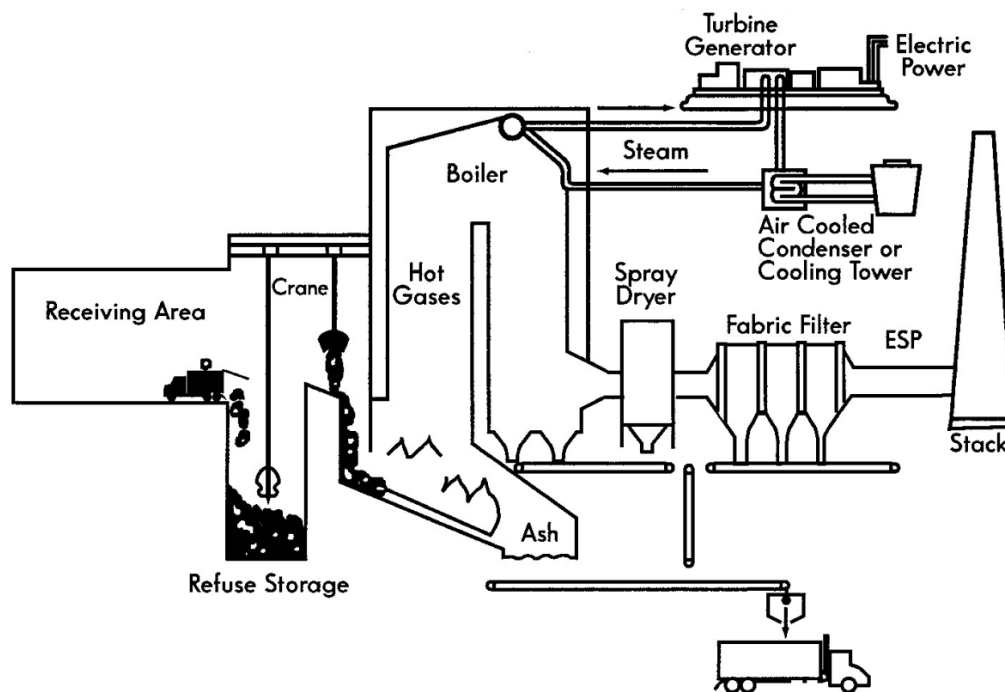


Figure 5: Typical Mass burn plant schematic [ETA]

A typical waste to energy site can be separated into four major components: the receiving area, the grate, the boiler and the air pollution control (APC) stage. Due to strict environmental regulations the APC system can occupy more than half of a facilities footprint. The receiving area consists of the tipping floor and the storage pit. The tipping

floor is a flat concrete surface where waste trucks empty their load onto the floor or directly into the pit. The tipping floor allows the facility personnel to physically sift or visually scan through the incoming refuse for white goods such as stoves, refrigerators and other appliances, as well as potentially dangerous items such as pressurized vessels or combustible liquids/gasses. White goods are removed for material recovery purposes while dangerous items such as propane tanks are removed to avoid equipment damage and personnel injury. The refuse is removed from the storage pit with a manually operated ‘crane and claw’ system that then drops the MSW into the hopper where it is fed onto the grate via a hydraulic ram.

To address the heterogeneous nature of the MSW crane operators will often “fluff” the MSW in the pit. This process involves repeatedly picking up a claw full of MSW and distributing it across the pit. The process has a twofold effect of breaking any bags or containers that may be containing the waste and mixing the waste to create a more homogenous fuel. WTE facilities accept waste from many different producers including construction and demolition (C&D), commercial, industrial and residential refuse. The waste that is produced by each of these sectors is highly dissimilar in terms of material composition and heating value. WTE plants operate most efficiently when fed a consistent stream of fuel, hence the attempt to homogenize as much as possible the MSW while it is stored in the pit. However, this fluffing effort is only partially effective in creating a homogenous fuel and is primarily used for bag breaking purposes. Figure 6 shows the claw just before beginning a fluffing operation



Figure 6: Claw prior to fluffing the pit

Refuse Derived Fuels

Refuse derived fuel is a fuel produced by shredding, sorting and dehydrating MSW in order to generate a higher heating value fuel than raw MSW. RDF can be used in cement plants, waste to energy plants or co-combusted in a coal fired power plant. RDF is primarily composed of organic matter such as plastics and biodegradable waste that have been removed from the MSW stream by a series of shredding, magnetic separation and air knifing operations. Once the non-combustibles have been removed the RDF is commonly compressed into pellets, logs, or bricks and combusted onsite or sold to local combustion facility.

RDF plants focus on generating revenue from both material recovery and fuel production and rely on profits from the material recovery side to remain a successful business operation. Sustainable waste management practices are beginning to develop across the nation and showing annual increase in curbside recycling participation. Recycling rates have increased from 8 to 28% in the past three decades with much of this increase attributed to single or dual stream community curbside recycling programs. This trend of source separation of recoverable from MSW may eventually hinder the

successful operation of RDF plants, as MSW is becoming a more concentrated stream of non-recoverable materials. If curbside recycling rates continue to rise the community will essentially replace the need for material recovery from MSW streams and essentially force RDF plants to adopt a shred and burn or simply mass burn operation.

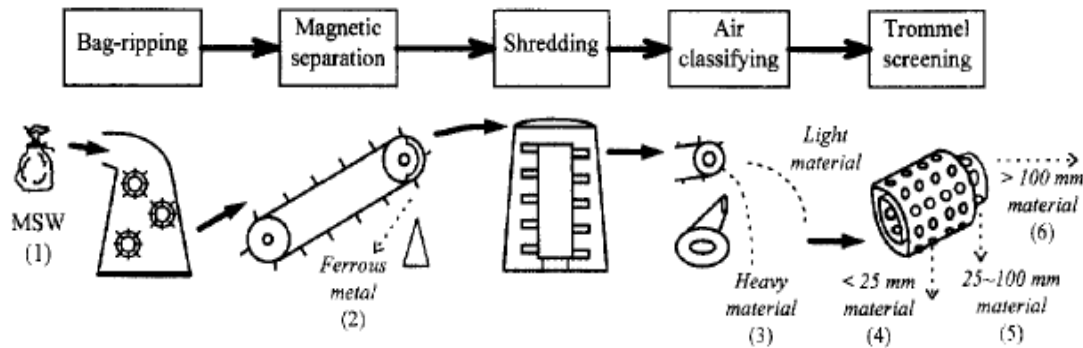


Figure 7: RDF process line [Chang]

Occasionally RDF plants have been adapted towards a ‘shred and burn’ tactic where only minimal preprocessing occurs to produce the RDF, in these facilities the waste is size reduced for more effective metal recovery and sent through a magnetic separator, once the metal has been collected the processed refuse is combusted in either a semi-suspension or moving bed reactor. Figure 7 is an example of the preparation process of MSW into RDF. This process requires extensive handling and transport of the MSW resulting in complex systems that are expensive to maintain and require increased operating personnel. According to operation managers of some RDF plants the operations are economically sound, however, if given the chance to redesign the system they would lean towards a mass burn plant due its simplicity and proven success.

Some incineration plants operate in a sort of hybrid state between RDF and Mass burn and are given the name ‘shred and burn’. Shred and burn facilities do not go through the process of pelletizing or autoclaving the refuse after the non-combustibles and recoverable items have been removed. Shred and burn plants do however remove ferrous and non-ferrous materials prior to combustion and in some cases practice further material separation and recovery. The concept of shred and burn is simple, MSW burns better and more evenly if size reduced and partially homogenized, however this technique

is often neglected due to the added costs and complexity of the system when compared to Mass burn plants.

RDF plants are known to cost more to operate and require almost double the personnel as compared to a mass burn WTE plant, this can be attributed to the complicated system of MSW handling and many stages of material recovery and sorting prior to incineration. Plants that are designed to operate with a higher energy content fuel such as RDF will not operate properly when fed raw MSW and thus require the removal of non-combustibles such as ferrous and non-ferrous metals. Mass burn plants are able to recover comparable amounts of ferrous and non-ferrous materials as RDF plants by magnetic and eddy current separation of the bottom ash. Mass burn plants are designed with this in mind so that the MSW containing non-combustibles will have limited inverse effects on the combustion process.

SEMASS

The SEMASS resource recovery facility in Rochester, Massachusetts is good example of a typical shred and burn facility. SEMASS consist of three separate combustion lines each with a design capacity of 900 tons per day. Figure 8 is a flow schematic of the refuse as it is processed from raw MSW to processed refuse fuel (PRF). The raw MSW is processed to a size of 6 inches minus diameter and then sent through magnetic separators that prepare it for the semi-suspension combustion units where light materials burn in suspension while the heavy materials burn on the moving grate at the bottom of the boiler. The SEMASS WTE facility produces 560,000 MWH of electricity per year and recovers over 40,000 tons per year of ferrous material. The facility has a high thermal efficiency and a high grate efficiency of 1.5 MW/m² compared to the average mass burn plant of 1 MW/m².

Although SEMASS is an economically profitable and environmentally respectable operation it has been described as overly complicated and expensive to operate and maintain. According to the developers of the facility, Energy Answers, the most frequent maintenance is done on the shredders. Each day any shredder that was in operation must be opened up and inspected for hammer wear so that hammers can be repaired or replaced before failure. SEMASS operates 4 top fed hammermill shredders,

where two are in operation, one is online for redundancy and the fourth is used as a replacement when one undergoes significant repairs or down time. Covanta Energy, the current owners of SEMASS, have explained that the facility is a successful implementation of the shred and burn technique, however if they were to redesign the plant they would most likely use a mass burn technique to simplify the process.

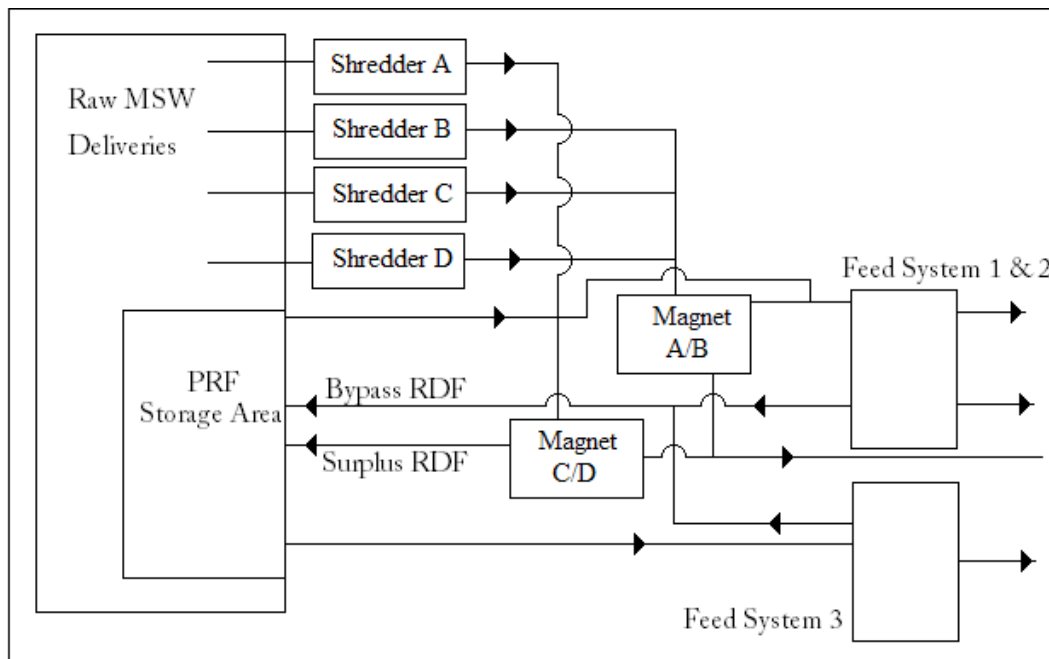


Figure 8: SEMASS refuse flow diagram

Observed effects of RDF combustion vs. Mass-Burn combustion

The following tables summarize the major effluents from MSW and RDF incineration. These values should be used as a comparison basis only and will vary amongst different incineration facilities. A study conducted by Chang et al. compared the effects of burning RDF and ‘as received’ MSW in the same incinerator with a focus on the ash properties and the quality of the flue gas effluent. RDF preparation included the standard shredding, magnetic separation, trommel screening and air classification to remove heavy non-combustibles. The major distinction between the fuels is summarized below in Table 1. Most notably is the decrease in moisture content and increase in total combustibles and overall heating value of RDF.

Table 1: Average properties of MSW and RDF [Chang]

	MSW	RDF	
		25-100 mm	>100 mm
Bulk Density (kg/m³)	290	335	171
Paper (%)	28.6	8	5.7
Plastics (%)	26.33	29.1	57.8
Metal (%)	7	1	0
Glass (%)	7.3	0	0
HHV (kcal/kg)	2278	2545	3715
LHV (kcal/kg)	1816	2095	3296
C (%)	20.1	24.5	29.2
H (%)	2.9	3.2	3.3
Cl (%)	0.18	0.16	0.23
S (%)	0.8	0.1	0.05
O (%)	12.6	11.69	15.9
Moisture (%)	50.6	47.6	40.28
Ash (%)	12.2	11.7	9.96
Combustibles (%)	37.2	40.7	49.76

Tables 2 and 3 support the argument that RDF incineration is capable of producing a more complete combustion process than Mass Burn plants as made evident in the higher quality effluent gasses and fly ash. Chang's findings also reported higher heavy metal concentration in bottom ash of the RDF combustion and was explained as a result of the higher paper content with printing ink found in RDF fuels [Chang]. The potentially polluting components of MSW are a result of incomplete combustion, with more of the non-combustibles removed the energy efficiency and grate temperature increase allowing for higher conversion of fuel to heat and in effect lower emissions.

Table 2: Flue gas comparison for RDF and MSW fuels [Chang]

	MSW	RDF	Standards
Particulate (mg/Nm ³)	5.7	3.15	220
CO ₂ (%)	6.65	7.9	
CO (ppm)	321	203	350
O ₂ (%)	12	11.2	-
H ₂ O (%)	26.6	14.1	-
SO _x (ppm)	13.5	15	300
NO _x (ppm)	18	9.2	250
HCl (ppm)	0.36	0.58	7
Pb (mg/Nm ³)	0.13	0.013	0.7
Cd (mg/Nm ³)	0.003	0.0095	0.7
Hg (mg/Nm ³)	10	5.35	60

The concept that RDF plants can achieve a higher energy efficiency while operating in a cleaner mode than Mass Burn plants gives incite to potential improvements in integrated solid waste management via Mass Burn incineration. The idea of recovering materials from MSW streams prior to incineration can take two routes. The first is demonstrated in RDF facilities that use automated systems to prepare a high heating value fuel by removing non-combustibles. The second and potentially more effective route would take advantage of source separation. Curbside recycling programs are on the rise and becoming more effective with the continual improvement in MRF's and increased participation in recycling programs. High curbside recycling participation rate may allow a shred and burn plant to operate under the same conditions of an RDF plant, yet the processing will be simplified to include only shredding.

Table 3: Fly ash comparison of RDF and MSW fuels [Chang]

	MSW	RDF	Standards
Pb (mg/L)	9.6	0.04	5
Cd (mg/L)	4.6	2.6	1
Cu (mg/L)	22	9.6	15
Zn (mg/L)	5.3	21.7	25
Cr(mg/L)	< 0.02	0.04	5
Hg(mg/L)	< 0.0002	<0.0002	0.2
As (mg/L)	<0.001	< 0.001	5
pH	5.6	5	
Cr ₆ (mg/L)	0.003	0.002	2.5
CN-(mg/L)	0.002	< 0.002	

Table 4: Bottom ash comparison for RDF and MSW fuels [Chang]

Analysis of bottom ash composition			
	MSW	RDF	Standards
Pb (mg/L)	0.03	0.12	5
Cd (mg/L)	0.02	0.06	1
Cu (mg/L)	0.33	0.39	15
Zn (mg/L)	1.6	16	25
Cr(mg/L)	0.03	0.12	5
Hg(mg/L)	0.0002	0.0002	0.2
As (mg/L)	0.001	0.001	5
pH	11.8	10.2	-
Cr6 (mg/L)	0.006	0.05	2.5
CN- (mg/L)	0.002	<0.002	-
Carbon Content (%)	2.65	0.65	-

WTE operating costs

Capital and operating costs for a proposed Mass burn plant have been broken down into several categories to give a relative idea of what components make up the majority of the expenses. This particular analysis corresponds to a facility rated at 330 tons/day (100,000 tons/yr) with a maximum output of 10 MW. Figure 9 was produced from data collected by Papagiannakis as an estimate of relative expenses for the construction of a proposed combustion facility in Athens, Greece. Nearly two thirds of the capital costs for the plant are tied up in the grate, boiler and APC systems while fuel handling, storage and the preparation system make up 20% with field purchases and engineering making up the balance. Assuming the costs of a new plant will be in the 100 million dollar range nearly 20 million dollars could be dedicated to the fuel handling and storage systems. With proper engineering design the addition of shredding lines could be implemented with minimal addition to the fuel transportation systems with potential reduction in the fuel combustion and clean up systems.

The operation costs of this plant allocate nearly 20 percent of the annual budget to operation and maintenance costs. This leads one to believe that even a small decrease in grate and boiler wear, combined with increased efficiency, could result in non-trivial reduction in costs. The implementation of a shredding system would undoubtedly increase labor costs and would require additional operation and maintenance; however it

is beneficial to note that nearly half of the operating costs are a result of capital investment, insurance and licensing, all unlikely to change with the addition of shredding.

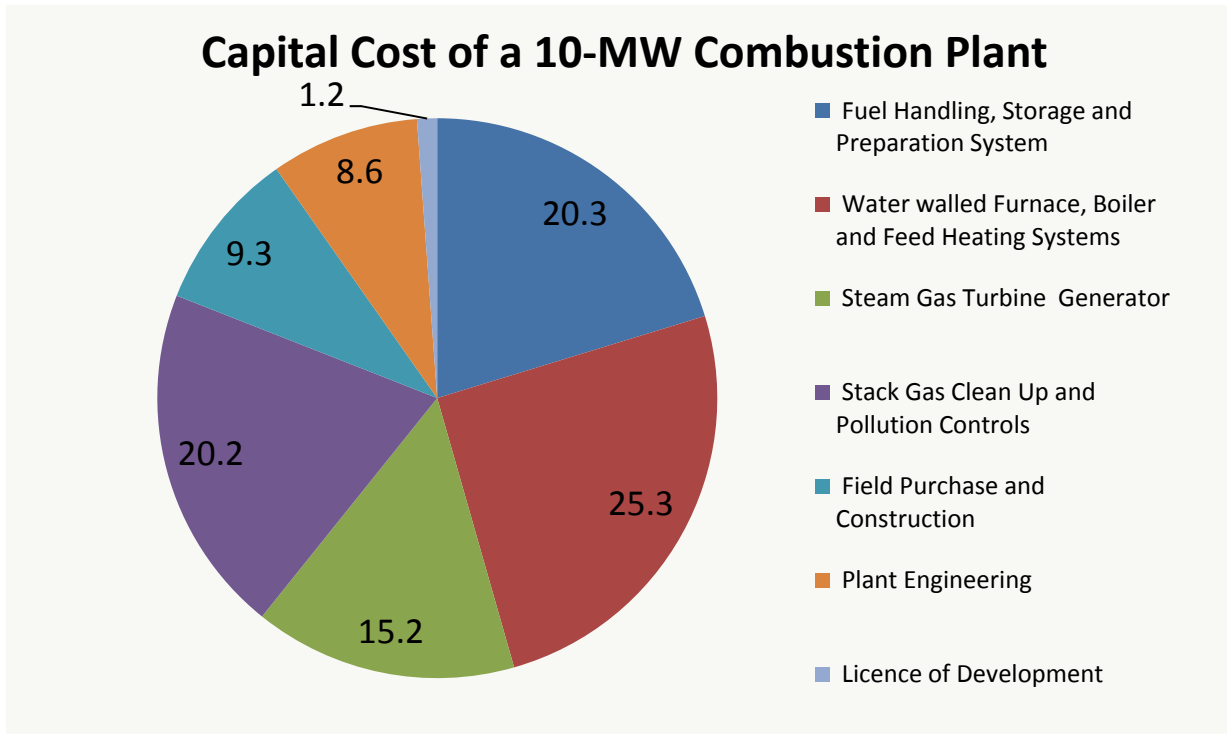


Figure 9: 10 MW Capital Cost breakdown [Papagiannakis]

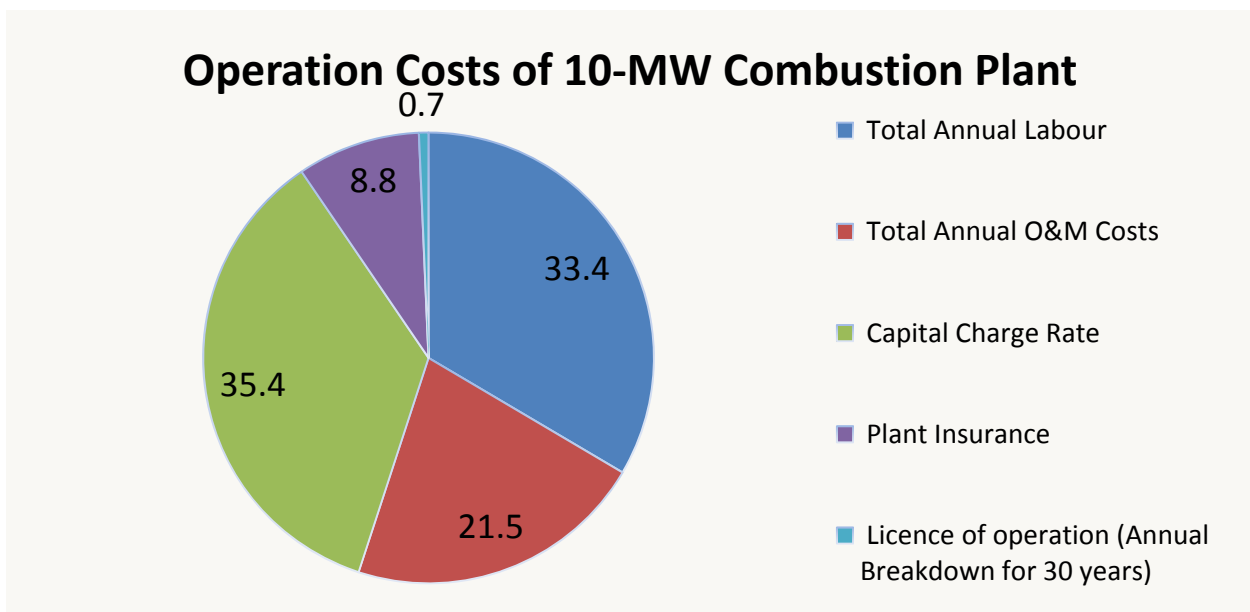


Figure 10: 10 MW Operational Cost breakdown [Papagiannakis]

2. Size Reduction Technology

Shredding and size reduction of MSW is most commonly utilized in the materials recovery sector of integrated solid waste management, i.e. recycling. Historically the major benefits of size reduction are threefold. First, shredding the bulk waste stream breaks the raw MSW into its basic components by tearing and breaking open paper, plastic, and glass containers such that material recovery and separation will be more effective. Secondly, shredding the MSW reduces the average particle size to a more workable size that can be better handled by any subsequent processing equipment or personnel. Lastly, and most importantly for material recovery facilities (MRF's), shredding produces different size distributions for the different material components of MSW, allowing for automated material separation such as air classifiers, screens and optical sorters.

Prior to 1985 the basic principal used in designing a size reducing device was focused on the application of brute impact force. The results of such ideology are larger and heavier machines with the affiliated increase in capital and operating costs. The composition of MSW is so widely varied that machines designed for MSW must be robust enough to handle both soft and ductile materials as well as tough and resilient materials such as metal and dense plastics. Table 5 is a summary conducted by Trezek et al. of the mechanical properties of some typical materials found in MSW. This table demonstrates well the variance in strength and ductility of common materials comprising MSW. Due to this composition variance the brute force method of size reduction can lead to undesired imbalances in the size reduction of different materials.

Table 5: Stress – Strain properties of some MSW components.

Material	Type of container	Ultimate strength (psi)	Ultimate strain (in./in.)	Rupture energy (ft.-lb./ in³)
Steel	12 oz. Can, beverage	82,000	0.005	9.4
Aluminum	12 oz. Can, beverage	31,000	0.012	26.5
Cardboard	Box, laundry detergent	6400	0.025	8.3
Paper	Bag, brown paper	4000	0.025	5.1
Plastic, PVC	Bottle, liquid soap	4000 to 5000	.36-.06	111-19
Plastic, PE	Bottle, shampoo	1000	.8-.9	56-66

Many devices capable of material size reduction are available on the market ranging from automobile shredders, which are able to process almost anything, to granulators and paper shredders that can process only relatively soft materials. There are two prominent categories of shredders used in the management of MSW; high-speed, low-torque (HSLT) hammermills and low-speed, high-torque (LSHT) shear shredders. There is little similarity in the principles behind size reduction via HSLT grinders and LSHT shredders. This difference leads to some inherent advantages and disadvantages regarding the acceptable MSW feed as well as the size distribution of the product and overall process capacity. HSLT machines are available in a wider range of size and capacity as a result of their maturity in the field of MSW processing. Tub-grinder type hammermills can reach capacities of up to 300 tons per hour; however this number is closely governed by the desired particle size as well as the raw MSW material composition. A more realistic value for continuous operation of such grinders will peak at about 150 tons/hour for larger machines.

The first shredders that were used for MSW size reduction were not specifically designed for processing a mixture of such a varying composition and material properties as MSW. Grinders and shear shredders should be designed with the material properties of their feedstock in mind to optimize throughput and minimize wear and tear of cutting surfaces. The original grinders used for MSW processing were of the hammermill family and had been adapted from their popular use for the comminution of grains or brittle materials such as rock and coal. These hammermills were initially designed to process higher hardness materials such as steel as well as brittle materials such as glass and granite. Having been designed for a fairly specific group of material properties these hammermills may not be the best choice for size reduction of MSW due to its highly heterogeneous nature.

High-Speed, Low-Torque Grinders (The Hammermill)



Figure 11: Diamond Z SWG 1600 hammermill

Low torque shredders such as the top fed horizontal hammermill utilize high speed rotating shafts (700-1200 rpm) that are equipped with fixed or pinned hammers used to crush the incoming material. The principal difference between these machines and the LSHT devices is that hammermills rely almost entirely on impact and abrasive forces to smash the refuse into smaller particles. Figure 12 shows an axial cross section of the rotating shaft and hammer, this drawing highlights the impact forces used in these machines to size reduce the refuse. It is important to notice that the hammermills do not have tight tolerances between the hammers and cutting or sizing bars; this is because size reduction is primarily a result of the hammer smashing the MSW. Due to their reliance on impact force, hammermills are generally more effective in processing brittle materials and can have problems with rags and stringy materials which can wrap around the shaft and cause overloading and disruption of the operation as shown in Figure 11, these issues

result from the low torque of the system. The impact force of the hammers is damped by ductile material while energy is absorbed and wasted in softening mechanisms lowering the intensity of the impact force. Hammermill shredders produce a less homogeneous product with brittle materials making up a higher portion of the fines than ductile materials. This is especially true for glass, a non-combustible material, resulting in unnecessary size reduction.

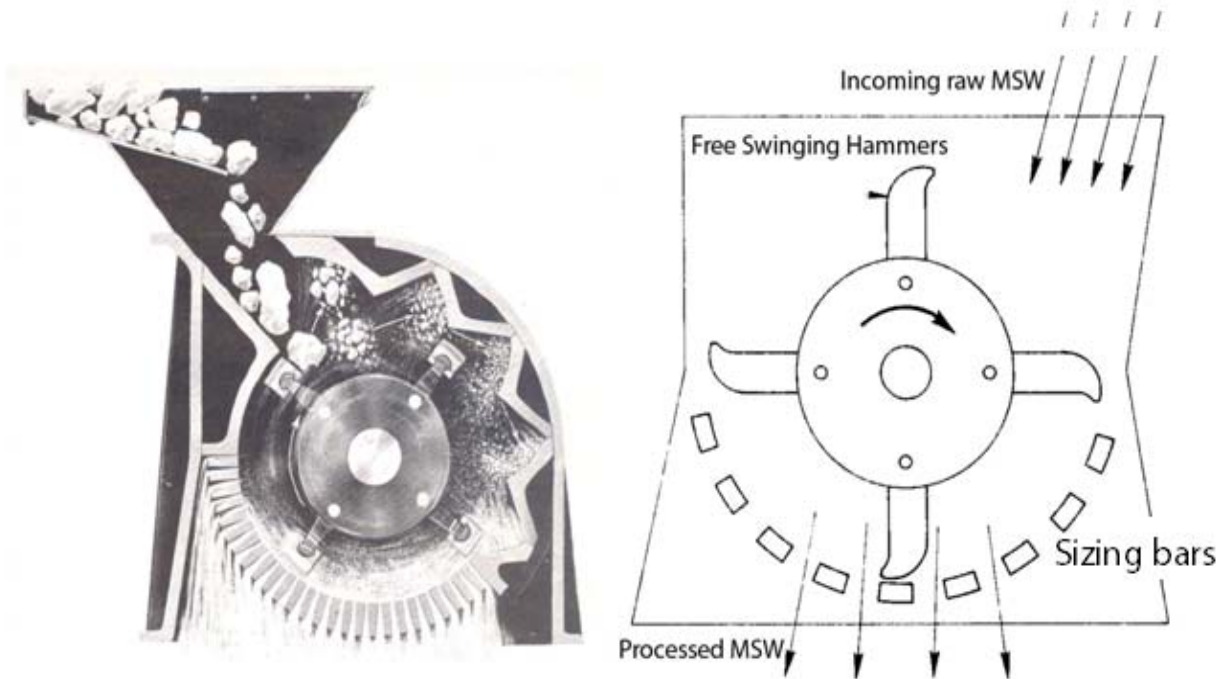


Figure 12: Internal arrangement of a hammermill shredder [Mining and Metallurgy Basics]

Generally the materials with higher heating values such as paper and petroleum based plastics are more ductile and may end up receiving less than the average size reduction, meaning energy and money is wasted on size reduction of material which benefits least from it, in terms of combustion. As shown in Figure 13 the amount of size reduction is not consistent across the different components of MSW, with glass and 'other' materials receiving a greater percentage of the overall size reduction.

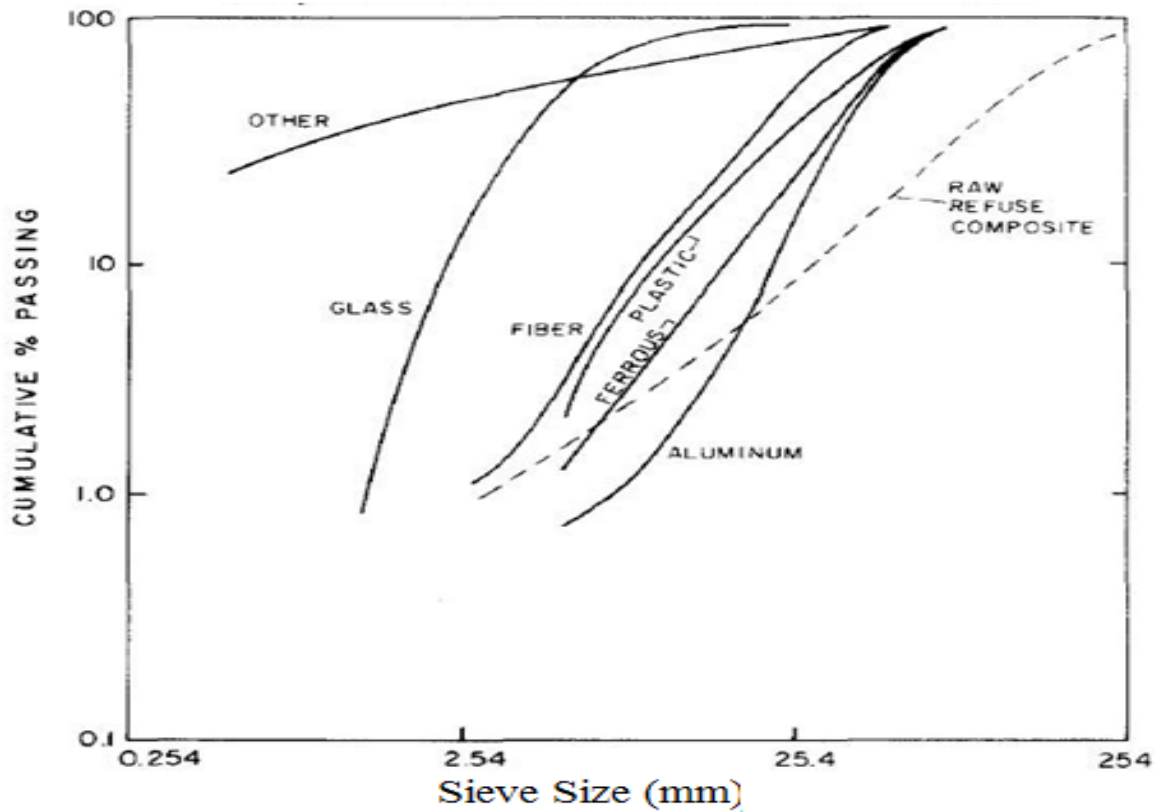


Figure 13: Composition distribution of hammermill shredded MSW [Trezek]

The HSLT shredders have specific energy consumptions ranging from 6-22 kWh/ton depending on the characteristic size of the shredded refuse and the material composition. A study by Trezek on MSW size reduction has shown that the specific energy consumption of a hammermill can be optimized by lowering the rotor speed by 25%. In this test, when the rotor speed was reduced from 1200 to 790 rpm, there was a 26 % reduction in power consumption for an equivalent amount of MSW processed on a per ton basis. The reason for this can be attributed to the fact that up to 20 % of a HSLT devices power is used to overcome bearing friction and windage of the rotor. If the machine is not loaded properly and consistently, a large fraction of the energy is used in idle spinning of the rotor.

The speed of the rotor plays a significant role in rotor windage and internal pressure in the shredding compartment. As can be seen in Figure 14 the pressure variation with shaft speed is highly non-linear and can lead to increasing energy losses due to windage at higher velocities. It is also important to note that increasing the

internal pressure of the grinder can facilitate in creating an explosive condition in the presence of a flammable mixture. Bearing friction is also a relatively large source of energy loss in high speed devices. MSW comminution creates a severe environment for bearings and connections with both dusty and wet conditions subject to high temperatures and long duty cycles, without proper maintenance bearings and other connections can wear significantly and become energy sinks.

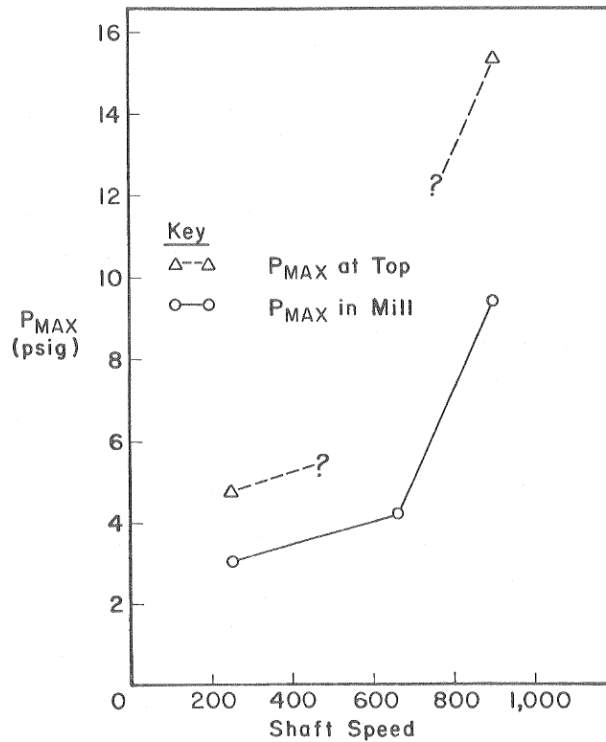


Figure 14: Chamber pressure vs. Hammermill shaft speed [Zalosh]

Over-processing of MSW can lead to particles that are too fine, which can bring about entrainment problems as small particles will enter the “freeboard” and can be released as particulate matter from the combustion process. Particles entering the freeboard will cause the system to lose some of the fuels heating value as well as increase pollution. It has also been shown that higher rotor speeds generate finer particles at a higher energy cost, especially for brittle materials processed in high speed devices. It is therefore necessary to choose the rotor speed according to the desired particle size because processing MSW to sizes smaller than necessary can result in unnecessary energy costs.

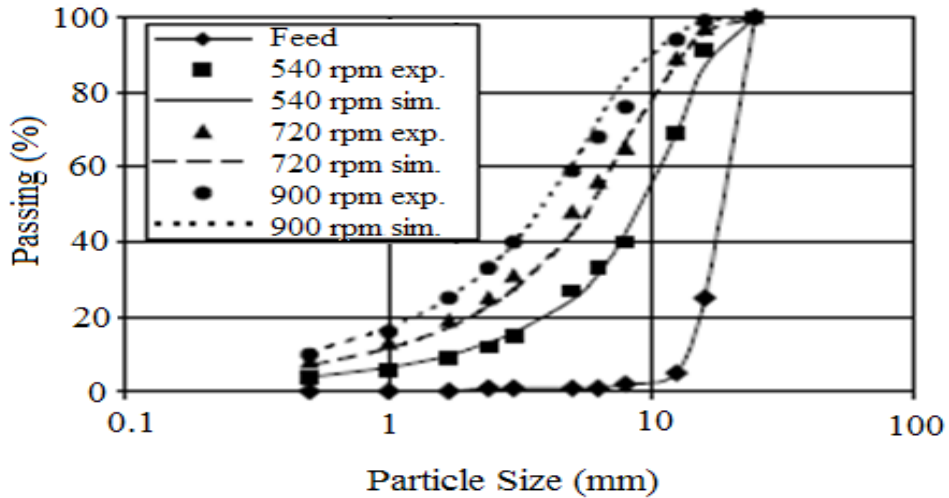


Figure 15: Particle size distribution for various hammermill speeds [Trezek]

As evident in Figure 15 the shaft speed of the hammermill has a noteworthy effect on the resulting particle size of MSW, shaft speed combined with the number and size of sizing bars and number of hammers used are the main adjustable parameters that can be used to set the mean effluent particle size. Figure 16 emphasizes the relationship between rotor velocity and particle size, this correlation is an important parameter to be cognizant of when operating a hammermill shredder due to the efficiency and maintenance benefits that are affiliated with lower shaft speed.

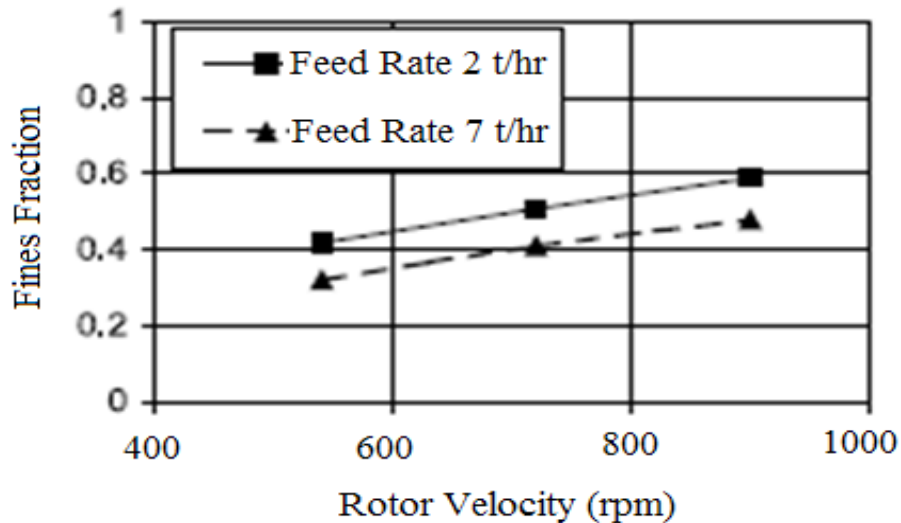


Figure 16: Fines fraction vs. Shaft speed [Trezek]

Figure 17 shows that the relationship between specific energy and particle size is non-linear. The energy required to achieve a desired particle size follows a geometric

relationship between energy and particle size, this non-linear relationship is an important characteristic when considering size reduction. Shredding the MSW unnecessarily can lead to even greater operation and maintenance costs. Seeing as raw MSW contains both large and small particles the size reduction devices must be designed to produce a consistent product size even when fed a wide size range of MSW. The operating principle of HSLT devices presents difficulties in achieving this goal as a result of not using tolerances to determine size reduction. The product size of MSW fed through a hammermill is mostly determined by the impact forces and the material properties of the raw MSW, again with brittle materials producing high quantities of fines and malleable material simply deforming rather than being size reduced.

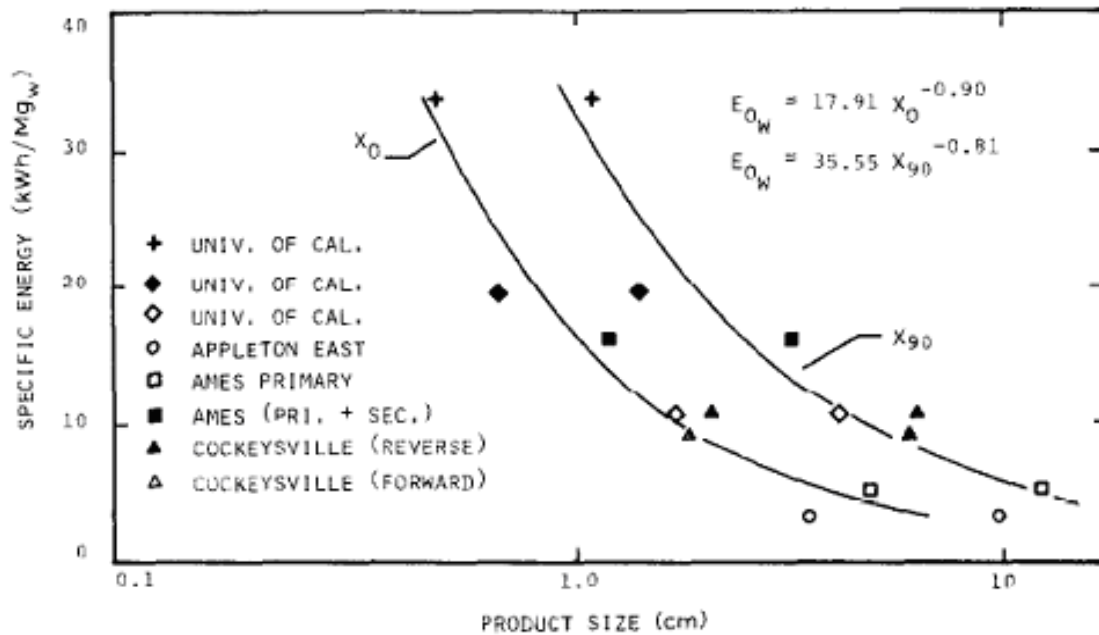


Figure 17: Particle size effect on specific energy of LSHT shredders [Trezek].

Moisture content in MSW can also vary widely from as little as 10% all the way up to 60 % as seen in some food waste. This moisture content can have a large effect on the power consumption of a shredder. Some of the more common materials found in MSW, such as paper, lose their tensile strength when wet; thus, the energy required in tearing paper decreases with increased moisture content. However, Trezek et al. have shown that the specific energy used (energy per unit of material) decreases with moisture content of MSW up to about 35%; at higher % moisture content the specific energy again increases.

This is unique to HSLT shredders because at high moisture content, the wet materials tend to absorb the impact energy of the hammer and deform rather than break, causing the product of moist materials to contain higher number of large particles. The wet material is also said to interfere with the smooth flow of the shredder as a result of material “wadding”. Wadding can lead to an uneven mass distribution in the grinder and impart excessive wear and vibration forces on the grinder, similar to what happens in clothes dryers when material collects on one side of the spindle.

Rotor windage results from the high surface velocities achieved in high speed hammermill devices. Windage can be a significant source of power loss due to viscous forces between the rotating hammer and the air entrained in the containment baffle. Windage losses can be as high as 20% as a result of high rotor speeds (1000rpm) and rough hammers surfaces with non-uniform geometries. Issues with escaping air are also problematic when designing high speed devices; Figure 18 shows common hammermill geometries and their respective windage vectors when exiting the containment baffle. It is clear that a wider throat opening will lead to lower windage losses and pressure build up; however for safety concerns of ejected materials the rotor is generally fully contained and windage losses are simply accepted. Sizing bars or cutting baffles should be minimized and placed as far away as the rotor as possible to minimize windage losses, yet when this is done the ability to properly size the MSW is limited due to the lack of flexibility in the design constraints.

Rotor speed plays into many aspects of the operation and efficiency of high rpm machines, in the case of MSW size reduction higher speeds allow for higher throughput but result in a finer product size and a lower efficiency. When operated at lower speeds energy efficiency increase, hammer wear decreases and coarser particle sizes results. The interconnectedness of all these aspects makes designing an optimal HSLT system somewhat more difficult when compared to a lower speed devices that rely more on cutting surfaces and tolerances than impact and abrasion forces for size reduction.

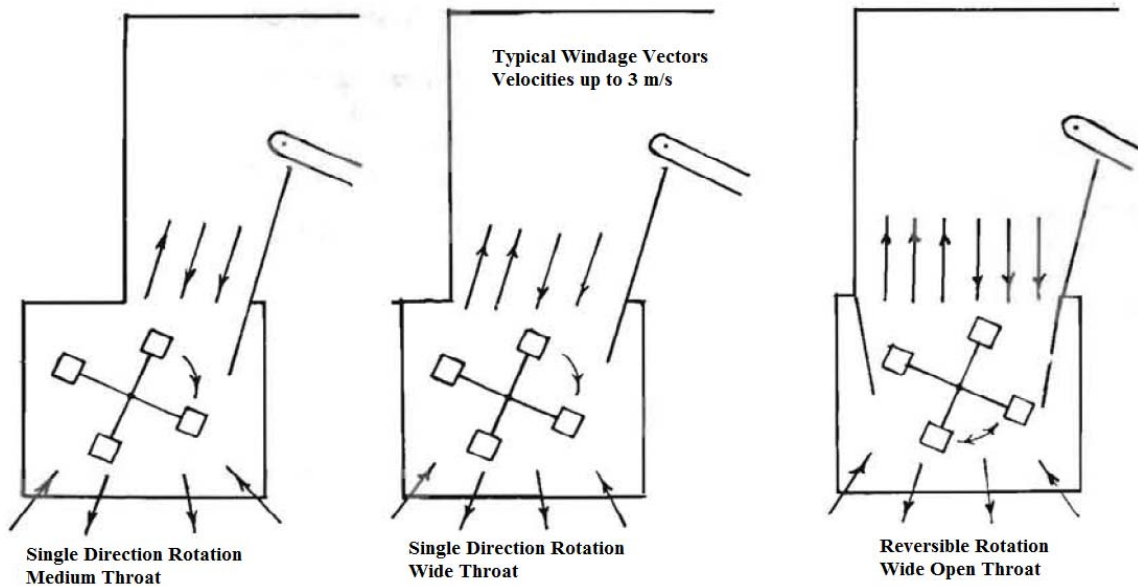


Figure 18: Windage vectors for HSLT devices [Trezek]

As in the case of all industrial processes, the safety of operators is of the utmost concern. One of the more common and dangerous safety issues involved with MSW shredding is that of unexpected explosions during shredding. Explosions are almost inevitable in the shredding of MSW and are often caused by the buildup of volatile explosive vapor around the rotor. This explosive vapor can come from propane and other compressed tanks that manage to make it past the floor pickers. The danger with high speed hammers is that they have a tendency to create sparks during the impact with metal objects commonly found in MSW. These types of incidents can be avoided in some cases by an observant operator who is constantly checking the feed for hair spray, spray paint, gas cans or any such highly flammable object but such vigilance is not practical in processes that handles ten to fifty tons of MSW per hour.

Low-Speed, High-Torque (Shear Shredders)



Figure 19: Cutting Shaft of LSHT shredder [SSI 3600 H]

Low-speed, high-torque shredders, such as rotary shear shredders operate on a different principle than the hammermill. Rotary shear devices rely on shear cutting and tearing forces with little to no impact force involved. Rotary shears are made in single, double or quad shaft configurations such that increased shaft numbers produce a smaller mean particle size. Shear shredders used in MSW processing are generally limited to two shaft designs in order to avoid unnecessary excess size reduction and energy consumption. The counter rotating shafts are fitted with cutting knives that intermesh and create large shear forces on any material trapped between them. These cutting knives or hooks are shown in the dual shaft configuration in Figure 19, the hooks must be designed such that they grab the incoming MSW and pull it between the neighboring shafts to achieve the shear cutting forces. The definition of LSHT shredders generally assumes a speed of between 10 and 50 rpm. The low shaft speed can have some hindering effects on capacity as they are often available in lower capacities than HSLT. The capacity of the shredder depends on the rotor speed and the volume available between cutting knives. Although industrially available shear shredders have capacities

topping out around 150 tons per hour, they have many positive features that make up for this.

In comparison to the specific energy range for HSLT devices of 6-22 kWh/ton, the LSHT machines tend to have lower power consumption, in the range of 3 -11 kWh/ton, depending on material composition and feed rate. The lower speed rotors do not need to overcome as much frictional resistance as the HSLT hammermill, lending to higher energy efficiency per ton processed. The lower specific energy required in rotary shear devices allows for more compact and space efficient designs. The high torque produced can vary depending on design, from 50-350 kNm as compared to the 1-4 kNm achieved with the hammermill. The high torque results in a more even particle distribution, because shear forces are the major breakage mechanism and are less sensitive to material properties. The major factor in particle size distribution of the product for shear devices is a function of the tolerances between cutting knives and the number of shafts used, with more shafts and smaller tolerances leading to smaller particle sizes. This is beneficial in creating a more uniform particle size when the raw MSW stream is highly varied in size and strength.

A unique feature of rotary shears is their ability to quickly stop shredding the incoming feed and reverse the rotors to discharge a non-shreddable object in the feed. Many of LSHT machines use hydraulic transmissions to drive the shafts. The hydraulic lines have two benefits, the ability to act as a damping mechanism when tough or unshreddable materials are encountered and to function as a torque signal. A simple control system can be employed that detects pressure spikes in the hydraulic lines, thus indicating a large increase in torque; this signal can be used to recognize non-shreddable items and automatically reject them or notify an operator. This ability has no counterpart in HSLT shredders because they rely on stored rotational energy to manage hard objects resulting in high energy loss and potential damage when a non-processable item is encountered. The low speed in combination with hydraulic drive lines allows for the shaft to cycle from forward to reverse in a matter of a few seconds, a favorable option when stopping and starting of the feed through the machine is a frequent occurrence.

A potential problem with the LSHT shredders is their ability to “grab” or “bite” the incoming MSW stream. Some materials, e.g. cardboard boxes or suitcases, may tend to

bridge between the two rotating shafts avoiding being pulled down into the cutting surface. However, this problem can be avoided by the addition of a pushing ram or sufficient head of material above the rotors. These shredders can face difficulties in processing some of the more tough metals that can be found in MSW because, in contrast to HSLT machines, the shear shredders do not have the benefit of stored rotational energy that can be used to rip apart tough objects, when necessary. However, as noted above, this problem is somewhat avoided by their ability to reject materials that cause too high of a resistance in the shaft rotation.

Safety issues such as explosions and ejected materials are of less concern when dealing with low rpm machines. Explosions require a flammable mixture of fuel and oxidizer as well as a source of ignition, both of which are less likely to occur in a low speed system. With the absence of impact forces, it is difficult for the machine to produce a spark necessary for ignition. The low speed also means that when a flammable vapor is encountered it is not vigorously mixed with surrounding air making it more difficult to reach the lower explosive limit. The ejection of materials is also less common in these devices because there are no fast moving parts that can project dangerous objects out of the hopper.

Operating Parameters

Capacity

The capacity of refuse comminution devices to be used for pre-shredding of MSW for the WTE application is a criterion that must not be overlooked and can be one of the more important aspects when choosing a shredder. Waste fired power plants can have capacities up to 3000 tons per day; in these high capacity operations it is common to have two or three separate boiler lines. Each separate line has its own hopper, grate and boiler, meaning that it may be desirable for each line to have their own shredding unit. The maximum installed capacity of the shredder should exceed the nominal demand it will be processing by nearly 30% to allow for downtime and the processing of non-ideal materials of high durability.

High speed hammermills generally are available with higher capacity than that of the low speed shredders designed specifically for MSW. The hammermills range from less than 1 ton/hour all the way up to 300 tons/hour at maximum operation capacity. The hammermills that are rated to 300 tons/hour typically are not operated at such a high rate in order to minimize excess wear and maintenance. Low speed shredders are limited in capacity by their rotor speed and tolerances. The maximum throughput is defined by the volumetric displacement between the cutting surface and the rpm of the shaft. These devices are available in sizes up to 100-200 tons/hour at maximum rating, but are more commonly designed for between 20 and 70 tons/hour. The lower capacity of shear shredders can presumably be increased by creating larger machines based on the same size reduction principal. The manufacturing of such machines is limited by the current low demand for such high throughput applications. In the event that pre-shredding MSW becomes common practice these machines will likely be scaled up in capacity to meet the customer's needs.

It is common for RDF plants to produce more shredded waste than their boilers are designed for such that the boiler capacity is always the limiting operation rather than the availability of fuel. This is accomplished by supplying the boiler feed conveyor up to 50 % more waste than it requires and using this excess waste as a buffer to ensure that the boiler is being operated at the desired throughput. The remaining waste is then sent via a return conveyor to a separate storage pit exclusively used for processed refuse storage.

Size

The size and geometry of a shredder is quite important when developing an efficient integrated system. The goal of MSW size reduction is to increase productivity and decrease capital cost of a WTE facility. The footprint of such facilities will have significant ties to the overall cost of constructing a new plant. If shredders are to be effective in improving the WTE process they will need to be compact and smoothly integrated into the existing waste handling system.

Energy Density

Rotor speed of LSHT shredders tends to have a significant influence on the power consumption and capacity of the device. As the rotor speed is decreased, the specific energy required to process waste is increased, which is the opposite trend encountered with HSLT shredding that lose efficiency in idle rotor spinning as well as windage and bearing friction. Figure 20 shows the trend of how specific energy is inversely proportional to the shaft speed in low torque size reduction equipment. Figure 20 is a collection of data from different shear shredders and manufactures designed specifically for MSW processing. In general the low speed high torque shredders can be designed to be more compact than HSLT of equivalent capacities.

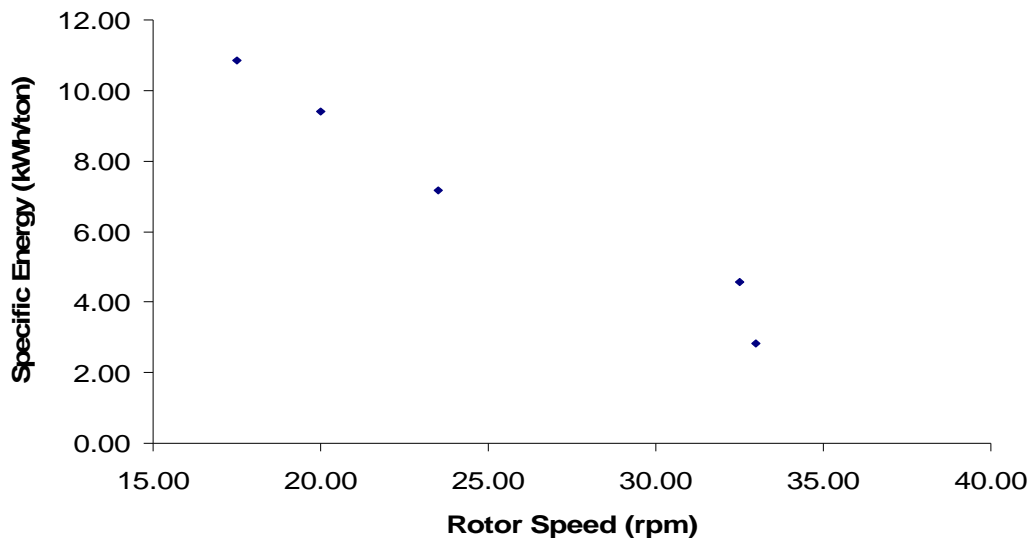


Figure 20: Rotor speed relationship to specific energy for LSHT.

The increased performance of low speed devices can mainly be accreted to the breaking mechanisms employed in comminution; shearing and tearing forces are less selective than impact forces when it comes to size distribution of the size reduced materials. Another interesting aspect of LSHT shredders is that the ratio of the shredders bulk volume to its throughput capacity tends to decrease with increased shaft speed, in other words higher rotor speeds can achieve a higher energy density and therefore process more material in a smaller volume than lower rotor speeds. Figure 21 demonstrates how energy density of the LSHT shredders increases as the rotor speed is

increased, indicating that the compactness of a shredder can be optimized by increasing the rotor speed. Although increasing rotor speed increase efficiency and improves size constraints, it can lower the quality of effluent and produce a coarser product.

Integration of such MSW size reduction machines into the waste-to-energy process requires that the benefits outweigh the initial and continual costs of operation. Operational costs of low speed shredders seem to be consistently lower than the hammermill, both with regard to energy consumption and maintenance. It is also beneficial that the LSHT devices tend to require less space than an equivalent capacity hammermill. Hammermill shredders were not originally designed to process MSW but because of their robustness and ability to process nearly anything they have been adopted in many MSW size reduction applications. It is necessary to design these devices with specific capabilities in mind; in the case of LSHT shredders, they can reject non-shreddable which are also generally non-combustible. Because of this ability, the device does not need to be over designed but rather intelligently designed such that they only shred the material that needs to be shredded.

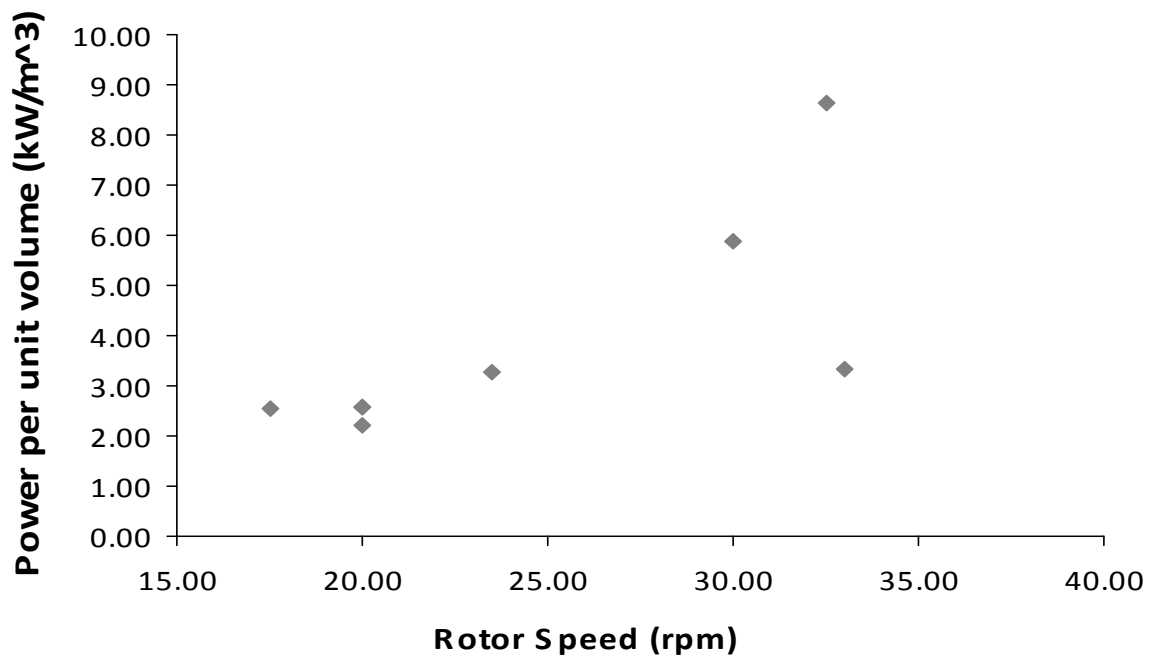


Figure 21: Energy density trends for LSHT shredders.

Safety Concerns

Comminution of MSW involves inherent risks that have been troubling the industry since its inception. Size reduction is a high power operation that makes use of engines in the range 500 hp to break, smash or shear relatively tough materials apart. This high power density process can lead to violent projectiles of shrapnel from the shredding chamber. Ballistically projected objects result from the high energy impact forces of rotating hammers that encounter a potentially non-shreddable material. Hammermills are often designed with either a solid metal plate or a chain curtain concealing the rotating shaft from outside of the shredder chamber to protect personnel and equipment from unexpected ejected material. The addition of a chamber guard often has negative impacts on windage issues that can lead to even more serious problems with explosions and blowouts.

Low speed shearing shredders have minimal impact forces and consequently do not frequently have issues with projected materials. Low speed size reduction is an overall less violent procedure because of the shearing mechanisms involved that contain no high speed components. Additionally many manufactures of the shear cutters have integrated a material rejection capability into the shredders which allows them to detect spikes in torque that signify a non-shreddable item. This signal can either notify the operator for inspection or in some cases activate a reversal of the shafts allowing for the undesired item to be automatically removed.

The throughput entering MSW shredders is often too high to realistically expect thorough screening to remove all dangerous materials. As a result it is not uncommon for potentially explosive materials such as gasoline, propane, paint thinner or hair spray to enter the shredder. Explosions are common to solid waste shredding operations utilizing both HSLT as well as LSHT devices. Based on discussion and experience the frequency of explosions is notably lower in operations that run low speed rotary shear shredders compared to hammermills.

In order for deflagration to occur when a flammable liquid or gas enters the shredder adequate oxidant/fuel mixing and an ignition source is required. High speed devices are even more dangerous due to the rotating hammers that can mix the

combustible gases in turbulent flow, thus potentially bringing the mixture to its lower explosive limit. Rotor windage has been credited with accelerating the development of explosive conditions via the increase in pressure and turbulence in the shredding chamber. The major source of damage and injury from shredding explosions results from the blowout of side and top panels as a result of the expanding gasses that are unable to escape quickly enough. As discussed early the chamber is usually physically confined to protect personnel from ejected materials; however this effort only makes the potential damage from explosions worse and more dangerous.

Operation and Maintenance

Both HSLT and LSHT shredders undergo severe wear and tear when processing municipal solid waste. When operating a hammermill, it is essential to the productivity of the machine that the cutting surfaces of the hammer be maintained, for this reason hammer tip replacement is a very common procedure and can be necessary as often as every 20 hours of operation. In some cases the tips can be maintained by adding a fresh bead of weld on the tips that have become rounded, this method is cheaper and more convenient than replacing the entire tip, but can result in lower performance depending on the quality and precision of the weld. As a result of operating at high speeds, the components of a hammermill are subjected to large amounts of vibrational and impact forces that lead to more maintenance than would be necessary for a shear shredder of equivalent capacity. Rotary shears also require replacement cutting surfaces but less frequently. An added bonus to the operator is that LSHT devices generally operate with a lower dust production rate and with less noise lending to a more comfortable work environment.

The continuous wear on the hammers tips is the largest reason for downtime of HSLT devices. Figure 22 shows the results of a study conducted by Trezek et al. on the effects of shaft speed on hammer wear in high rpm machines. The findings summarized in Table 6 show that significant wear reduction can be achieved when the shaft speed is decreased from 1200 to 790 rpm. The hammer wear was normalized by quantifying the mass loss on a per ton MSW basis. For normal non-hard faced hammers the total mass loss for 36 hammers was averaged at 0.107 lbs per ton MSW processed at 1200 rpm,

while when the MSW is processed at 790 rpm the mass loss decreases by 43% to only 0.061 lbs/ton. There was a slight shift in the particles size distribution towards a larger diameter, however there was no major effect on the size reduction efficiency or throughput capacity [Trezek]. As determined in a separate study by Trezek et al. the same reduction in shaft speed from 1200 to 790 rpm resulted in up to a 26% reduction in power consumption on a per ton basis.

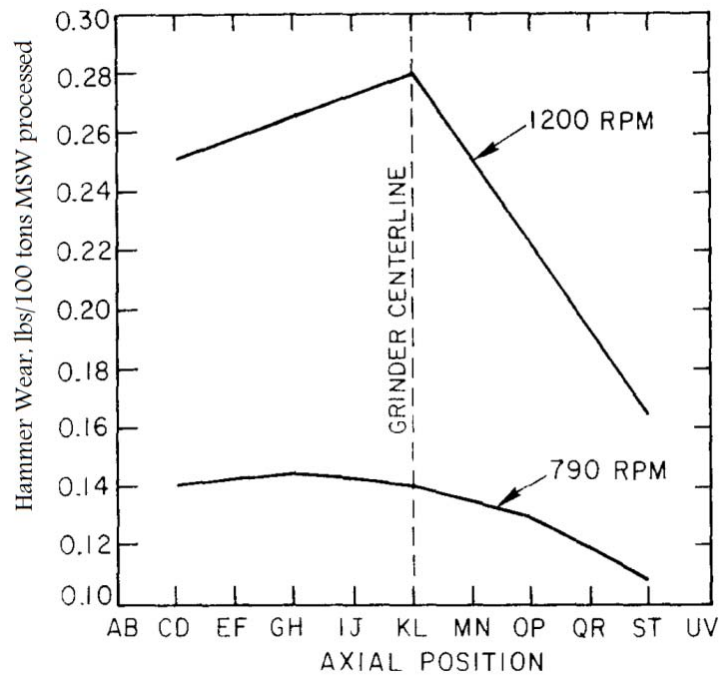


Figure 22: Hammer wear at low and high RPM [Trezek]

Table 6: Hammer material loss for HSLT grinders [Trezek]

	1200 RPM	790 RPM	% Decrease in Wear at Lower Speed
Full Set of Hard Faced Hammers (lb/ton)	0.068	0.047	31%
Full Set of Non-Hard Faced Hammers (lb/ton)	0.107	0.061	43%
Grate Bars (lb/ton)	0.053	0.034	36%

Operation and maintenance of size reduction equipment falls into several common categories both for HSLT and LSHT systems. Figure 23 shows the relative cost of some of the major accounting groups used in the management of such equipment, this data is specific to the Diamond Z SWG 1600, a hammermill specifically designed to process MSW. This piece of equipment is rated at a maximum of 300 tons per hour and is one of the largest available MSW hammermill grinders available. As evident from the figure, the major costs are fuel at 22%, conveyor replacement at 22%, tips and hammers at 4%, and labor at 8%. It may be surprising that conveyors make up such a large portion of the operation costs; however the conveyor receives a great deal of abuse as the processed MSW is ejected and causes abrasive forces on the conveyor surface. At nearly 1/4th of the total operation costs it is evident that there is room for improvement in this design, if integrated into a WTE plant there is a high priority to minimize conveying and handling of processed refuse.

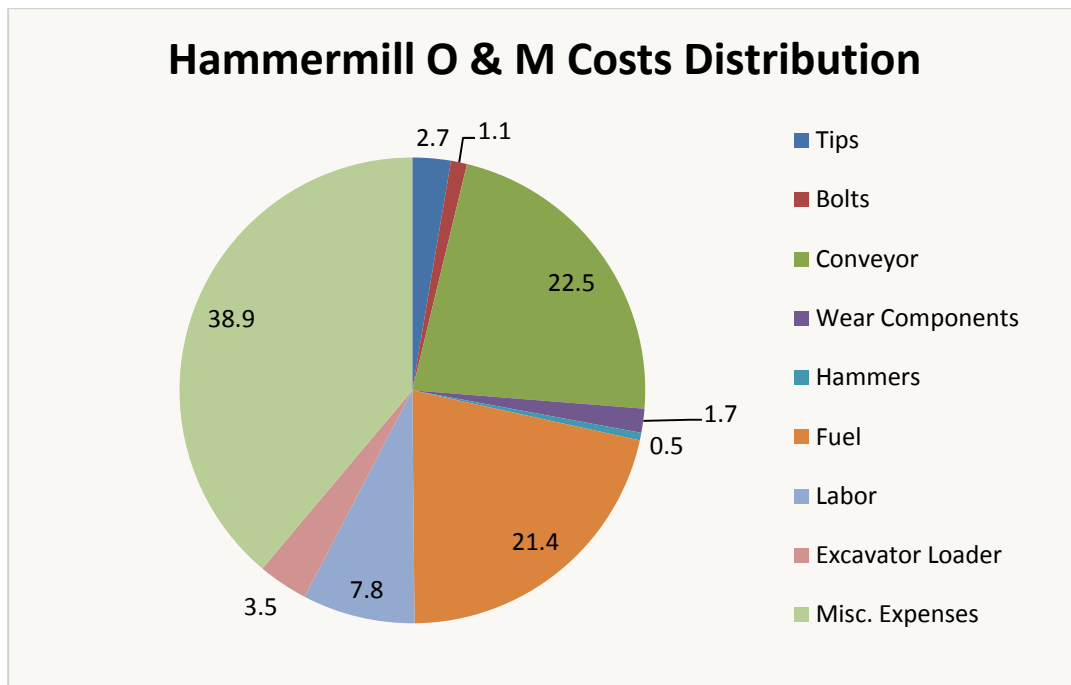


Figure 23: Typical Operation Costs for a Diamond Z SWG 1600 hammermill [Diamond Z Manufacturing]

Table 7 shows the actual breakdown of costs that were collected from customer surveyed information used for budgetary purposes; this particular data is associated with the SWG 1600 hammermill produced by Diamond Z Manufacturing. It is important to note that this operation cost does not include capital investment and includes labor costs for two operators at \$20.00 per hour. These estimates are derived from operational experience of this machine for use on a landfill face and such cannot be taken to represent what the cost may be when integrated into a WTE facility, however they should be used to understand the major contributions to O&M costs and get a sense of what MSW size comminution costs in functioning profitable operations. Based on discussions with several facilities a ballpark number for total size reduction expenses including capital costs is in the range of 8-10 dollars per ton MSW processed, of course this number is subject to change based on desired size reduction and material composition.

Table 7: Operating Expenses SWG 1600 [Diamond Z Manufacturing]

Operating Expenses: SWG 1600 Grinder	
	Cost (\$/ton)
Tips	0.12
Bolts	0.05
Conveyor	1.01
Wear Components	0.08
Hammers	0.02
Fuel	0.96
Labor	0.35
Excavator Loader	0.16
Misc. Expenses	1.74
Total	4.4827

3. Size Reduction Effects

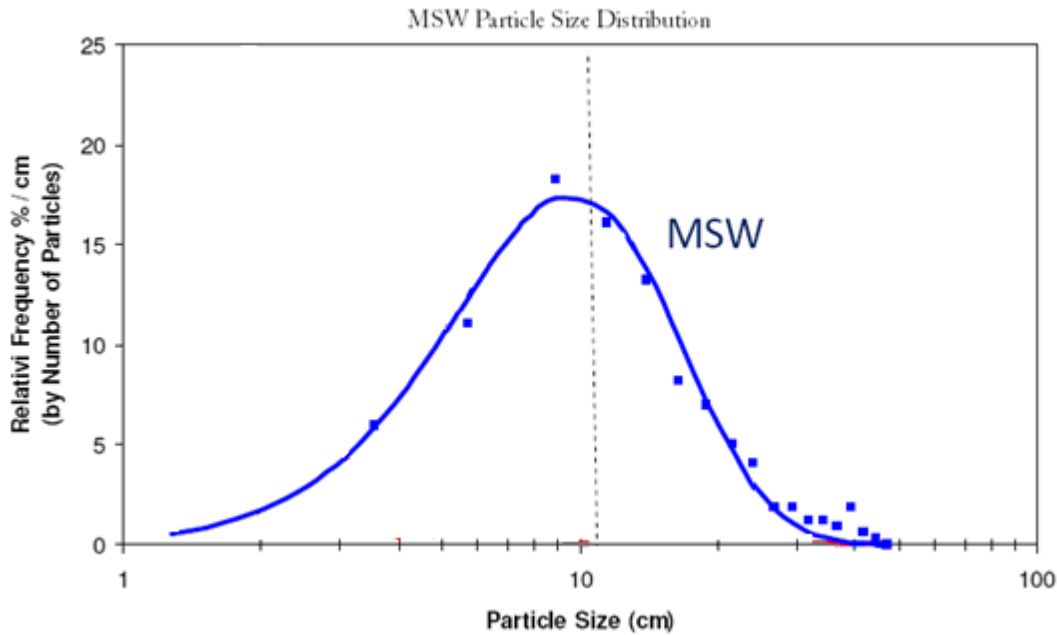


Figure 24: MSW Particle Size Distribution [Nakamura]

The figure above represents the distribution of raw MSW particle sizes for New York City and demonstrates well the mean particle size along with the wide range of particle found in MSW streams. The particle size of raw MSW ranges from 10 to 600 mm while hammermill grinded MSW ranges from less than 0.1 mm up to a maximum of 150 mm [Trezek]. The reason for this increase in particle size range is due to the shredding of soft materials and the shattering of brittle materials such as glass and ceramics when a HSLT device is used. Shredding is required in RDF type WTE facilities because different materials tend to break in to distinctive size ranges allowing for easier sorting and recovery. The overall effect of shredding tends to reduce particle size between 3 to 4 times and with an average size of 100 mm minus, depending on feed composition, rotor speed and sizing bars. Of course, decreasing the particle size of combustible materials increases the surface to volume ratio, thus allowing for quicker heat and mass transfer and combustion rates; therefore, the feed rate of shredded material per unit surface area of the grate should be greater than that with “as received” MSW.

MSW streams are inherently non-homogeneous leading to varying ranges of heating values. The effectiveness of combustion and pollution control can be improved if the heating value of a fuel is more uniform and known more precisely. The daily variability of raw MSW is 36 % and 37 % for moisture and ash, respectively. Between 70% and 80 % of the composition variability is within the same day. This indicates that the daily variability of MSW is mainly a function of and moisture content rather than combustible content and that the bulk combustible content of MSW is surprisingly homogenous. Much of the heterogeneous nature of MSW comes from that fact that the producer has bagged their waste. The bag to bag variability is high and if bags are not broken prior to incineration the composition mixing of the MSW stream will be relatively low. Shredding or grinding of MSW acts as both a bag breaker and a pre-mixer so the variability of processed MSW is much lower than that of as received bagged MSW.

Finally, the passage of primary air through a packed bed of shredded MSW should encounter a greater pressure drop, on the average, and thus the drying, volatilization, and combustion phenomena through the bed should be more intense and evenly distributed. The primary air can also be decreased due to the increased homogeneity of heating values and particle size coupled with improved reaction kinetics.

Combustions Benefits

Shin et al. have investigated both experimentally and theoretically the effect of particle size on combustion characteristics in a fixed bed via the study of wood particles. This study used cubic wood samples to simulate the combustion properties of MSW in a fixed bed. They showed that increasing the mean particle size from 10 to 30 mm resulted in a decrease in the flame propagation speed (FPS) from 0.8 cm/min to 0.6 cm/min indicating a combustion rate dependence on particle size. Figure 25 shows their results relating particle size to flame propagation speed; as the particle size increases, the air supply for stable combustion also increases due to the decrease in total surface area via larger particles, allowing for less convective heat loss. The dependence of the required air supply rate on particle size becomes more sensitive for smaller particle sizes due to the ability for convective cooling to quench the flame more easily. It should be further

investigated as to the extent of this phenomena and how it would affect the ability to control combustion in a MSW grate. The same beneficial effect of smaller particle size should occur for radiant heat transfer which also depends on particle surface area.

Reaction Kinetics

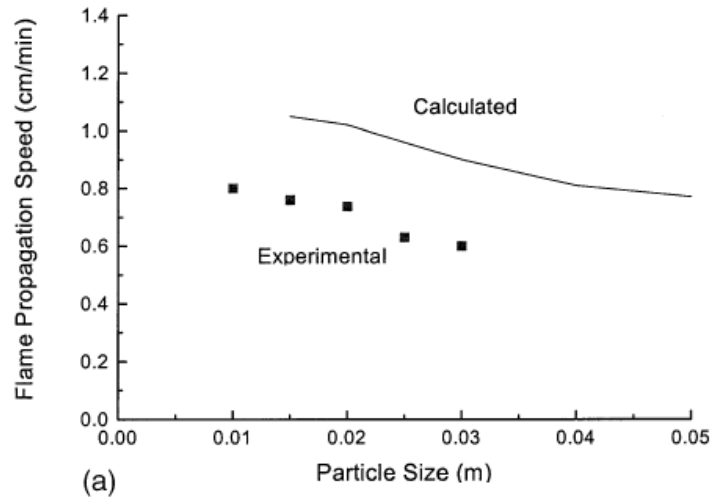


Figure 25: Effect of particle size on flame propagation speed [Shin].

Flame propagation speeds in a fixed bed can be used as an analog to the required residence time for particles in a moving grate reactor. Increasing the flame speed essentially increases rate at which MSW can be combusted and therefore controls the maximum refuse throughput while still achieving complete combustion. In a fixed bed FPS is controlled by particle size, heating value, air supply velocity, and the heat transfer environment. Decreasing the particle size improves the reaction kinetics as a result of a larger over all surface area, however the convective heat transfer away from the particles also increase which can lead to flame quenching or lowered (FPS). There exist a need for optimization between the increased combustion rate and the increased heat loss resulting from smaller particles sizes. However, as shown in Figure 26 smaller particles can achieve higher FPS at lower air supply rates. Lowering the air supply rate lowers the convective heat transfer by lowering Reynolds number and the convective heat transfer coefficient between the air and the particle. The range of stable combustion decreases

significantly with the decrease particle size as a result of these changes in the heat transfer environment.

These figures make apparent the difficulties that can be faced in designing a system meant to combust MSW particles of highly heterogeneous nature both in heating value and particle shape and size. Processing the MSW into a more homogenous stream allows the designer of the system to choose an air supply rate that reaches maximum flame propagation speeds with minimal excess supply air without quenching the flames of the smaller particles.

Primary Combustion Air Requirements

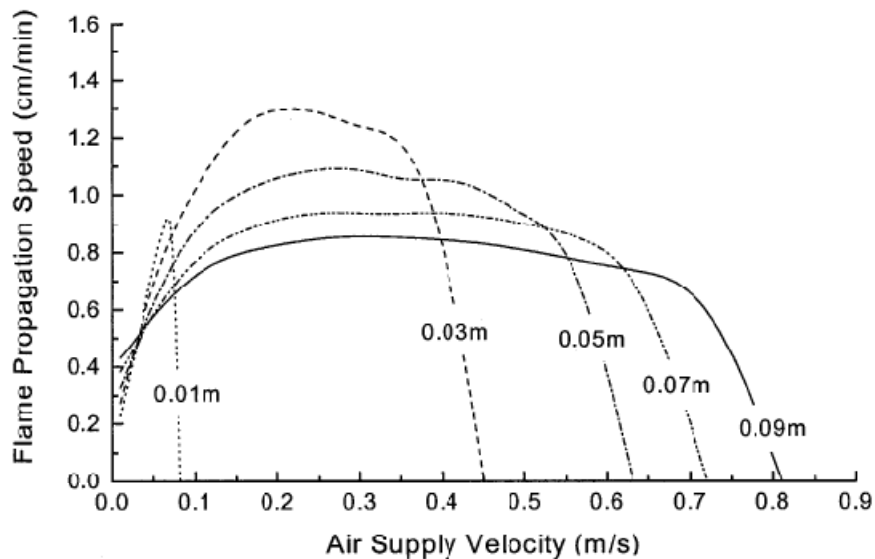


Figure 26: Effect of particle size on combustion air supply velocity [Shin]

Low excess air results in higher overall thermal efficiency, avoidance of hotspots in the furnace and boiler which accelerate the corrosion process causing increased downtime. Uniform temperature distribution will maximize heat transfer in the passes of the boiler. Pressure drop across a packed bed is a function of particle size, shape, roughness, void fraction and supply air velocity. In terms MSW incineration the mean particles size and air supply rate are the most realistically controllable parameters to influence pressure drop across the moving bed. A higher pressure drop through the

packed bed can lead to more vigorous particle and combustion gas mixing that can lead to higher combustion efficiency. Smaller more homogenous particles can pack more tightly and efficiently in a small space leading to a higher tortuosity and effectively greater turbulence. This higher pressure drop will require air supply equipment adjustments that are capable of producing a greater pressure differential at a smaller volumetric flow rate than current mass burn systems.

Ergun's Equation relates particle diameter and void fraction or bed porosity to friction factor and Reynolds number. The pressure drop in the laminar creeping regime is proportional to velocity and in the turbulent range proportional to the square of velocity. Such that in the turbulent regime small increase in velocity can produce large increases in pressure drop. Decreasing particle diameter and bed void fraction would both result in higher friction factors and thus increase turbulence and mixing. However it is necessary to keep in mind that over mixing of the particles and combustion air can actually be detrimental to combustion processes do to heat losses and result combustion efficiency losses.

Particle Mixing

The design of an efficient reactor of any kind relies on sufficient particle mixing to increase reaction kinetics and gas diffusion; this concept is congruent in the design WTE plants. Nakamura et al. have constructed a full scale model of a reverse acting grate designed to study flow, mixing and size segregation of MSW in a moving bed reactor. This study has resulted in interesting and applicable information regarding the size reduction and homogenization of MSW. As shown in Figure 27 the mixing diffusion coefficient increases significantly with smaller particles sizes at medium to high grate reciprocation speeds. The idea of comminution aims at increasing the combustion efficiency as well as lowering the size necessary to thermally process MSW with the overall effect of lowering capital investments.

The particle size range of MSW processed in high speed devices actually increases due to the tendency to smash or shatter brittle materials into small fines. This method of size reduction could potentially lead to a larger range of mixing coefficients and actually be detrimental towards the combustion process. MSW processed through a

slow speed shear shredder has a lower potential for this wider range of particle sizes as a result of minimal impact forces involved in the process.

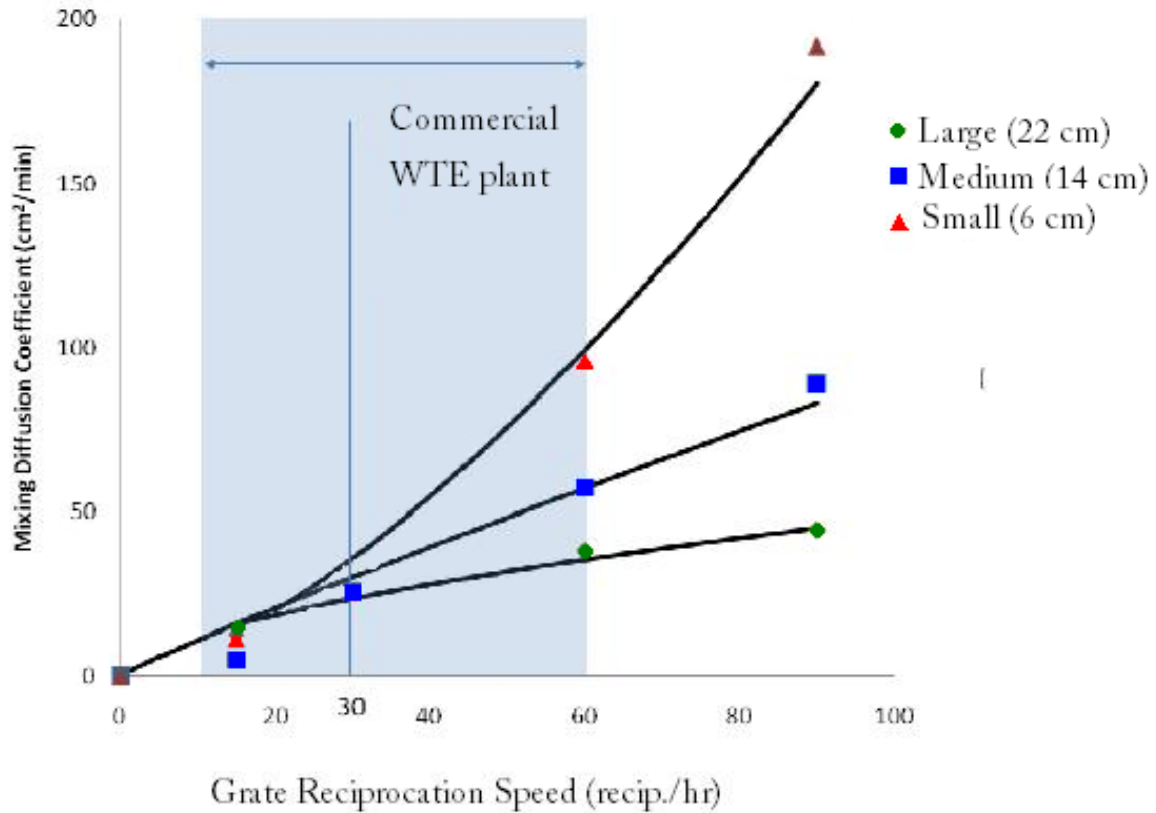


Figure 27: Mixing coefficient for several particles sizes [Nakamura]

It is seen in Figure 28 that as the intensity of the bed mixing increases, there is a sharp rise in the bed combustion efficiency followed by a slight drop off when the mixing intensity is further increased. This drop off could be a result of increased heat loss due to convective heat transfer. Yang et al have indicated that increasing the mixing coefficient leads to a slight delay in the bed ignition but greatly enhances the combustion processes during the primary combustion period in the bed and that medium-level mixing results in the lowest CO emission at the furnace exit and the highest combustion efficiency in the bed as can be seen in Figure 28. In this context bed combustion efficiency is defined below as:

$$\text{Bed Combustion Efficiency} = 100\% \left(1 - \frac{\text{unreleased volatiles} + \text{residual carbon in ash}}{\text{original volatiles and carbon}} \right)$$

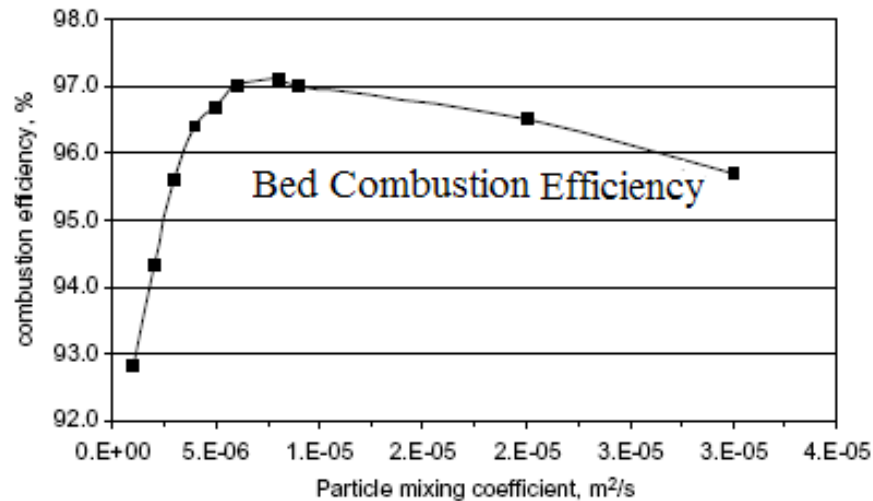


Figure 28: Bed combustion efficiency as function of particle mixing [Yang]

Retention time

Although this study only shows retention times for raw MSW it is still valuable to note the large variation in retention time as a function of particle diameter. In most cases of combustion theory larger particles will require a longer duration in the moving bed to be fully combusted and converted into ash, however as shown below the larger particles tend to have shorter retention times leading to incomplete combustion and larger ash particles. The major benefit that can be seen from shredding MSW for combustion in terms of residence times is a result of the increase regularity in particle size and shape. A more heterogeneous fuel such as raw MSW will result in a wide range of particle sizes that will require varied retention times as well as varied quantities of excess air, as a result it is necessary to design the system to meet the need of the most demanding particles that require long residence times and high excess primary air in order to achieve maximum conversion and energy recovery.

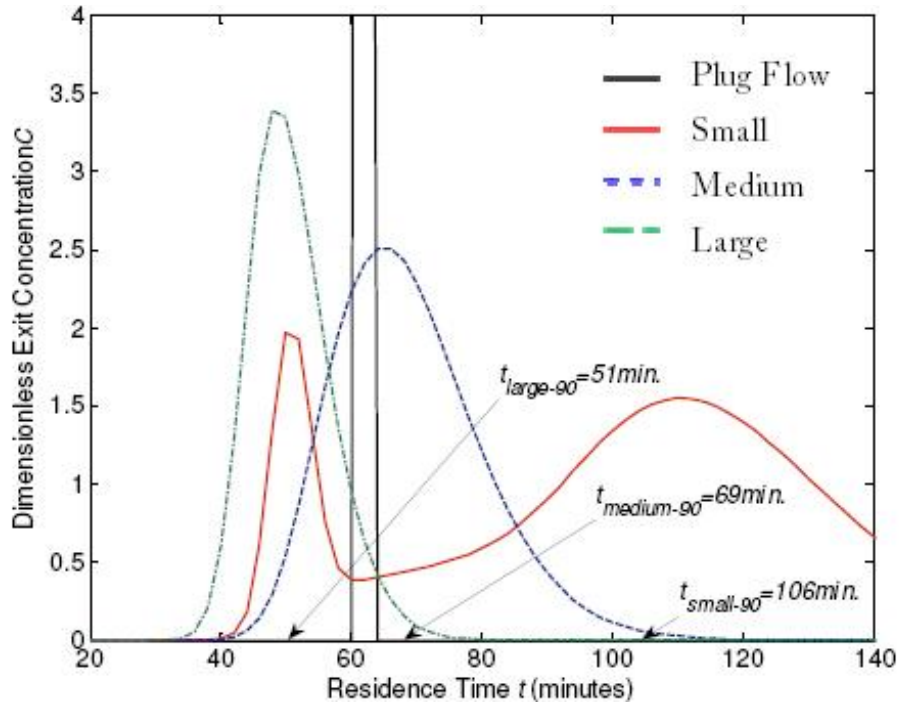


Figure 29: Residence time for several particle sizes [Nakamura]

Due to the Brazil Nut Effect (BNE) the larger particles rise to the top of the bed while the smaller particles migrate to the bottom where the reciprocating grate can push them back up towards the inlet of the grate. The larger particles will tend to roll down the top surface of the bed and thus have shorter residence times. With a more even distribution of particle sizes the reciprocation speed and throughput rate can be fine tuned for more complete combustion of all ranges of particles sizes. As shown in Figure 29 small particles show a dual peak distribution in residence times that span the range of residence times for all particles sizes. Producing a more homogenous size distribution of MSW via shredding could result in a smaller and more consistent range of residence times allowing for more accurate design for effective combustion and heat recovery.

Decreasing the mean particle diameter combined with a smaller range of sizes will produce faster combustion rates and allow for a shorter required residence time for complete conversion. Smaller variety in particle size will lessen the BNE and minimize the amount of MSW that makes its way across the bed before it is able to be fully combusted.

Landfilling Benefits

Density

The MSW capacity of a sanitary landfill is governed by the available airspace determined by zoning restrictions and the in place density of said refuse. It is common practice in landfilling operations to use compactors to increase the density and stability of the refuse face. Several landfills operators have taken advantage of further extending the operating life of their landfills by the use of shredders. The operator of the Albany city landfill, Joe Giebelhaus, has been shredding MSW using a high speed hammermill for the past several years, and has successfully extended the operating life of the landfill by over one and a half years.

It has been proven to be economically feasible and profitable to operate with a shredder on site. The landfill receives monthly revenues of \$1,000,000 from tipping fees. A volume reduction of 30 % in the landfill density can extend the expected the life of MSW management by 1 month for every 3 months of operating with the shredder, easily generating enough revenue to overcome initial capital costs. In a separate study of milled refuse in Madison Wisconsin, Reinhardt et al. produced similar results regarding density, with a 33 % increase in effective density on a wet basis and a 22 % increase on a dry basis. An additional benefit of increased MSW density is that a greater tonnage can be deposited each day, between the required daily applications of Daily Cover (e.g. 15 cm of soil is required by EPA).

Table 8: Tokoma Farms Road Landfill in-place density for shredded and non-shredded MSW [Jones].

	Test Period	In-place Density (kg/m³)	% Increase
Shredded MSW	7/20/00 - 08/07/00	516.38	28.69
	08/07/00 - 09/01/00	534.07	15.96
	07/20/00 - 09/01/00	529.21	16.67
Non-Shredded MSW	07/20/00 - 08/07/00	401.24	-
	09/02/00 - 09/25/00	460.55	-
	09/25/00 - 10/12/00	475.11	-
	07/20/00 - 10/12/00	453.61	-
	Average Increase	-	-

The Tokoma Farms Road Landfill in south Florida has been shredding MSW since it started receiving waste in June of 1999. Belcorp Inc. performs the shredding using a high speed low torque hammermill shredder with the goal of extending the life of the landfill. Belcorp contracted Jones, Edmunds & Associates, Inc. (JEA) to perform a year long investigation on the effect shredding has on in-place density of MSW in a landfill. In-place density is defined as the relationship between the solid waste tonnages to the airspace volume used for a specific time period. The investigation has shown that shredding MSW can lead to an increase of nearly 30 % in the in-place density, with an average improvement of 20%.



Figure 30: SWG 1600 hammermill used at Albany city landfill.

Figure 30 is a photograph of the solid waste grinder used at the Albany city landfill. The SWG 1600 is fully on-site mobile, track mounted, and self-propelled, it can be driven on the face of the landfill for direct depositing of shredded refuse in the landfill cell. This machine is one of the larger available hammermills and can reach a maximum throughput of MSW of 300 tons per hour powered by a 1650 Hp diesel motor. The

operation of the SWG 1600 requires two personnel, one to operate the actual machine and one to operate the front end loader that places the raw MSW in the receiving tub.

Landfill Gas Production

The benefits of shredding are not limited to volume reduction. As seen with the case of increased rate of reactions in the combustion processes, the decomposition rate of waste in landfills is increased with shredded material. The increased rate of decomposition generates larger quantities of methane on an annual basis. The net production of landfill gas will remain the same; however the time frame for collection is decreased significantly due to decreased particle size. Landfill gas collection systems must be employed to both recover energy from the waste but also mitigate green house gas emission (GHG). The landfill gas production rate also benefits from the more uniform flow of leechate throughout the refuse; the more evenly packed waste eliminates bridging that causes leechate to flow through channels. More densely compacted MSW can achieve the necessary saturation to enter the anaerobic zone more readily with less of a need for leechate recirculation. This leads not only to more rapid decomposition but more uniform decomposition leading to a LFG collection system with more simple controls and regulation.

Landfill gas is a combination of methane and carbon dioxide, in many cases a landfill will collect this gas and simply flare the combustible mixture to avoid added GHG emissions. The problem with landfill gas is that methane is a much stronger greenhouse gas than carbon dioxide and thus it is required that landfills be cognizant of this and either convert the methane to CO₂ by flaring or running a LFG turbine which can actually extract useful energy from this LFG. A recent study by Sponza et al has focused on the effects that shredding MSW has on anaerobic activity of the refuse in landfills. The results of this study reported that the methane percentages of the control, compacted and shredded waste were 36%, 46% and 60% respectively. This is promising result for sanitary landfills that aim to collect LFG for energy production; the increase ratio of methane to CO₂ gives the mixture a higher heating value and allows for it to burn cleaner in a gas turbine. It was also shown that the initial methane production for the shredded

refuse was much higher than both the control and the compacted simulated landfill reactors. Because the actual composition of the refuse is unchanged via compaction and shredding the eventual methane production should be similar in the duration of degradation, however, the increased production rate and higher quality of LFG allows for easier collection and means that the landfill can be capped with less concerns for continued bio-degradation once the majority of methane has been produced.

Table 9: Comparison of characteristics of simulated anaerobic landfilling [Sponza]

	Initial			Final		
	Control	Compacted	Shredded	Control	Compacted	Shredded
Water content (%)	85	85	85	86	89	88
Organic matter (%) (in DS)	91	91	91	67	70	63
% C (in DS)	51	50.5	50.5	38	39	35
TN (mg/g) (in waste)	8.5	8	8	0.5	0.3	0.3
TP (mg/g) (in waste)	6.7	6.5	6.5	0.9	0.3	0.4
NH ₄ -N (mg/g) (in waste)	0.57	0.56	0.56	0.14	0.3	0.1
Waste quantity (g)	1000	1400	1000	299	589	285

The table above gives a summary of the characteristics of the shredded and compacted waste used in the simulated anaerobic landfill reactors conducted by Sponza et al. These results suggest that shredded waste degrades faster and more completely than compacted or raw ‘as received’ waste as evidenced by the lower organic content as well as the lower waste quantity at the completion of the test period.

Transportation

The benefits of increased density go beyond just improved storage capacity; a higher MSW density can also save money in the transportation aspect of MSW management. As much as 70% of the cost of managing one ton of municipal solid wastes is due to collection and transportation. When it is necessary to transport MSW over long distances, either to landfills or WTE facilities, it is necessary for the small collection trucks usually 3-4 tons of MSW to unload at a Waste Transfer Stations (WTS) where front end loaders load the long distance trucks, or rail cars that will transport the wastes to their final destination with capacities of 20 tons for trucks and even higher for rail cars.

Transfer stations are generally equipped with one or more waste compacting device setup to receive waste. The concept behind a transfer station is that higher capacity trailers are used to make the long distant trips between waste generation and disposal sites. This allows for fewer trips and a smaller crew resulting in decreased operation costs. Compactors are capable of increasing the in-transit density of MSW by a factor of 2 to 3 compared to loose MSW resulting in fewer trips.

It is clear that compacted raw MSW can achieve a higher density than non-compacted shredded MSW. However shredded MSW can compress further than unprocessed waste due to the increased packing efficiency that is possible with smaller particles size. The more uniform shredded MSW results in less wear and tear on the compactor than as received MSW. In the event that a landfill or WTE plant decides that it will benefit from shredding MSW, it could be beneficial to do this at the transfer station and thus capitalize twice on the increased density of shredded MSW.

4. Size Reduction Integration

Potential Location

When designing a shredding system it is important to be aware of the relative elevations that the raw refuse will enter the size reduction hopper and that of the point at which they exit the machine. The heterogeneous nature of MSW can bring about some challenges in conveyor transportation. If the material input and output points are on essentially the same grade level the input conveyor must be inclined within the constraints of available room, as well the horizontal length of the conveyor belt is strictly determined by the required elevation gain as a function of incline angle. The input hopper can be at an elevation of between 15 and 20 feet above the base of the machine resulting in clever designs to minimize conveyor use. It is also necessary to have sufficient space below the exit point that can allow for a second conveyor to transport the waste to either a storage pit or the boiler hopper.

The pit must be designed to meet strict safety and hygienic standards. If waste sits in the pit for more than three days it can reach temperatures between 90 and 100 C

which can lead to fire hazards. As well methane gas production can be an issue. It will be necessary to look into how the shredding of MSW in a pit will increase the rate of methane production in the short time it sits in the pit. As discussed above shredded waste enters the anaerobic methane producing state quicker than either compacted or as received waste, which can lead to increased occurrences of pit fires if not addressed properly.

Shredder Location and Capacity

The integration of shredding equipment into the traditional layout of a WTE facility is a multifaceted issue. It is necessary to determine if the majority of waste will be stored as raw 'as received' MSW or if it is more efficient to store primarily size reduced refuse. The location of the shredder will depend on which storage technique is adopted and at what rate the MSW will be shredded. Because WTE plants run at load factors of 80% or higher it is required that sufficient fuel be available to feed the grate and boiler. This is complicated by the fact that trash is typically only delivered 8-10 hours of the day and is not delivered on weekends or holidays. The standard operation requires that facilities have at least 3 days of storage capacity to ensure smooth and continuous operation of the power plant.

There are two basic schematics that can be implemented for pre-shredding integration. Case 1 as illustrated below is designed such that primarily processed MSW is stored in the pit, in this case the tipping floor can be used as temporary storage as the MSW is delivered. Once the visual picking has occurred the MSW is sent directly to the shredder where it is size reduced and dumped or conveyed into a storage pit designed specifically for processed MSW. This system must be capable of processing the MSW at the rate it is received, which in most cases is roughly three times the average boiler feed rate.

Case 1: Shred MSW at rate it is received with crane and claw

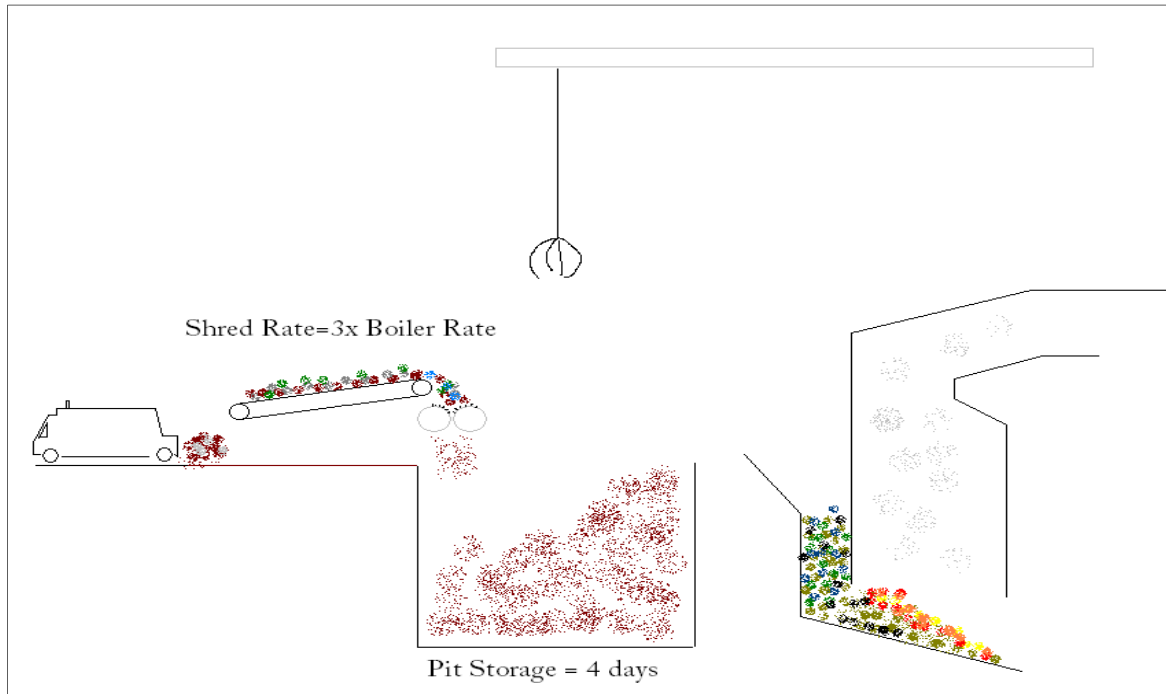


Figure 31: Processed refuse pit storage with claw

Once the MSW is processed and stored in the pit it then needs to be transported to the hopper and eventually onto the moving grate. The current method of transporting MSW from pit to hopper is via use of a large crane claw, however it has been suggested that these claws will not be effective in picking up the smaller processed MSW. This claw and crane system is an expensive portion of the MSW handling and feed system and it is proposed that it could be replaced with a conveyor system for transporting size reduced MSW. Raw MSW frequently encounters issues when transported via conveyor, however the conveying of more homogenous shredded MSW is a common practice in MRF and RDF plants. The large elevation changes that the MSW undergoes during this transportation is quite important and will be one of the key constraining factors on the size and cost of such a handling system. Excessive handling or overly complex transport systems can result in prohibitive cost issues that will not allow for an economical benefit to be seen from size reduction of MSW for combustion disposal.

Case 1b: Shred MSW at rate it is received with conveyer

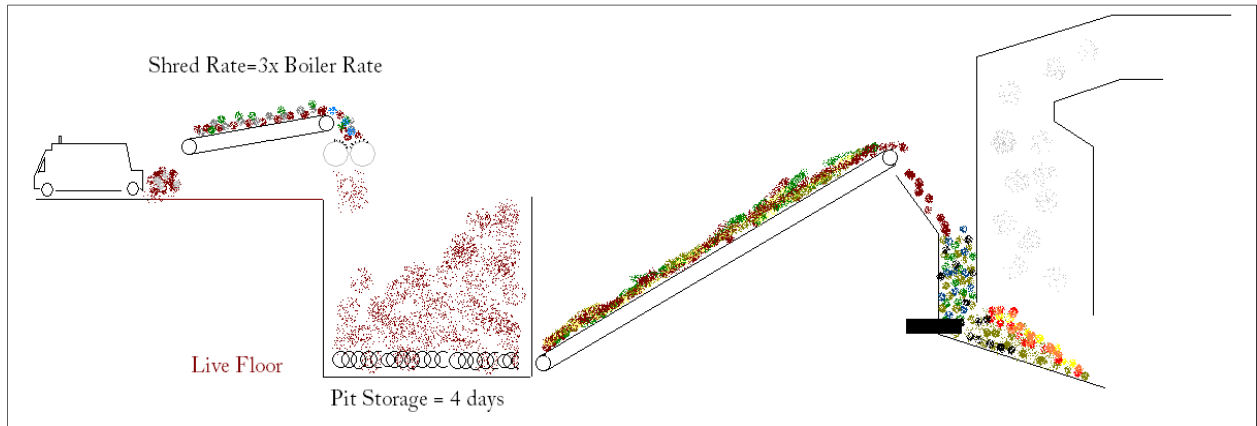


Figure 32: Processed refuse pit storage with conveyor

It is clear that if a system is designed to process the MSW at the rate it is delivered to the tipping floor the system will incur significantly greater capital investment compared to a system that shreds continuously rather than only during waste delivery. The benefits of Case 1 is that only one storage pit is required and this pit can potentially be designed with a smaller footprint and volume. The key to the smaller pit is in the increased density achievable with the processed MSW, however uncompact processed MSW can actually decrease in density due to a fluffing phenomena. This fluffing issue could be addressed by dropping the MSW from a significant height from the shredder to the pit which will bring about additional issues in conveyor length operating space.

Case 2: Isolated shredding of MSW at boiler feed rate.

The second method of integrating the shredding system into incineration plants is shown below. In case 2 MSW is stored in the main pit as raw MSW and is fed to the shredder at the mass flow rate that will be fed into the boiler. In this setup there is still a need for a small secondary pit to act as a buffer to ensure there is sufficient fuel for the boiler, however as shown in the lower figure the hopper itself can act as this buffer. The major reason for the second conveyor from the small pit to the hopper is to act as a safety feature in the event of explosions or fires in the grinder. As shown in the case 2b the shredder feeds directly into the hopper, which makes the most logical and economical

sense if it were possible to eliminate the possibility for explosions. However it has not yet been shown that shredder explosions can be eliminated and it will be necessary to take precautionary measures, such as physical shielding and special isolation from the boiler.

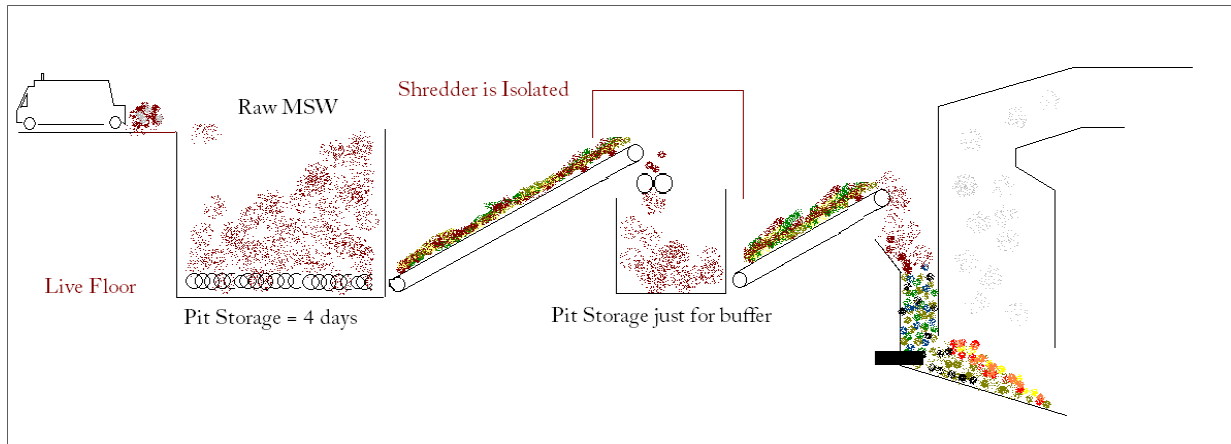


Figure 33: Raw MSW pit storage isolated shredder

The ideal placement for smooth integration and operation is shown below in Case 2b. In this case MSW handling is minimized and processed refuse can be directly deposited into the hopper without the need for a crane and claw system. Again it is important to recognize the proximity of the shredder to the boiler. This can be an unsettling placement for some plant operators due to the risk of bringing down the entire boiler the event of an explosion or blowout.

Case 2b: Shred MSW at boiler hopper and boiler feed rate.

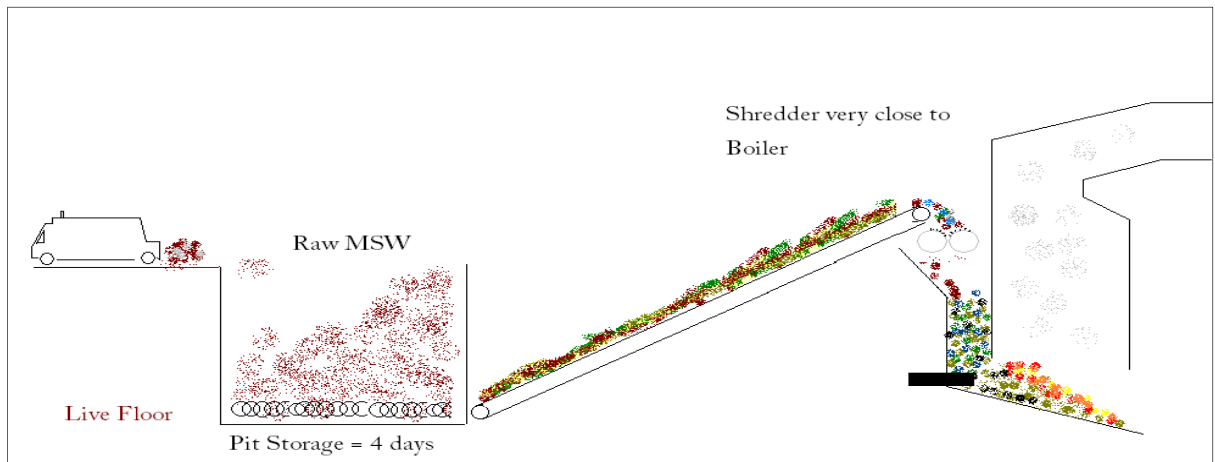


Figure 34: Raw refuse pit storage

5. Previous Investigations of MSW shredding

Shredding MSW for Mass Burn WTE facilities has been experimented with in the past in more of a trial and error method rather than an a true engineering approach. The development of Waste-to-Energy plants has followed this method of extracting successful design components of previous plants and making small adjustments based on experience and observation. This form of WTE maturity has had a negative influence on the idea of shredding MSW for Mass Burn disposal. The complexity of combustion kinetics and fluid dynamics involved on even heterogeneous particles in a fixed bed has limited the ability of engineers to accurately simulate or model MSW combustion and much of the development in boiler and grate design has been highly empirical. In the past 35 years pre-shredding of MSW has been juggled around and discussed as a possible way to improve combustion efficiency in WTE plants as it has been so successfully done in powderized coal fire power plants.

Hempstead WTE facility

During the mid 1980s a small waste incinerator operation outside of Hempstead, New York began shredding MSW in a hammermill grinder to homogenize the fuel for easier handling in the incinerator. The results of this shredding were positive and proved to be beneficial in the combustion process. This operation, however, was short lived due to odor complaints of nearby residents. The original problem that the operator faced was high occurrence of fires in the hammermill baffle during grinding. The benefits of shredding were favorable enough that it was decided that the waste should be saturated with water during the shredding process to avoid the fires and then air dried prior to incineration. This wetting process was carried out for a short duration until the odor produced from the damp waste became strong enough to bring about complaints that eventually led to the abandonment of the entire shredding effort. [Davis]

Town of Merrick Household Garbage and Recycling Collection

Mr. Roy Davis manager of the materials recovery department in Merrick, NY has been operating a SSI PR600 shredder for over 5 years to process bulky waste. This bulky waste includes mattress, furniture and other large items that are normally not accepted at WTE plants and are diverted to the nearest or cheapest landfill. Mr. Davis realized that he was frequently shipping large quantities of combustible material to an out of state landfill at high transportation and tipping costs. In 2002 Mr. Davis purchased the Pri-Max shredder shown below for roughly \$750,000 that is used to process up to 150 tons per hour of bulky MSW. This situation is successful due to the vicinity of the Covanta Hempstead MSW incineration plant located only 8 miles down the road, allowing Mr. Davis to send the newly size reduced bulky material to a close location at a cheaper costs than the out of state landfill. The tipping fees for the bulky waste dropped at Mr. Davis facility start at \$92 and increase depending on quantity and contractual agreements, which is more than enough to cover the operating and maintenance costs of the shredder, transportation to the WTE plant and the WTE tipping fees.



Figure 35: Pri-Max 6000 Shear Shredder

This integration of material recovery/transfer stations with the incineration plant demonstrates that shredding is indeed profitable for certain applications. The shredder used in the town of Merrick is a low speed, high torque device as shown in Figure 35. These high torques are excellent at processing materials that just would not make it through a hammermill grinder, such as mattresses and other elastic materials. The

problems that hammermills encounter with mattresses are twofold; firstly they have the ability to absorb the hammers energy while undergoing only deformation and not size reduction. Secondly the bed springs found in most mattresses tend to wrap around the high speed shaft which stops the rotation of the hammer due to its inability to overcome the torque. According to Mr. Davis, mattresses are very common in the bulky waste he receives. Unfortunately WTE plants tend to reject these items due to issues they cause on the grate, yet the synthetic material used in mattress has a very high heating value and once processed in the shredder makes a favorable fuel that WTE facilities are happy to accept.

In the event that a community produces only small amounts of bulky waste it may be beneficial for a WTE plant to have only one of the multiple boiler lines equipped with shredding capabilities. This would allow a higher landfill diversion rate since many bulky items that are not accepted at WTE plants are sent directly to the landfill at a high transportation cost. Individual communities and WTE facilities considering pre-shredding will need to evaluate their typical MSW composition in order to determine if shredding is a viable option for them.

6. Discussion

Pre-shredding MSW for processing in a moving grate combustion facility results in several advantages over standard Mass Burn operations. As in all aspects of waste management, local economics and regulatory issues determine what method or system is best suited for individual communities. The implementation of size reduction systems into WTE plants has not yet proven to be a broadly profitable investment for all waste management operations. Choosing to upgrade an existing plant or designing a new facility to include shredding must be evaluated on a case by case basis to determine if the benefits are worth the additional capital investment and operating costs.

In estimating the cost that would be incurred by adding a LSHT device to a small 100,000 tons/y WTE facility, similar to the Athens plant proposal discussed previously, it is assumed that the initial investment for the Mass Burn plant is \$80 million. This size plant would process on average 330 tons/ day, i.e. substantially less than 50 tons/hour, thus requiring a single small shear shredder. The capital investment for this size of

shredder would range between \$500,000 and \$2,000,000 depending on the complexity of the handling system, or in terms of percentages about .5% to 3% above the mass burn plant alone. The per ton cost of shredding would be between \$8-\$10 with about half going to capital investment and half being used for O&M costs. Estimating the O&M cost of the above discussed plant at \$30/ton the additional maintenance costs would increase by nearly 13%. This may seem like a large increase but it should be kept in mind that by far the majority of the cost of operating a WTE facility is dedicated to paying back initial capital investment, which increases by less than 2% with the addition of shredding equipment.

At an average electrical production rate of 650 kWh per ton of MSW, the required 3-11 kWh/ton for LSHT shredding devices and even the higher 6-26 kWh/ton for HSLT grinders is less than 2% of that generated from the combustion of MSW and should be more than accounted for by the improved combustion efficiency of the plant. The major factor in determining the feasibility of pre-shredding MSW would be the decrease in capital and operation costs as a result of the enhanced combustion and APC benefits. In general, the addition of pre-shredding capabilities will likely be more successful in the design of new plants where their integration can be streamlined into the system rather than retrofitted facilities. It is recommended that pilot scale shredding systems be experimented with in the design of the next generation WTE plants.

The broad-spectrum size and material composition of an MSW stream is a critically valuable source of information when size reduction is being considered. There are key issues that should be assessed in the decision process for implementing shredding technologies. Firstly, MSW streams with consistently large quantities of bulky waste will be more likely to benefit from size reduction. Bulky waste rejected from a WTE plant must be transported to a landfill resulting in excess handling and added costs to the waste management provider. The town of Merrick, NY, cited in this study, is a good example of how bulky waste has been diverted from landfilling to incineration with the use of a LSHT shear shredder.

Other waste stream characteristics such as high metal content may limit the feasibility of pre-shredding. Shredding or grinding of construction and demolition waste can be harsh on the cutting surfaces thus leading to higher wear, increased operating costs, and

decreased productivity. The higher the metal and non-combustible content in the waste the less logical would be to invest in shredding technologies, due to the added energy required in processing these tough non-combustible materials.

The integration of energy and material recovery in the waste management field is causing composition changes in MSW stream that eventually ends up on the tipping floor of a combustion plant. The increased recycling rate of comingled materials such as paper fiber, metals, and glass results in a higher organic fraction in waste that is processed in an incinerator. This has varying effects on the combustion properties and bulk heating value of the refuse, the removal of cans and glass bottles acts to increase the HHV, however lower paper fiber volume leads to a significant drop in HHV. This is another aspect that must be evaluated when proposing size reduction for WTE operations.

7. Conclusions

Energy and material recovery from municipal solid wastes, via waste-to-energy technologies, is an essential component of integrated waste management and has the potential to facilitate the transition from landfilling towards a more sustainable waste management practice that emulates the ecological synchronization observed in nature. The long term goal for MSW management is not to achieve 100% disposal via Waste-to-Energy, but rather to effect a net improvement in resource conservation and waste minimization, thus complementing recycling. Combustion or gasification, with energy recovery, of MSW can allow landfilling to be phased out. In order for this transition to occur, in the United States, the public must accept, and the government must support, the construction of new WTE plants on a large scale.

Shredding of MSW, prior to combustion on a moving grate, has the potential to improve operating characteristics and lower capital investments of new WTE facilities. However, one of the more prominent issues associated with mass burn plants is the highly heterogeneous nature of MSW as it is received on the tipping floor. Due to the varying size and composition of MSW as it enters the boiler, many parameters are operating outside of the optimum range or require extra care and maintenance to insure optimum performance. These include uniform distribution of primary air, bed mixing, fuel loading rate, effluent ash and gas composition, and excessive thermal wear on the

grate and waterwall. All of these factors play a role in the overall performance of a WTE plant and can be improved with the integration of size reduction and homogenization of the fuel.

Reducing the mean particle size of the MSW stream improves reaction kinetics and flame propagation speed as a result of the higher available surface area. This has the further benefit of lowering the amount of required combustion air to meet the desired combustion rate. Smaller particles also facilitate bed mixing and reduce the necessary retention time for complete combustion.

This study has shown that shredding the MSW in a LSHT device results in a decreased variance of particle size, as compared to raw MSW or MSW ground by means of HSLT hammermills. Reducing the particle size distribution allows for a more controlled combustion process that will minimize incomplete combustion. Also, reducing excess air flow will lower the amount of flue gases that need to be treated and result in lower capital and operating costs of the Air Pollution Control system. Finally, the fuel throughput per unit of grate surface area can be increased, as a result of shorter retention time and increased combustion rate, which will increase the plant capacity and lead to lower capital costs per ton of MSW processed.

MSW comminution devices have undergone significant development over the past several decades and the trend has been to move away from high speed hammermill shredders to low speed shearing devices. This transition has benefits for the integration of shredding into WTE designs. The LSHT machines are safer, more efficient and more compact than equivalent capacity HSLT grinders. Additionally shear shredders produce a more constant size distribution owing to the fact that the shearing mechanism is less sensitive to material composition. However, low speed devices have certain drawbacks associated with them. Primarily their novelty and lack of maturity in the field of MSW comminution is detrimental to their popularity. Also, the throughput capacities of low rpm shredders are typically lower than available hammermills and the requirement of multiple machines operating in parallel could have a hindering affect on their integration into the design of new WTE facilities.

Increased efficiency and performance characteristics favor LSHT shear shredders over older hammermill technology. However, because these high-torque shredders have

not yet been tested and documented on a large scale, to the same extent as hammermills, more research, pilot and prototype testing are needed. Also, due to the lower capacity of LSHT shredders, an array of several lines in parallel may be necessary to handle tonnages typical of landfills and WTE facilities. The costs of such machines play a large role in which type of shredder a facility decides to use. If the feed is heavily laden with C & D material with a higher metal and concrete fraction it may make more sense to use a high speed grinder that excels with brittle materials; or to forego size reduction all together. The auto-reversing option available with some LSHT shredders could become a nuisance if the feed is heavily burdened with non-shreddable items, thus causing the machine to be reversing rotation frequently.

With regard to shredding MSW prior to landfilling, this has been demonstrated to be a profitable investment using HSLT shredders, by increasing the bulk density of MSW and thus the landfill capacity. On the other hand, RDF plants have shown that shredding and sorting MSW can be a costly process. Therefore, WTE operators in general prefer mass burn to RDF plants. However, application of the LSHT shredders should lead to a decrease in operating problems and costs associated with shredding equipment. The improvement of shredding technology of the high torque devices may prove to be what is needed to make shredding MSW for Waste-to-Energy a common practice. By using a LSHT shredder as opposed to HSLT, the floor area required for shredding can be decreased appreciably, thus lowering initial capital investment. Higher efficiencies and lower operating costs may justify use of such devices. The limiting factor in the debate between LSHT and HSLT shredders may end up being initial capital investment for the high torque shredders because, at this time, more machines will be necessary to process the same quantity as a single hammermill. Of course, there is no technical reason why larger size LSHT shredders cannot be scaled up further, if there is industrial demand for such shredders by the WTE industry.

Waste incineration in the U.S. has had appreciable opposition in the past decades and this has limited its use as a sustainable form of solid waste management. With the trend in Europe of increased investment in new WTE plants, it is probable that the U.S. will follow suit and begin the phasing out of landfills. Pre-shredding of MSW can have a beneficial effect on the WTE industry, provided that the shredder system is designed

correctly and effort is made to simplify as much as possible the materials handling systems associated with the shredding operation.

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