PART I. THERMAL BREAKDOWN CHARACTERISTICS OF MUNICIPAL SOLID WASTE COMPONENTS IN VARYING OXYGEN ENVIRONMENTS

AND

PART II. MUNICIPAL SOLID WASTE MANAGEMENT IN CHINA

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Thermal Breakdown Characteristics of Municipal Solid Waste Components in Varying Oxygen Environments and Municipal Solid Waste Management in China

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EXECUTIVE SUMMARY

This thesis was prepared in two sections, the first being a write up and analysis of over one hundred thermo-gravimetric experiments carried out during 2004-5 and aimed at increasing the understanding of the thermal breakdown of municipal solid waste (MSW) components, the second being a more general literature search investigating the state of the MSW management in China. Due to the increasing use of and investment in waste-to-energy technologies in Asia, these two realms of knowledge are inextricably linked. Below is a brief summary of the two parts of this thesis; a more detailed summary is provided in the main text.

Section I: Thermal Breakdown Characteristics of Municipal Solid Waste Components in Varying Oxygen Environments

The effect of oxygen concentration on the volatilization rate and combustion behavior of various components of MSW was investigated by means of thermo-gravimetric analysis (TGA). Eight characteristic components of MSW were examined including paper, cardboard, wood, textile, rubber, polyethylene teraphthalate (PETE), low density polyethylene (LDPE) and food waste. Samples of these materials were heated in a Netzsch TGA apparatus to 1000 degrees Celsius at a rate of 20 degrees Kelvin per minute under oxygen gas concentrations of 0, 10, 20, 30, 50, 90 and 100 percent by volume. Nitrogen was used as the balance gas.

Experimental results showed three or four distinct stages of thermal breakdown with onset temperature and rate of decay varying greatly between the different components. A four phase thermal breakdown model is put forward to analyze the data and make suggestions on the improved design of WTE facilities. The mass decay associated with transport inhibited volatilization at the gas-solid interface was identified as a key factor in determining the level of un-combusted organic residue, such as that found in incinerator bottom ash. Results also confirmed the favorable action of oxygen on combustion for most components, although PETE and LDPE compounds showed retarded reaction rates at higher oxygen concentrations.

Section II: Municipal Solid Waste Management (MSW) in China

In 2004, China surpassed the USA as the world's leading producer of solid waste with over 1 billion tons. Almost one fifth of this waste is MSW, with an estimated production of 190 million tons per year and rising. While MSW collection systems in China's cities are not significantly inferior to those of developed countries, disposal and treatment of

waste is an area of deep concern both within China and internationally. Over one third of China's 623 major cities are already surrounded by trash and the World Bank estimates that only 20% of China's MSW is properly disposed of at the present time. One of the most serious aspects of the problem is the prevalent use of basic landfills without liner, gas collection or leachate treatment systems.

An increasing number of cities have been turning to waste-to-energy (WTE) as a viable alternative to landfilling. There are at least 19 WTE facilities in China, which is relatively few when compared to neighbors Japan, Korea and Taiwan. However, the number will rise significantly in the coming years due to China's aim to use WTE to dispose of 30% of its MSW by 2030. Another factor in the increasing number of WTE facilities is the low capital costs per daily ton in China, which have been as low as one third of those in the west.

One potential barrier is the fact that Chinese MSW has an average heating value of only 3300 MJ/kg which is less than one third of MSW in developed countries. For this reason, China has been pushed to develop its own local brand of fluidized bed combustion technology which is amenable to the use of auxiliary fuels and can handle the high moisture contents of MSW experienced in this country.

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I was gifted with an educational environment that I could never have imagined before, and will be forever grateful to.

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PART I: THERMAL BREAKDOWN CHARACTERISTICS OF MUNICIPAL SOLID WASTE COMPONENTS IN VARYING OXYGEN ENVIRONMENTS

1. SUMMARY

The effect of oxygen concentration on the volatilization rate and combustion behavior of various components of municipal solid waste (MSW) was investigated by means of thermo-gravimetric analysis (TGA). Eight characteristic components of MSW were examined including paper, cardboard, wood, textile, rubber, polyethylene teraphthalate (PETE), low density polyethylene (LDPE) and food waste. Samples of these materials were heated in a Netzsch TGA apparatus to 1000 degrees Celsius at a rate of 20 degrees Kelvin per minute under oxygen gas concentrations of 0, 10, 20, 30, 50, 90 and 100 percent by volume. Nitrogen was used as the balance gas.

Experimental results showed that components display either three or four distinct phases of breakdown during heating: The first phase was dehydration which was observed between 50-150°C; the second showed the most significant and rapid mass loss and represents volatilization at temperatures of 300-500°C depending on the component; the third phase was transport-limited volatilization that occurred more slowly than the second stage due to physical resistance at the solid/gas interface and exhibits non-linear mass loss at temperatures ranging from 330 to 970°C, but generally below 550°C; a fourth and final stage was observed for three of the eight components (paper, rubber and food waste) and indicated the decomposition, at temperatures of over 600°C, of a relatively stable chemical compound or possibly an intermediary substance.

For most components, it was found that increasing oxygen concentration did not affect the first phase of breakdown, slightly accelerated the onset of molecular volatilization in the second phase, increased the rate of mass change in the third phase, and reduced the temperature required to reach residual mass in the final phase. Experimental results also displayed unexpected interactions between plastic or rubber compounds and the oxygen gas including retarded reaction rates and increased residual mass when compared to experiments in an air environment. A thermo-molecular model is discussed to explain the four phase thermal breakdown and anomalies observed.

The results for experiments in an air gas environment (20% oxygen) suggest that problems related to attaining complete combustion in waste-to-energy (WTE) combustors are more influenced by gas transport resistances during the volatilization phase than pure temperature effects. As such, mechanical agitation, oxygen enhancement, and pre-treatment methods, such as shredding, will likely prove more effective in reducing unburned organics in combustor bottom ash than increasing temperature.

It is hoped that this study will provide some insight into the potential for using oxygen-enhanced combustion in future Waste-to-Energy (WTE) designs, as well as increase the understanding of combustion chemistry in existing WTE systems.

2. INTRODUCTION AND BACKGROUND

2.1 Introduction to Municipal Solid Waste

The rate of Municipal Solid Waste (MSW) generation in the USA has been increasing at an average annual rate of over five percent during the last decade and reached a level of 1.19 metric tons per person per year in 2002 or a total of 336 million tons annually [1]. The collection and disposal of this garbage represents a significant cost to society, both economically and environmentally. Compounding this problem, rapid economic growth and environmental degradation in developing countries such as China and India are making MSW management increasingly urgent on a global scale. This problem is especially critical in view of the attendant generation of greenhouse gases – methane from landfills and carbon dioxide from both landfills and waste-to-energy (WTE) facilities contribute no small part to the pressing problems associated with global warming.

2.2 Components of MSW

MSW contains waste products arising from all aspects of human activity and as such is an extremely complex and heterogeneous material. Typically, MSW is classified by its major components as shown in *Table 1*. Increasingly, it has been shown that a few chemical compounds within MSW contribute significantly to environmental and health impacts. For example, trace amounts of lead and mercury emissions have been shown to be toxic to the nervous system, kidney and immune function [2], dioxin has been shown to act as a carcinogen in laboratory animals, and chlorine contributes significantly to corrosion of boiler tubes in WTE systems [3]. While most waste management systems deal with waste as an aggregate material, an understanding of the behavior of individual chemical components such as those shown in *Table 1* can be extremely useful when optimizing the design of MSW management systems.

Table 1: *Estimates of MSW Composition in the USA [5]*

Source	*NYC Waste SCS Engineers 1992*	*US Waste EPA 2000*	*Typical Waste Tchobanoglous 1990*
Paper	31	37.4	40
Plastic	9	10.7	7
Food waste	13	11.2	9
Yard waste	4	12	18.5
Misc. Organics	25	12.5	8
Glass	10	5.5	8
Iron	4	6	6
Other Metals	1	1.8	3.5
Fines/other	3	2.9	
	100	100	100

2.3 Waste-to-Energy Technology

As mentioned above, one method for MSW disposal is Waste-to-Energy (WTE) which recovers heat from MSW combustion to produce electricity and useful heat. Presently 7.7% of MSW in the United States, or approximately 26 million tons per year, is treated using WTE technology and produces over 2.5 GW of power continuously [4].

Worldwide, over 130 million tons of MSW are combusted annually in over 600 WTE facilities [5] off-setting the fuel consumption of at least eight large-scale coal power plants and greatly reducing the area of land required for landfilling.

2.3.1 Environmental Benefits

The benefits of WTE technology are the 90% volume reduction of waste, energy recovery, convenient metal recovery, destruction of organic pollutants and ability to control hazardous emissions to the environment. Additionally, it has been shown in recent years that the contribution to global greenhouse gas emissions from WTE is 1.3 tons (of carbon dioxide equivalent) less than landfilling per ton of MSW [6]. A WTE plant significantly reduces atmospheric emissions of several hundred different kinds of dangerous volatile organic compounds and chlorinated compounds which emanate from landfills [4].

2.3.2 Economic Aspects

However the significant capital cost deters municipalities from using WTE technology in many countries in favor of more simple, economical, but environmentally damaging, landfilling. In the United States, the disposal cost at a WTE is typically above $60 per ton of MSW as opposed to $20 per ton or less for landfilling, even after taking into account the revenue earned from the sale of electricity [5]. For this reason, WTE has been most popular in economically affluent countries with high population densities such that landfilling is restricted by other land use demands. For example, mountainous Japan has over 100 facilities and the small island of Taiwan over 20. WTE is also popular in countries with strict environmental standards such as the USA (over 100 facilities), Germany, Denmark, and the Netherlands.

2.3.3 Future of WTE

Due to the environmental benefits associated with modern WTE, there is a need to find ways to improve WTE performance and reduce the capital cost to encourage the use of this environmentally favorable technology. As international concern about global warming intensifies, the ability of WTE facilities to reduce greenhouse gas emissions, as compared to landfilling, will become an increasingly important factor when choosing a method for MSW management. There is also a large potential market for WTE technology in developing countries as they become increasingly aware of environmental issues, and work to tighten environmental legislation and regulations. Much of this cleanup process hinges, however, on the affordability of WTE.

The high cost of WTE in the USA has been partly caused by strict air pollution control regulations leading to advanced air pollution control systems accounting for up to a third of the capital investment for a new facility. Another factor is the stagnant market in the U.S., which has seen virtually no new WTE plants constructed in the preceding decades and market competition focusing on operational efficiency of existing facilities rather than technology innovation. The future could lie in China where a number of research institutions are developing low cost WTE technology under the funding of the Chinese State Environmental Protection Agency (SEPA). It seems likely that China will be the supplier of much needed low-cost WTE facilities in the developing world, who cannot afford more expensive western technologies. If a system of carbon credits, or carbon trading (such as is being developed in Europe) is implemented, then this will also improve the economics of WTE systems.

2.4 Oxygen Enhanced Combustion

2.4.1 Benefits of OEC

Oxygen enhanced combustion (OEC) is an increasingly accepted technology that has been shown to reduce pollutants, increase energy efficiency, improve flame characteristics and assist heat transfer in a number of industrial processes [7]. Most importantly, it represents a potential to reduce the capital cost of combustor units due to greatly reduced exhaust gas volumes and combustor size. Industrial applications so far have mainly focused on the modification of industrial heating processes such as metal and glass furnaces to increase capacity and improve heat transfer of existing furnaces, however one of the major suppliers of WTE technology, the German company Martin GmbH, has recently developed a design using an oxygen-enhanced combustion gas stream [8], and other firms have also showed interest in including OEC in the next generation of WTE systems.

2.4.2 OEC and MSW

While the benefits of oxygen enhanced combustion have been documented for many kinds of combustors [7,10,11,12,13], there has been no investigation into the effect of oxygen enhanced combustion on individual components of MSW. An understanding of the effect of additional oxygen on individual components could be used to optimize combustion parameters such as temperature and retention time, and also help to identify the most problematic components of the waste stream so they can be intelligently sorted and removed. In an integrated waste management system (IWM), information such as heat content, toxicity levels and combustion characteristics can be used to optimize processing of MSW into streams for recycling, composting, WTE and landfilling. Individual component information would also allow the calculation of MSW heating characteristics such as weight loss and heat release over time from simple MSW composition data, thus simplifying the design of WTEs for different regional or projected MSW compositions.

2.5 Thermo-gravimetric Analysis

Thermo-gravimetric Analysis (TGA) is a reliable and widely used laboratory technique employed to study the extent of mass changes due to volatilization and combustion of fuel components, and in addition allows great flexibility in controlling the composition of the combustion gases. Although data from the TGA cannot directly explain the chemical and thermal degradation mechanism, it allows extremely accurate measurements of fuel mass as a function of temperature in a characteristic thermo-gram, allows calculation of kinetic parameters, and assists in the understanding of chemical reactions occurring in the furnace. This information is important for WTE systems as it affects many aspects of the combustor design including the length of grate, temperature profile of combustion chamber, retention time, speed of grate motion, as well as giving information on the change in mass and volume of the MSW as it travels down the grate.

The purpose of this study is two fold, firstly to understand the characteristic breakdown behavior of different MSW components during combustion, and secondly to gain insight into how these components might be affected by varying concentrations of oxygen, as would be observed in an oxygen-enhanced WTE combustor. This report will present thermo-grams of eight components of MSW: white paper, cardboard, wood, textile, rubber, PETE, LDPE and food waste, in oxygen concentrations ranging from 0 to 100 percent. Some discussion is also presented on the implications of the results on WTE combustor design.

3. EXPERIMENTAL SETUP

3.1 TGA Instrument

3.1.1 General Description

All experiments were carried out using a Netzsch STA 409 PC/4/H thermo-gravimetric analysis (TGA) unit (see *Figure 1*) capable also of differential thermal analysis (DTA) measurements. The Netzsch instrument employs a sample carrier rod that holds a ceramic crucible containing the test sample within a vertically mounted furnace (*Figure 2*).

***Figure 1**: Netzsch STA 409 PC*

***Figure 2**: Ceramic Crucible and Furnace*

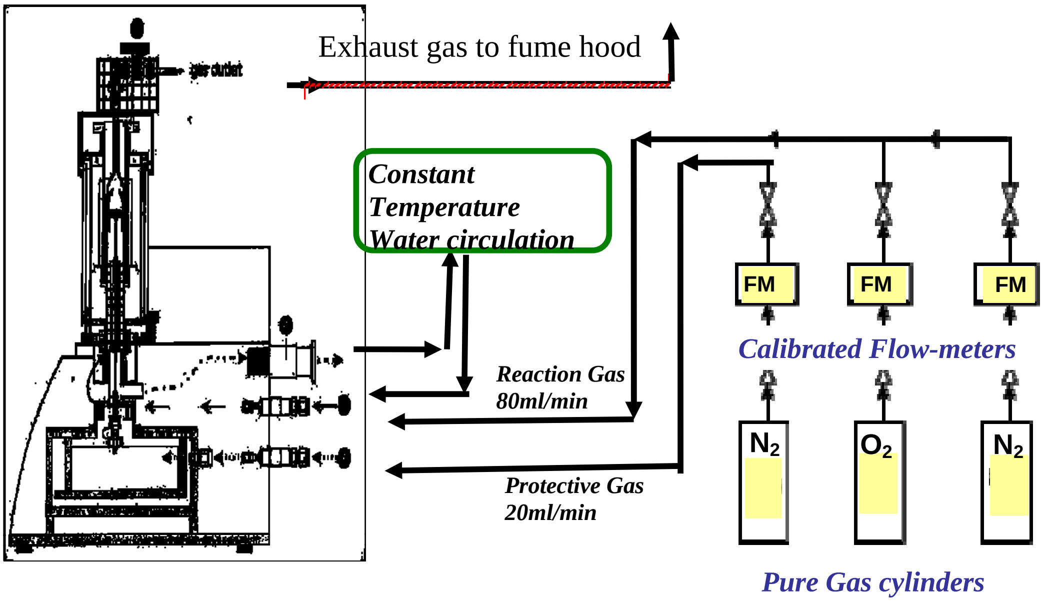
This system typically gives more consistent results than those that employ a hang-down wire because of the tendency for volatilized gases from the sample to condense on the wire and impact mass change readings. Changes in mass are measured by an electro-mechanical balance scale contained in a temperature controlled chamber at the base of the sample carrier rod. A constant temperature thermo-bath maintained at 25 ± 0.01^{o}C supplies a steady flow of cooling water through the balance scale chamber to ensure accurate weight measurements.

3.1.2 Temperature Control and Data Acquisition

The TGA apparatus is computer controlled and uses Netzsch software for continuous data acquisition and furnace temperature programming. A program ramping the temperature at 20°K per minute to a furnace temperature of 1000°C was used as an input for the Netzsch STA software which then controlled the instrument accordingly. All temperature data was digitally recorded at a resolution of 20 data points per minute using an S-type thermocouple mounted directly under the sample carrier. Thermo-grams were displayed and analyzed using the separate 'Netzsch Proteus Thermal Analysis' software package.

The TGA instrument requires two separate gas streams, the reaction gas enters the system at the base of the furnace and comprises the majority of the flow, while the protective gas enters upstream and envelopes the scale mechanism before being mixed with the reaction gas at the base of the furnace. The reaction gas and the protective gas mix thoroughly in a chamber above the balance scale before entering the furnace, flowing around the sample and carrier, and finally being exhausted into a fume hood as shown in *Figure 3*.

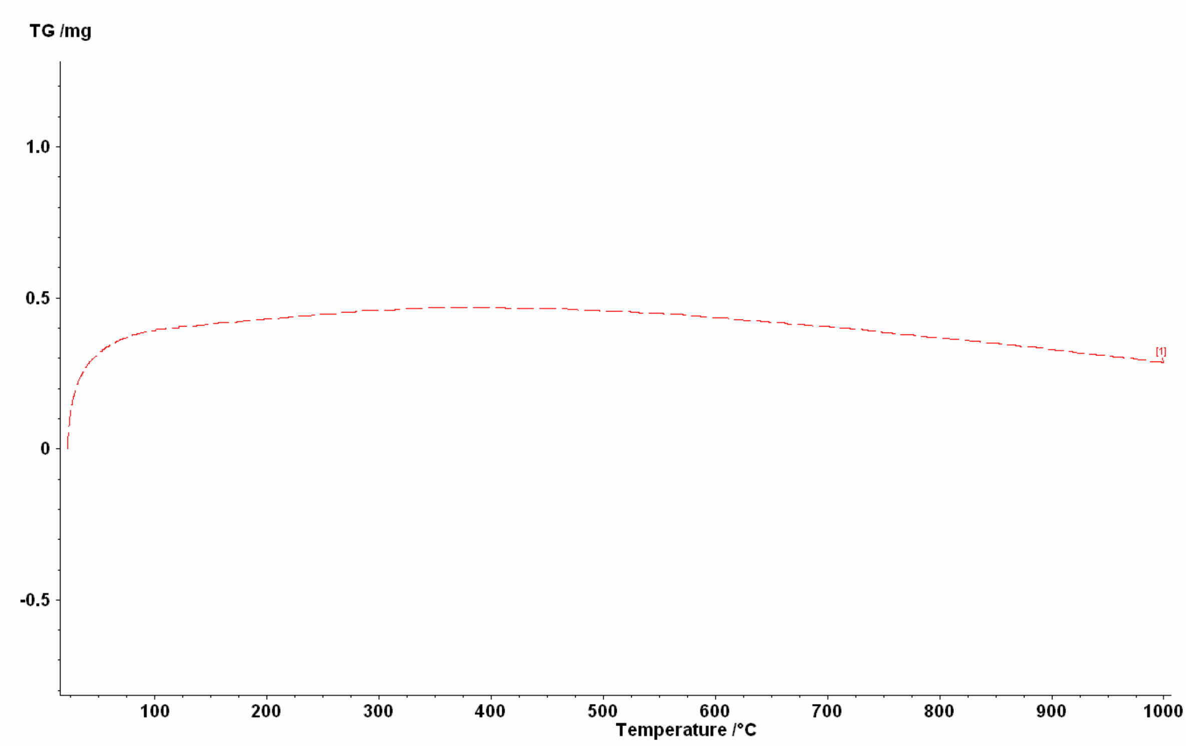
Figure 3: *Schematic of Netzsch STA 409 PC/4/H TGA Unit and Gas Setup*



3.1.3 TGA Baseline and Buoyancy Effects

For each experiment that is carried out, a TGA baseline needs to be performed and subtracted from experimental results to account for buoyancy effects in the furnace. A baseline test is run without any sample in the crucible such that recorded mass changes are due to buoyancy effects alone. Due to the flow of gas around the ceramic sample crucible, a slight pressure differential is developed, which causes slight deviations in the weight measurements recorded by the balance scale. These deviations vary with temperature and have a characteristic shape as shown in the base-line for an air mixture in *Figure 4*. The deviations depend on the kind of gas, gas mixture, gas flow rate, size and shape of sample crucible, and the temperature of the furnace. By keeping all of these variables are kept constant, the buoyancy deviations can be eliminated by subtracting the baseline from experimental data.

Figure 4: *TGA Base-line for 100ml/minute Air Mixture*



3.2 Combustion Gas Setup

3.2.1 Gas Flow System

In each experiment, the gas flowed from the gas cylinder, through a one way stop-valve, a needle-valve and flow meter before entering the TGA instrument. Exhaust gases were vented into a stainless steel fume hood.

In each experiment, the reaction gas was set at 80 ml/minute and the protective gas at 20 ml/min giving a total of 100ml/minute gas flow. A mixture of nitrogen and oxygen was used as the reaction gas, and nitrogen was used as the protective gas, except in experiments requiring greater than 80% oxygen, in which case oxygen was also used as the protective gas.

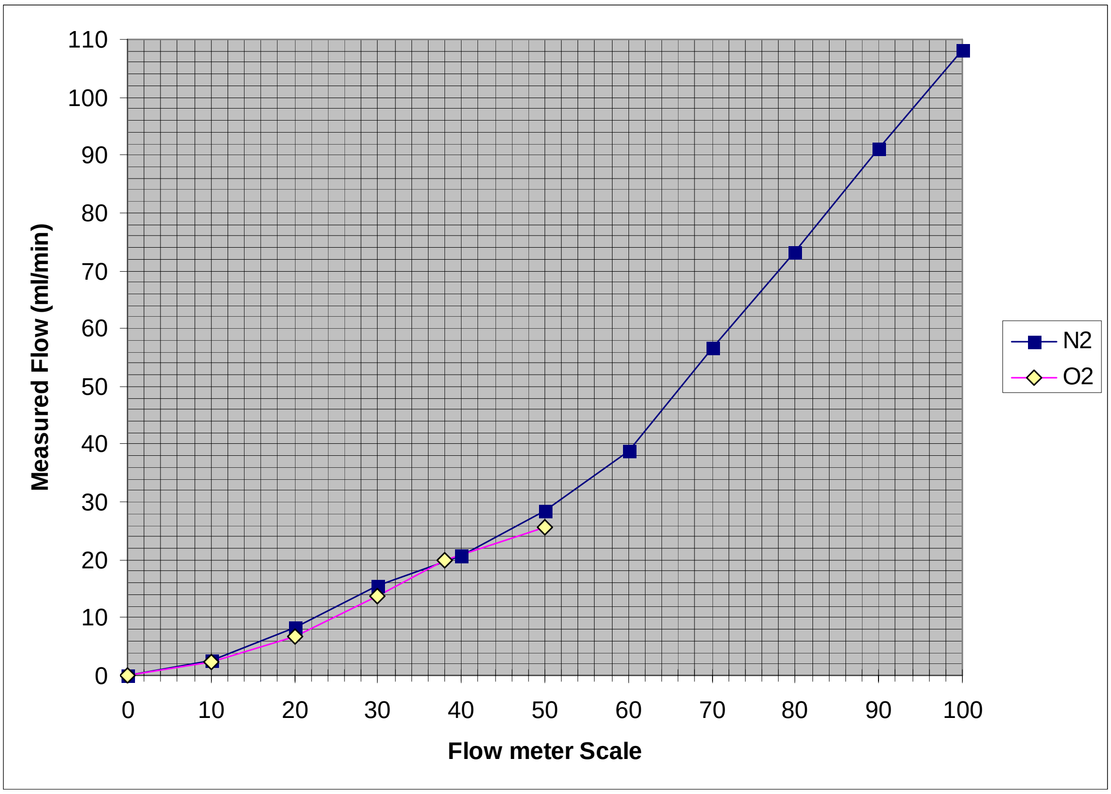
3.2.2 Equipment Used

The nitrogen and oxygen gases used for experimental work were of high purity (99.9%) and were purchased through T.W. Smith Company in New York. The flow rates were measured using two laboratory style Gilmont flow-meters (GF-1060) with ranges of approximately 0-100 ml per minute for the reaction gas. A Matheson flow-meter (FM-1050) was used to measure the protective gas flow rate. Connections were made with brass or stainless steel swage-lok fixtures and ¼" external diameter Teflon lined PVC was used as tubing material. Stainless steel low-flow swage-lok needle valves (part number SS-SS4) were used to adjust gas flow to the desired level.

3.2.3 Flow-meter Calibration

Each flow-meter was individually calibrated for each gas at the relevant flow rates using a fixed volume 1-10-100 milliliter bubble-o-meter purchased from Bubble-o-meter limited. An example of calibration charts generated is shown in *Figure 5*.

Figure 5: *Calibration of Matheson FM-1050 Flow-meter for Pure Nitrogen and Pure Oxygen*



The bubble-o-meter consists of a vertically mounted precision made glass tube of fixed volume with a rubber bulb filled with a soap solution fixed at the base. Compression of the rubber bulb forms a soap film at the base of the tube. The film rises in the tube at a velocity dependent on the gas flow rate. By timing the travel of the film past two calibration marks, one obtains the volumetric rate of flow of gas at atmospheric pressure and room temperature [14].

3.2.4 Selection of Oxygen Concentrations

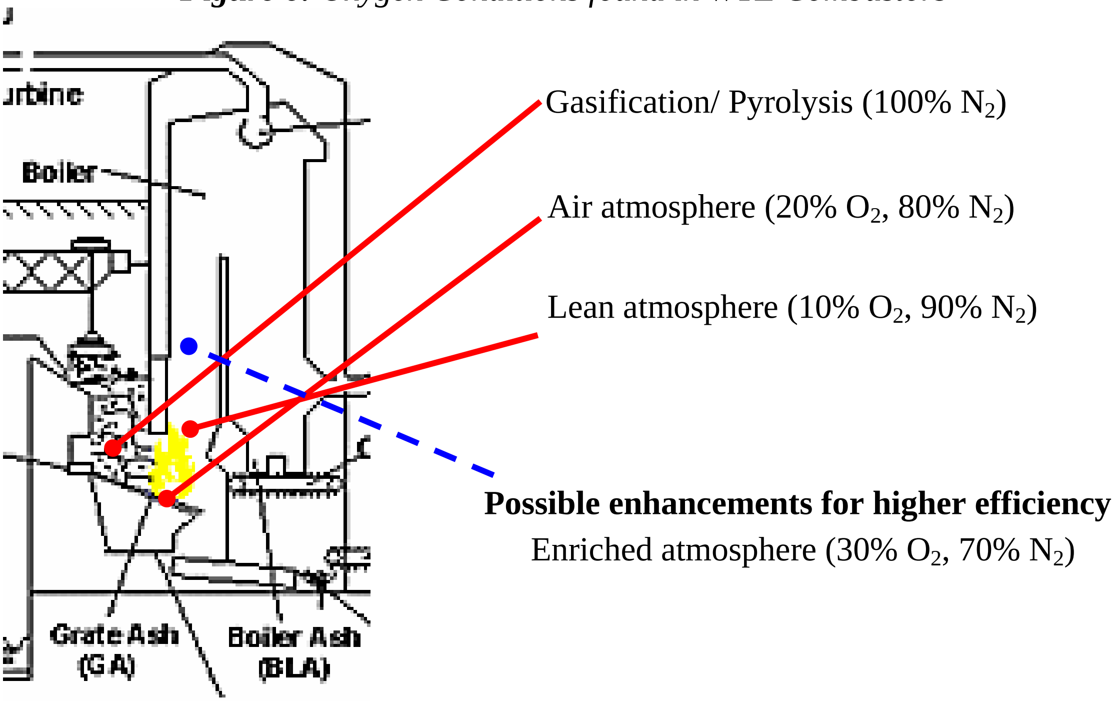
Experiments for each component were carried out at seven different oxygen concentrations: 0, 10, 20, 30, 50, 90 and 100%. These concentrations were selected to give a comprehensive spectrum of gas environments that might be found in different regions of a normal WTE combustor or an oxygen enhanced combustor.

A 100% nitrogen environment simulates pyrolysis or an oxygen deprived environment. A 10% oxygen-lean environment would be expected in the area above the burning fuel in a WTE combustor as oxygen is consumed by gas reactions. A 20%

oxygen or air environment occurs immediately as the under-fire air passes over the MSW. If additional oxygen lancing or oxygen enriching in the over-fire air is used, levels of 30-50% oxygen could be reached.

A schematic of the oxygen regimes in a WTE combustor can be seen in *Figure 6*. A 90% or 100% oxygen environment would only be seen in a fully oxygenated combustor that does not use air as an oxidant. Conditions of this kind appear in special purpose designs such as zero-emission coal plants, but the cost of oxygen is presently too high to make them economical.

Figure 6: *Oxygen Conditions found in WTE Combustors*



3.3 MSW Samples

3.3.1 Sample Selection

As noted previously, a representative sample set of eight MSW components was selected in order to accurately represent the main fractions of the waste. The eight components are shown in *Table 2* along with typical moisture content, combustion residue and energy content data. The inorganic fraction of waste, including metals and glass, was not included in the set of experimental samples because they do not play a significant role during MSW combustion.

Table 2: *MSW Components used in Experiments and Typical Physical Characteristics [5]*

8 Components used in Experiments	Typical % Composition in MSW	Moisture (% mass)	Volatile Matter (% mass)	Residual Mass (% mass)	Energy Content (Btu/lb)
White Paper	34	10.2	75.9	5.4	6799
Cardboard	6	5.2	77.5	5	7428

Wood	2	12	75.1	0.5	7352
Textile	2	10	66	6.5	7960
Rubber	0.5	1.2	83.9	9.9	10890
No. 1 PETE	3	0.2	95.8	2	16024
No. 4 LDPE	2	0.2	98.5	1.2	18687
Food Waste	9	78.7	16.6	0.7	1707

3.3.2 Relation to MSW

These components account for over 60% of MSW by mass. The remainder of the MSW not included in the sample component group is made up of either non-combustible inorganic materials (metals, ash, glass, etc., around 20% of MSW mass), or components possessing similar characteristics to one or more of the selected components. For example, yard waste has characteristics similar to wood or food waste.

3.3.3 Sample Preparation

The sample sizes were between 10mg and 30mg and were sliced into small pieces less than 1 mm in diameter using a stainless steel razor blade. The same sample source was used throughout the experiments for each component, except in the case of the food waste which decomposes rapidly, and required a fresh sample for each experiment.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Experimental Results Part A: Air Combustion Gas

4.1.1 *Four Phase Component Breakdown Model*

The first group of experiments was carried out in a 20% oxygen and 80% nitrogen gas atmosphere, representative of combustion in air. These experiments are intended to be used as a base-line for other experiments varying the oxygen level as shown in section 4.4: '*Experimental Results Part B*'.

A typical thermo-gram is shown in *Figure 7* which shows the thermal degradation curve of a white paper sample. The x-axis of the thermo-gram represents the temperature in degrees Celsius and can be easily converted to a time scale due to the constant temperature ramp of 20K/min. Each experiment required approximately 50 minutes to run, and then a further hour for the furnace to return to room temperature. The y-axis represents the percentage mass change over time for each component, starting at 100% and finishing with a solid residue of between 0-25% of original mass. The shape of the thermo-gram can be seen to have several dips and plateaus. For the purposes of these experiments, it was convenient to classify these mass changes into four phases as described below:

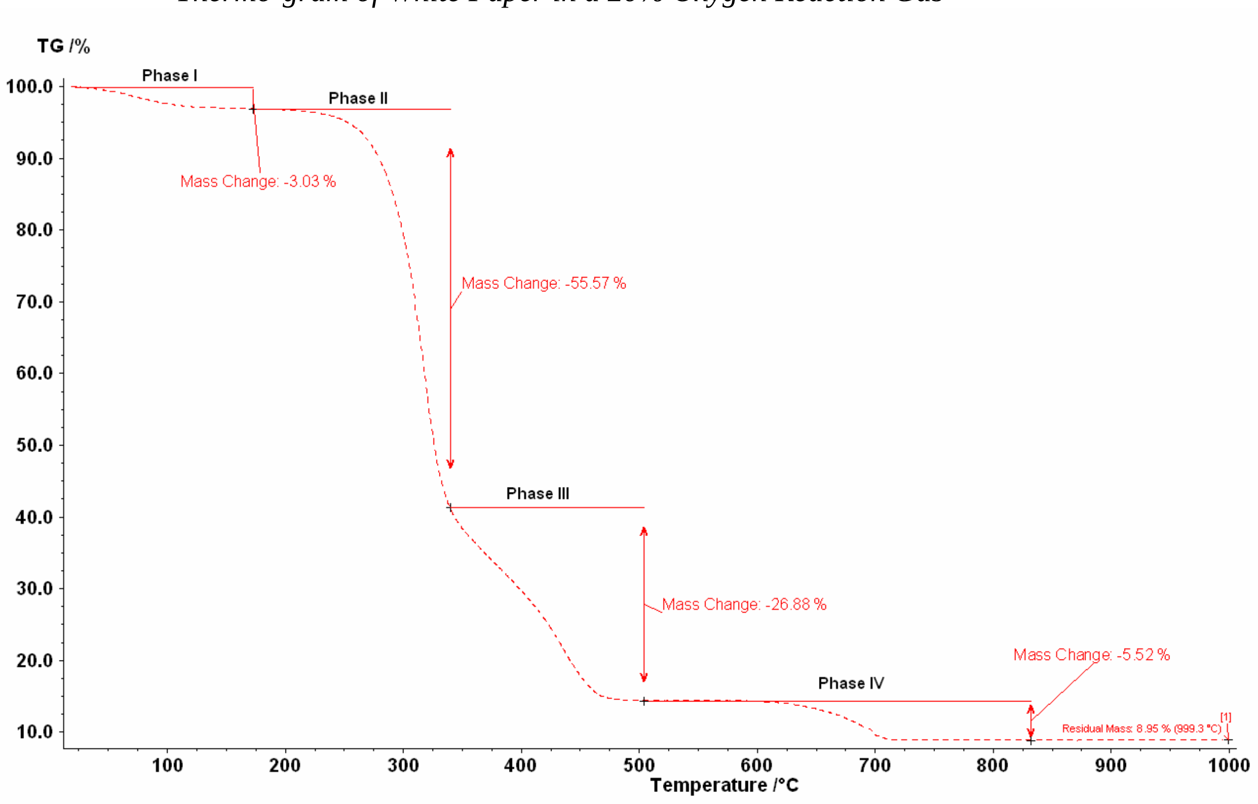
- **Phase I :**
  Occurring between 50 and 150°C. Represents dehydration as the moisture fraction evaporates.

- **Phase II :**
  Begins around 300°C and mass loss accelerates rapidly after a gradual start. Represents the volatilization of organic compounds into combustion gases that will be oxidized in the downstream gaseous environment.

- **Phase III**
  A continuation of the preceding volatilization phase as it starts to be impeded by resistance to gas transport at the gas/solid interface of the sample. This resistance acts on both the ability of oxygen to reach the fuel, and the ease of escape of volatilized gases. The mass change rate generally varies in a non-linear fashion with temperature. The resistance is due to the solid residue that remains after volatilization which is made of metal oxides and other inert species. This layer becomes increasingly thick as the reaction progresses, forming a semi-impermeable layer on the surface of the MSW particle.

- **Phase IV**
  Shows the volatilization / combustion of a more persistent or stable fraction or intermediate compound of the sample. Phase IV breakdown can continues to 700°C and beyond.

Figure 7: *Four-phase Breakdown Model:*
Thermo-gram of White Paper in a 20% Oxygen Reaction Gas



4.1.2 Explanation of Four Phase Breakdown of White Paper

The changing rate of mass change in the thermo-gram of white paper in air can be explained by a combination of chemical properties and energy/mass transport mechanisms. For example, the Phase II onset temperature represents the level of energy required to break down the lignin and hemi-cellulose of paper fibers into a gas; however, before the onset temperature is reached, some molecules already reach this energy state due to an uneven energy distribution and this gives rise to the gradual acceleration of mass loss around 250°C as an increasingly large proportion of molecules reach this activation energy.

Once the maximum rate of volatilization is reached, it continues until the mass transport at the solid/gas interface begins to be restricted by the inert residue remaining after volatilization. This inhibited volatilization is designated as Phase III in *Figure 7*. The residual clay and ash fraction of white paper slows the flow rate of escaping volatilized gases between 320-480°C. This temperature range shows a slightly curved thermo-gram representing the opposing influences of increasing temperature and increasing resistance of the thickening residue layer on the particle surface.

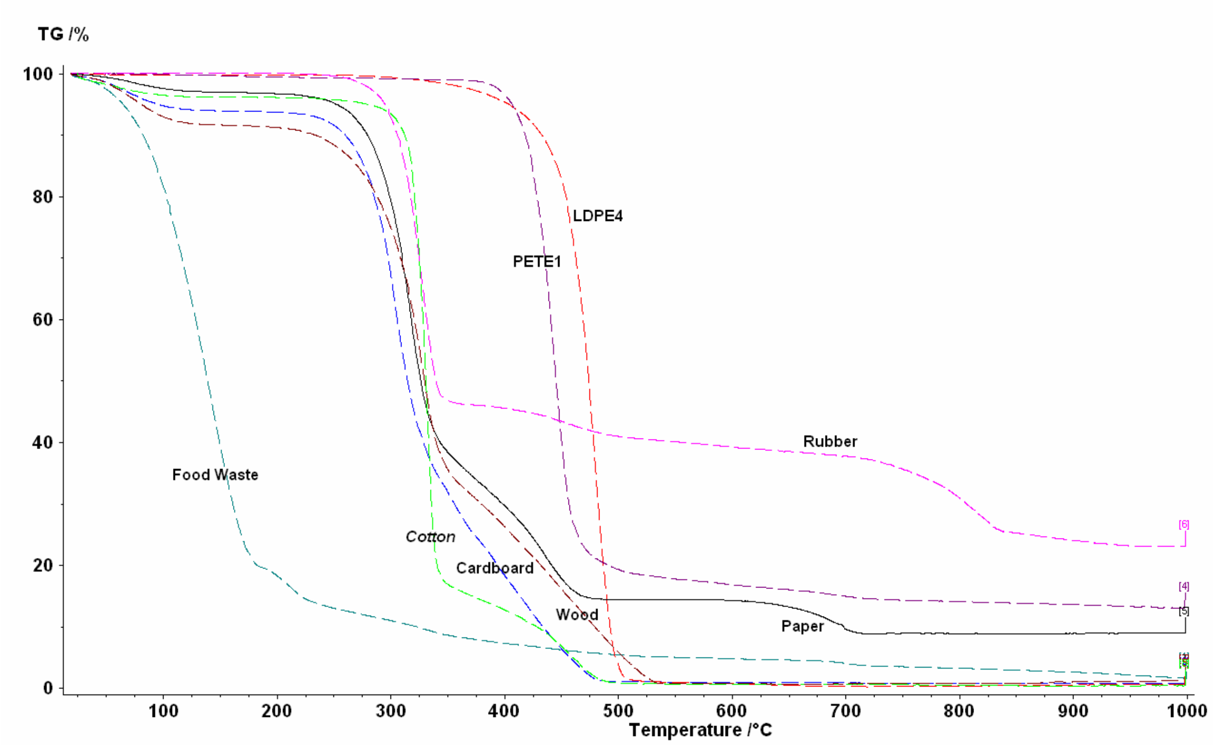
Between 480-600°C there is no change of mass indicating that no reactions are occurring in this temperature range. Above 600°C there is a further breakdown during Phase IV, indicating the existence of a more stable molecule or intermediate compound that is inert below this temperature.

Important temperatures to note are the Phase II onset of volatilization temperature which is estimated by extrapolating backwards from the point of maximum rate of mass loss and can be seen to be 297.4°C in *Figure 7*. Phase III begins at 336°C, and the transport-restricted volatilization is complete at 471°. Combustion reaches completion after Phase IV at 712°C and the residual mass was 8.95% of the original mass.

4.1.3 Results for 8 MSW Components in Air

The thermo-gram and four-phase breakdown analysis of white paper can help us to analyze the breakdown of all eight experimental components shown in *Figure 8*. *Table 3* summarizes the mass changes and important temperatures associated with each phase.

Figure 8: *Thermo-grams of 8 MSW components in 20% Oxygen (Air) Environment*



4.1.4 Discussion of Results

It can be seen that the food waste is the first to lose significant mass due to its high water content, while most other components lose the largest proportion of their mass through volatilization between 300-500 degrees Celsius beginning with cardboard, wood, paper, rubber, cotton, and then PETE and LDPE at a slightly higher temperature. In these experiments, rubber was observed to have the highest residual mass around 22% while paper, cotton and PETE had around a 10% residual mass. The other components had almost no residual mass. Phase IV breakdown was only seen in white paper, rubber, and to a small extent in food waste, with the other 5 components not reacting further after Phase II and III volatilization.

Table 3*: Experimental Mass Changes and Temperatures of MSW Components in Air*

	Mass Changes (% of total mass)					Temperatures (Degrees C)			
	Phase I: Dehydration	Phase II: Volatilization	Phase III: Un Inhibited Volatilization	Phase IV: Persistent Component	Residual Mass	Phase II onset	Phase III onset	Phase IV onset	Final
White Paper	3.3	53.6	28.6	5.6	8.9	297	337	624	711
Cardboard	6.1	52.1	41	-	0.8	279	322	-	488
Wood	8.5	53.7	36.6	-	1.2	290	345	-	540
Textile	3.8	76.8	18.9	-	0.4	319	343	-	491
Rubber	0	52.6	9.7	14.7	23	305	343	704	971
No. 1 PETE	0.6	75.7	9.7	-	13	422	468	-	736
No. 4 LDPE	0.3	98.3	0.7	-	0.6	452	502	-	531
Food Waste	78.4	-	17.8	1.1	2.9	80	180	684	730

4.1.5 Temperature Required for Complete Combustion

If we analyze the temperature required for complete combustion from *Table 3*, we see that the 8 MSW components can be put into order of ease of combustion as follows: cardboard, textile, LDPE, wood, white paper, food waste, PETE and finally rubber.

Cardboard, textile, LDPE and wood samples had all completed thermal degradation by 540°C. White paper, food waste and PETE had a small fraction (1-6%) of the mass that did not break down until above 700°C. Rubber was the most difficult to break down with 14.7% mass not beginning degradation until above 704°C, and an extension of inhibited volatilization was seen to continue up to almost 1000°C. The MSW fractions such as rubber which require high temperatures to break down are likely to be responsible for residual organic matter in WTE bottom ash.

4.1.6 Aggregate Analysis of Four Phase Breakdown for MSW

By weighting the mass change of each component by the associated percentage composition in MSW, summing up each phase of breakdown, and assuming that yard waste can be approximated by the wood sample, a summary of MSW combustion mechanisms was obtained and shown in *Table 4*. It can be seen that only an estimated 2.1% of MSW breaks down at the high temperatures in Phase IV. A small amount of phase III breakdown persists up to 970°C, although over 95% is complete before 550°C.

Table 4: MSW breakdown by Mechanism

Mass Fraction	*Proposed Mechanism*	*Temperature Range (degC)*	*% of MSW Mass*
Phase I Breakdown	*Dehydration*	*50-150*	**10.3**
Phase II Breakdown	*Un-inhibited Volatilization*	*300-500*	**38.1**
Phase III Breakdown	*Inhibited Volatilization*	*330-970*	**21.8**
Phase IV Breakdown	*Persistent Component*	*600-850*	**2.1**
Component Residue	*No reaction*	-	**4.1**
Inorganic	*No reaction*	-	**18**
Other components (unaccounted for) Eg leather, reactive metals	*Unknown*	-	**5.6**

4.2 Application of Results to WTE Combustor Design

4.2.1 Implications for WTE Combustion

When applied to the workings of a WTE combustor, these results provide us with insight into redesign possibilities for both fuel processing, temperature profiles and combustor sizing. In all experiments, the great majority of mass change occurs during phases II and III between 300°C and 550°C, except in the case of food waste which occurs earlier. This implies that a similar majority of heat energy is released within this temperature window. It should be noted that in these experiments the heat release from the sample was negligible when compared to the temperature of the furnace, however in a real WTE system the fuel is the only source of heat and hence determines the furnace temperature. The furnace temperature is of critical importance due to several factors including the attainment of complete combustion, combustion efficiency, heat transfer issues, production of thermal nitrogen oxides and the structural integrity of the furnace. While there has been much discussion on the optimal temperature for an MSW combustor, these results suggest that other factors such as grate motion and particle size play a more important role in optimizing the energy recovery of the system as discussed below.

A further design issue emphasized by these results is the sudden release of heat during the Phase II breakdown. Ideally, Phase II should be extended or retarded to distribute heat more evenly and to reduce the extreme temperatures and their associated corrosion problems and maintenance costs.

4.2.2 Reducing Unburned Organic Material in Bottom Ash

The experimental results allow us to hypothesize solutions to the problem of residual unburned organic material contained in WTE bottom ash. A typical WTE operates at 850°C which is sufficient to combust all MSW components examined except for small amounts of Phase III residual in rubber, PETE and food waste, and a small percentage of components displaying Phase IV breakdown behavior. Because these residuals are in phase III, it can be concluded that they are more influenced by transport mechanisms and physical limitations than pure temperature effects. This implies that raising the combustion temperature will not necessarily ensure complete combustion of these unburned components.

If raising temperature cannot solve problems of incomplete fuel utilization in WTE combustors, then we must consider other methods to solve the problem of unburned residue. One method that is already put to use is some form of mechanical agitation and mixing that acts to break away the residual layer that forms on MSW particles as they burn. By exposing fresh particle surface, volatilization is returned to the high rates of mass loss in Phase II. Another solution would be to reduce particle size by pre-shredding the waste, increasing the surface area of particles and hence increase the proportion of waste in lower temperature Phase II un-inhibited combustion, as opposed to Phase III. Agitation would still, however, be required if shredding were used.

Present WTE designs use a very slow grate or rolling motion, which would be insufficient to produce the accelerations required to disrupt the solid/gas phase resistance. A fluidized bed, which incorporates particle impacts, would be more effective and further developments of this technology should be expected in the future. A vibrating combustion grate, which has not been attempted to the knowledge of the author, would be another potential solution.

4.2.3 Summary for Part A

Our experimental results suggest that while the persistent components in Phase IV require high temperatures to degrade, they are not a critical factor because they only account for 2.1% of MSW mass, as opposed to 21.8% in Phase III. While high temperatures are required to combust the aforementioned 2.1%, the larger problem lies in providing oxygen to the 21.8% so that it can be combusted which is unrelated to temperature. In these experiments, the particle size was small and kept consistent between all samples. To extrapolate to a large scale WTE incinerator, factors such as particle size and shape will need to be considered due to the large role they play in the transport and volatilization rates.

4.3 Experimental Results Part B: <u>Varying Oxygen Concentration</u>

4.3.1 Oxygen Enhancement

The experiments reported in the '*4.1 Experimental Results Part A'* were all carried out in simulated air gas environments. This section presents results from experiments with an oxygen concentration varying from 0 to 100%. The experimental results showed a number of interesting features that are shown in the *Figures 8 to 10* below. It should be noted that due to the nature of our gas mixing apparatus, the gas concentrations are only accurate to within plus or minus 5% of the stated concentrations.

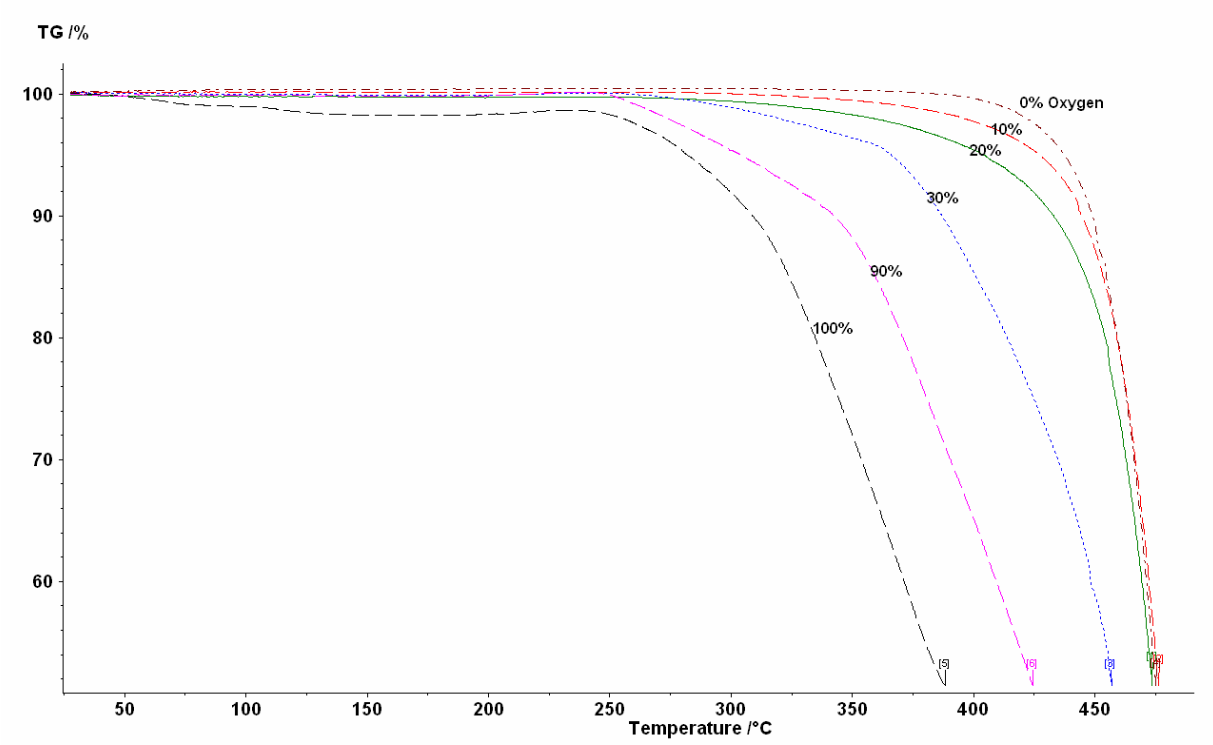
Several changes were observed in combustion behavior as oxygen concentration increased: breakdown at lower temperatures, accelerated rate of breakdown, and in some cases a reduction of residual mass. Additionally, an unusual retarding effect was noted for the breakdown of LDPE, PETE and rubber as oxygen concentrations increased. These phenomena are described below.

4.3.2 Reduced Phase II Onset Temperature

Figure 9 shows the accelerated onset of Phase II volatilization which was present in all samples, but is shown here for the LDPE component. Phase II onset occurs around 440°C for LDPE in air conditions (20% oxygen), but decreases to 390°C and 300°C in

30% and 100% oxygen environments, respectively. In the 100% oxygen gas environment a part of the sample starts to break down as early as 50°C.

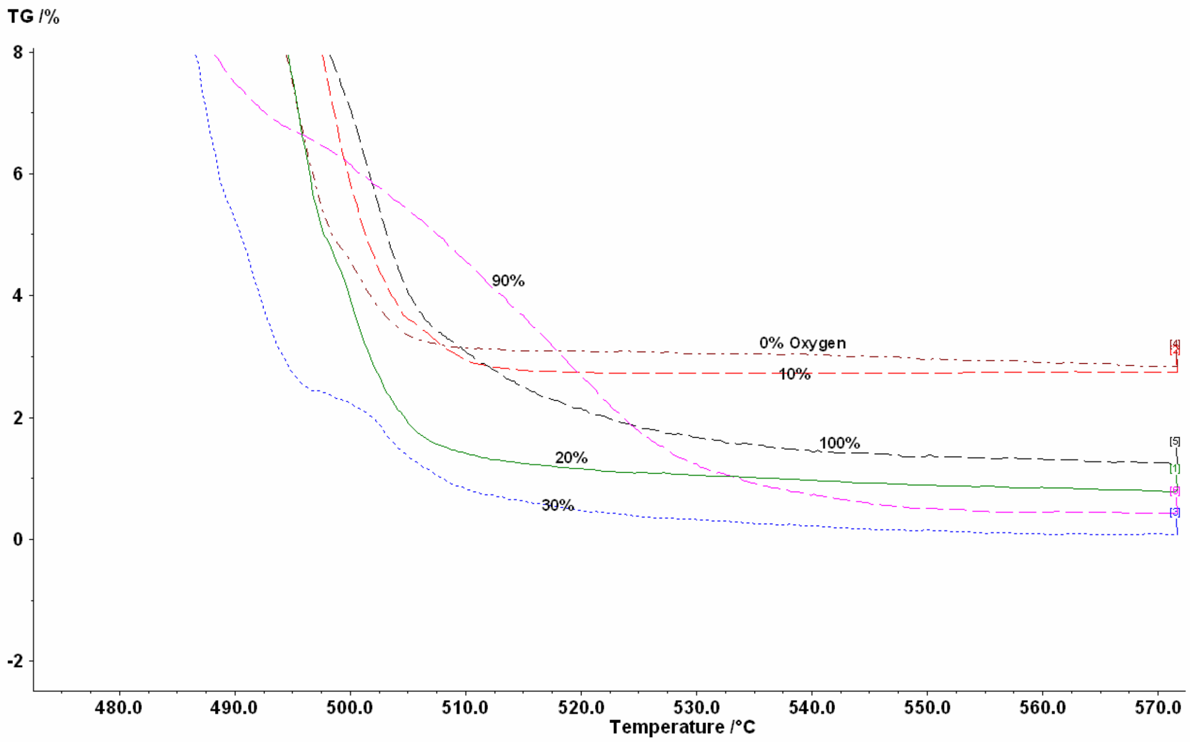
***Figure 9**: Onset of Phase II Volatilization of LDPE with increasing Oxygen Concentration*



4.3.3 Non-linear Response for Rubber and Plastic Compounds

Figure 10 shows the unusual non-linear response of the Phase III inhibited volatilization mass change of LDPE with oxygen concentration. It seems that while increasing the oxygen concentration from 0 to 30% increases both the speed and extent of LDPE breakdown, further increases in oxygen have a retarding effect. Although unusual, the trends in the LDPE results were also seen two other components (PETE and rubber), and seem to indicate an underlying mechanism related to the plastic or rubber structure of these components. It is clear that there are some complex chemical reaction mechanisms involving oxygen that take place at oxygen concentrations above 30% that act to impede volatilization. This is especially so in the case of the 90% oxygen thermo-gram which shows the appearance of a persistent intermediate compound. However, the removal of nitrogen from the mixture (ie.100% O_2) seems to return the thermo-gram back to its original shape profile, although with an altered residual mass.

***Figure 10:** Phase III breakdown of LDPE in varying Oxygen concentrations*



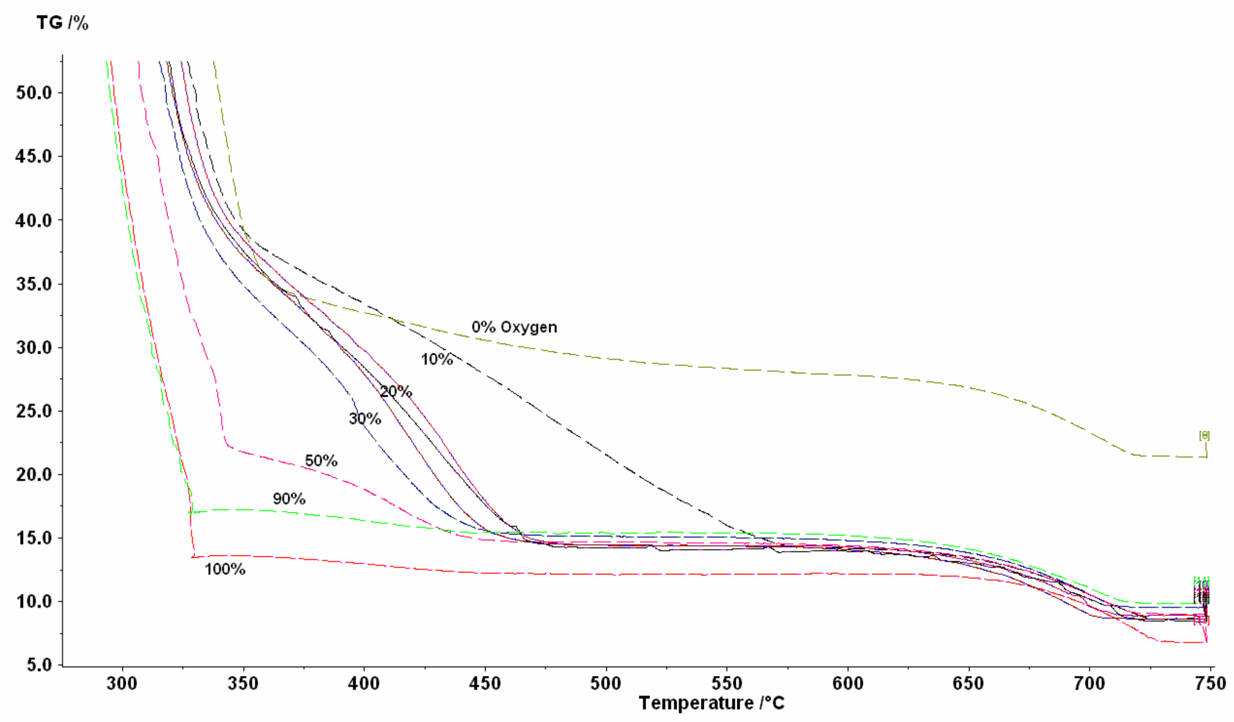
4.3.4 Acceleration of Volatilization Rates

For the majority of components such as textile, cotton, wood, cardboard and paper, the effect of increasing oxygen concentration on the Phase III breakdown was to increase the rate of mass loss such that it more closely resembles the Phase II un-inhibited breakdown. This effect can be clearly seen in *Figure 11* which shows the thermo-grams of white paper at varying oxygen concentrations: In an anoxic gas environment, there is a significant fraction of paper, about 15%, that cannot decompose, but with increasing oxygen concentrations, this fraction decomposes with an increasingly steep gradient. At 100% oxygen concentration, Phase III disappears entirely and becomes part of the steep Phase II volatilization. Additionally, the removal of nitrogen from the mixture (100% oxygen) causes the residual mass to decrease to 4% from around 8% in all experiments that used nitrogen gas.

4.3.5 Experimental Quality Control Test

The three lines indicated by the "20%" label in *Figure 11* represent repeated tests under the same experimental conditions of 20% oxygen and give some idea as to the level of accuracy and repeatability of the tests carried out in this study. While some variation can be seen, fluctuations are within 5% and do not overlap with the thermo-grams from 10% or 30% oxygen experiments, giving a reasonable degree of confidence for these results.

Figure 11: *Thermo-grams of Paper in Different Oxygen Concentrations*



4.4 Discussion of the Plateaus in the Thermo-grams

The thermo-grams of increasing oxygen concentration in *Figure 11* show the expected result of an increased mass loss for the combustion at any given temperature up to about 460^{o}C. This can be considered as confirmation of the current understanding that oxidation reaction rates are normally faster than pyrolysis or gasification reactions. Beyond 460^{o}C the air curve forms a plateau and indicates no mass loss for some time. A possible explanation for this is given below.

4.4.1 Postulation of Multiple Mechanisms

A plateau occurs on the 100% oxygen thermo-gram from about 360^{o}C to about 650^{o}C and beyond that the residual mass is eventually reached. The occurrence of a plateau or more than one mass loss rate is normally associated with multiple mechanisms that are dominant at different temperatures or times of reaction [15,16,17]. Typically, this is seen when a sample contains more than one type of compound or molecule. This is indeed the case for paper, and more so for MSW, which is a mixture of various compounds, some saturated some cross-linked and some unsaturated.

4.4.2 Partial Oxidation of Molecular Backbone

Paper can be considered an unsaturated cellulose structure that has the potential to be oxygenated in various places. It consists of a long unsaturated hydrocarbon backbone compound that can be linked with oxygen addition reactions as well as simultaneously releasing partially oxidized reaction products. The chemical structure of the various MSW components provides a basis for understanding why the different degradation phases occur in the experiments performed. The first, major process which occurs between the temperatures of 300^{o}C to about 350^{o}C is very likely the combustion of the backbone. The second, minor process occurs between 350^{o}C and 550^{o}C and can be attributed to the combustion of aromatic rings or saturated cellulose material. The plateau is probably a manifestation of the oxygen addition reactions, which are the first, yet most energy intensive reactions when oxidizing hydrocarbons. Once the oxygen addition occurs, the complete carbon oxidation process, to CO_2, can occur more rapidly.

4.4.3 Applicability to WTE / OEC systems

Further investigation into this process was carried out by changing the amounts of oxygen. Oxygen concentrations of 10% and 30% are of particular interest and serve two purposes: The first objective was to elucidate the effect of oxygen and confirm that the suggested Phase II and Phase III division of the combustion process is dependant on the oxygen concentration as would be expected. Secondly, the 30% oxygen condition simulated an oxygen enhanced combustion atmosphere. The 10% oxygen atmosphere simulates a region in the combustor that is deficient in oxygen. This kind of atmosphere can occur either down stream of the fuel in the combustor or in a fuel rich zone. Therefore, these tests provided an insight into the combustion performance of MSW that may be extrapolated to waste tires.

Figures 9 and 11 show the results of the oxygen enhanced combustion as compared to that of air. As expected, the MSW oxidizes more quickly in the presence of increased oxygen. Furthermore, the oxidation of the primary MSW components, i.e. the plateau and Phase II decay process, moved to a lower temperature. This is consistent with a mechanism dependant on oxygen concentration and indicates that more oxygen is available for oxidizing the unsaturated hydrocarbon structures while simultaneously oxidizing the other saturated or cross-linked molecules. Other heating ramp rates displayed similar results.

4.4.4 Possible Role of Oxygen Addition in Plateaus

One possible explanation for the increased mass shown in the thermo-gram plateaus in *Figure 10* is the occurrence of oxygen addition reactions. It can be seen that as the oxygen content increases from 0% to 30%, the plateau moves to lower temperatures and the two combustion processes become more pronounced. The observed trend of the movement of the plateau is expected to continue, but in fact reverses for the LDPE, PETE and rubber samples as oxygen concentration is raised to 50%, 90% and 100%. The observation that the plateau occurs at a higher mass fraction for increased oxygen may be due to oxygen addition at certain positions on these MSW molecules. For example, oxygen may be inserted in the double bond region of a given compound, thus adding some weight to the compound. This insertion would ultimately lead to complete oxidation at higher temperatures. In fact, some indication may be evident in the increased oxidation rates for the Phase II decomposition in *Figure 11*.

This hypothesis is also supported by the fact that all experiments carried out in a pure N_2 atmosphere had smooth mass loss curves. One explanation for this observation is that only enough energy needs to be imparted to gasify or release the compounds from the solid, and no additions occur. This can occur through many processes, such as breaking the carbon bonds on the backbone or breaking the bonds between the backbone and other cross-linked molecules. Once that bond is broken, the aromatic ring has a high enough vapor pressure to stay in the gas phase and be carried away in the reaction gas.

5. CONCLUSIONS

5.1 General

These results give insight into the complex relationship between oxygen in the combustion gas, and the combustion behavior of different chemical components of MSW. Two sets of experimental results were presented: the first analyzed the different behavior of eight MSW components in an air environment in order to better understand WTE combustion, and the second investigated the effect of varying oxygen concentrations on the volatilization and combustion phenomena of these different components. A framework of four phases of mass breakdown was used to describe experimental results, including Phase I dehydration; Phase II volatilization; Phase III inhibited volatilization; and Phase IV involving a persistent component or intermediary.

5.2 Combustion of MSW fuel

Results from MSW components in air showed that about 10% of the MSW mass was lost as moisture in Phase I, the majority was lost in Phases II and III, and only 2.1% was lost in Phase IV. The vast majority of mass loss, and hence heat release, occurred between 300°C and 500°C. These results suggest that increasing combustor temperature will not be effective at reducing the amount of residual carbon in WTE bottom ash as the residual components are limited by transport limitations at the solid/gas interface rather than by temperature. These results were further confirmed in the oxygen enhanced experiments which showed higher oxygen concentrations reduced these limitations. As such, it is suggested that agitation inside the combustor, oxygen enhancement and pre-shredding are three methods used to assist combustion in a WTE.

5.3 Oxygen Enhanced Combustion

Results from varying oxygen concentration were found to alter the combustion behavior of MSW components in a number of expected, and also unexpected, ways. Oxygen accelerated the onset of Phase II decomposition significantly for all components. Adding oxygen above 30% concentration had mixed effects on Phase III volatilization – for LDPE, PETE and rubber samples, the rate of mass loss was retarded. It is postulated that oxygen addition reactions occur with the backbone structure of these molecules and form relatively stable intermediary compounds. However, for most components, a higher oxygen concentration accelerated Phase III transport-inhibited volatilization and even reduced the residual mass when using 100% Oxygen in some cases.

5.4 Explanation of Plateaus in Experimental Results

The existence of several plateaus of little or no mass change in most samples is unusual for most traditional combustion research and indicates the existence of several compounds even within the MSW component samples selected. Many MSW molecules contain long chain polymers or molecules that present different opportunities for combustion such as breaking of the backbone, addition of oxygen onto the backbone, or volatilization of branches. Each of these processes have different activation energies which depend on related bond strengths, and may offer an alternative explanation for the plateaus observed in these experiments.

5.5 Topics for Future Research

- Transport mechanisms at the solid/gas interface of an MSW particle size during combustion.
- Combustion chemistry of long chain polymers in an oxygen enhanced environment.
- Effect of particle size on MSW combustion characteristics.
- The effect of grate vibration in a WTE on organic residue in bottom ash.
- Design of an oxygen-enriched or 100% oxygen WTE system.

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Part II:

MUNICIPAL SOLID WASTE MANAGEMENT IN CHINA

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PART II: MUNICIPAL SOLID WASTE MANAGEMENT IN CHINA

7. SUMMARY

This section has two objectives: To give an introduction to the environmental challenges being faced in China at the beginning of the twenty first century, and to present an outline of the waste management situation in China with a focus on waste-to-energy technologies.

This century is set to be China's century, but serious environmental problems are creating a bottleneck for economic growth for this new economic giant. According to the World Bank, the benefits of over two decades of rapid GDP growth are beginning to be reversed by the cost of environmental and ecological damage. One of the most serious problems is that of waste management as China has become the world leader in solid waste production with over a billion tons per year. One part of this massive amount is municipal solid waste (MSW) production which is estimated to be 190 million tons per year. The World Bank stated that the biggest waste management problem facing China is the lack of modern sanitary landfills. Over one third of China's 623 major cities are already surrounded by trash and only 20% of China's MSW is properly collected and disposed of at the present time.

An increasing number of cities have been turning to waste-to-energy (WTE) as a viable alternative. There are at least 19 WTE facilities in China, which is relatively few when compared to neighbors Japan, Korea and Taiwan. However, WTE capital costs per daily ton have been as low as one third of those in the west which challenges conventional thinking about the affordability of MSW combustion facilities. Chinese MSW has an average heating value of 3300MJ/kg which is less than one third of western MSW, and for this reason, China has been pushed to develop its own local brand of fluidized bed combustion technology which is amenable to the use of auxiliary fuels and can handle the high moisture contents of MSW experienced in this country.

Waste-to-energy technology was recently placed on the Chinese governments list of 'encouraged technologies', and the country aims to create WTE facilities to dispose of 30% of its MSW in the coming decades. If current trends continue, China is set to become a huge market for WTE technology during this period.

8. INTRODUCTION TO CHINA

8.1 General Information

The Peoples Republic of China is the most populous country in the world, with a population of over 1.3 billion and one of the fastest growing economies in all of history. China's wealth quadrupled in the last 20 years and presently still growing at 8-9% per year. China now has a GDP of $7.2 trillion (purchasing power parity dollars = $US1.3trillion) which ranks it as second only to the United States [1]. These factors have seen China become a world leader in many regards including being the worlds largest consumer of steel at 142 million tons per year [2], the largest producer of electronic equipment (over 80% of world production), greatest number of cellular phones users (269 million and rising [3]), and was recently given the dubious honor of surpassing the USA as being the worlds largest producer of solid waste with over one billion tons per year [4].

8.2 History

For centuries China stood as a leading civilization, outpacing the rest of the world in the arts and sciences, but in the 19th and early 20th centuries, the country was beset by civil unrest, major famines, military defeats, and foreign occupation. After World War II, the Communists under Mao Zedong established an autocratic socialist system that, while ensuring China's sovereignty, imposed strict controls over everyday life and cost the lives of tens of millions of people. After 1978, his successor Deng Xiaoping and other leaders focused on market-oriented economic development and by 2000 vast improvements in economic well-being had been experienced by the country. For much of the population, living standards have improved dramatically and the room for personal choice has expanded, yet political controls remain tight [1].

8.3 Awareness of China in the West

In recent years, the economic success and increasing power of China has created great interest from the West. This is reflected by the increasing frequency that China is included on the front page of western magazines and periodicals; some examples are given below.

The June 27, 2005, *Time Magazine* cover showed Mao Zedong wearing a Louis Vuitton shirt and discussed China's rise to power over the last decades - pointing out that China now trains over four times as many engineers as the USA. The December 6, 2004, issue of *Business Week Magazine* led with the cover story "*The China Price: The three scariest words in US Industry*" discussing the extreme competitiveness of Chinese manufacturing operations and the migration of manufacturing jobs to China leading to the USA's annual $US150 billion trade deficit with China. The April 23rd, 2005, issue of *The Economist* contained a number of China related articles including "*The China Question*" analyzing its rise in military spending and "*Managing Unrest*" about the hostile political relations between China and Japan. China maintains a standing army of 2.3 million soldiers and increased military spending by 13% this year to 247.7 billion Chinese Yuan ($US31b) [5]. In the June 20, 2005, issue, the *U.S. News and World Report* cover story "*The China Challenge: What the awakening giant will mean for America*" stated that in China, there are an estimated 2 million people whose net worth is at least $US40 million, but at the same time an average laborers wage is $US50/month. This years May 9 issue of *Newsweek*, in a special report titled *"China's Century"*, mentioned that over 60,000 supermarkets have been built in China since the first was constructed in 1993 (almost 14 per day), and 300 million people have been lifted out of poverty since economic reforms began in 1979.

Whether it be in the political, economic, military, or social realm, it is clear that China must be considered as a major player in the modern world, and will be increasingly dominant in the future.

9. ENVIRONMENTAL PROBLEMS IN CHINA

9.1 Introduction

The environmental situation in China is indeed dire. By focusing so intensively on manufacturing and technology, China has caused, and continues to cause, catastrophic and irreversible damage to its land, water and air. A report released in 1998 by the World Health Organization noted that seven of the ten most polluted cities in the world can be found in China, and that acid rain falls on about 30% of China's land area [6].

9.2 Political Environment

Environmental problems are always political ones because they can have great impact on the health, wealth, and even the life and death of members of the general population. Pan Yue, the deputy head of the State Environmental Protection Agency (SEPA) calls environmental pollution "the bottleneck constraining economic growth in China" [7]. Although public opposition has been suppressed by the communist government in the past, the growing middle class are starting to cautiously demand better environmental standards to go along with their newly found wealth. World leaders from developed nations are also putting pressure on China to restrain its rampant growth and apparent disregard for the natural environment due to the global scale of China's pollution problems.

Only in the last decade has legislation begun to establish regulations to curb this environmental damage. On the national level, policies are formulated by the State Environmental Protection Agency (SEPA) and approved by the State Council. The role of SEPA, which was only recently elevated to ministerial level in 1998, is to disseminate national environmental policy and regulations, collect data and provide technological advice on both national and international environmental issues. Although still an infant government organ compared to China's great political organizations such as the *Land and Resources Bureau* or the *Reform and Development Council* (both deeply involved with encouraging economic growth in China), SEPA is slowly gaining public support as well as political strength as more Chinese leaders start to take environmental problems seriously. However, this ministry of state is woefully under-funded, and incredibly has a staff of only 300 people at a national level with which to manage the environmental problems of over one fifth of the world's population [8]. The government made a commitment to raise spending on environmental protection to 1.5% of GDP (or $US16.5b) by the year 2005 in its 10th five year plan, but this goal has yet to be reached [4].

9.3 Water Resources

9.3.1 Water Supply

Looking at China as a whole, the country has a huge water resource of 2,800 billion cubic meters of water annually, however, in per capita terms this amounts to only one quarter of the global per capita average for water availability making it one of the lowest in the world. China's water resources are concentrated in the south such that the north and west experience frequent droughts [9]. Around half the population, i.e., 650 million people, have water supplies that are contaminated by animal or human waste according to SEPA studies. In most rural villages it is normal to dump garbage and sewage in rivers as well as wash clothes, dishes and even oneself in the same water. A large proportion of the rural population do not have proper running water, sewage treatment, and waste collection systems. Brown et al estimates that demands for water by industries are projected to grow from 52 billion tons in 1995 to 269 billion tons in 2030 and that residential demand for water is also projected to increase to 31 billion tons at the same time [10].

9.3.2 *Waste Water Discharge*

Waste water discharge is estimated at 20.4 billion tons of sewage and 19.7 billion tons of industrial waste water [13]. The sewage treatment rate in China was almost zero before 1970; reached 3% in the 1980s; and averaged only 10% in the year 2000. In major cities, with populations of over 500,000, the sewage treatment rate is expected to reach 60% by the end of this year due to aggressive policies by the government. For provincial capitals and key resort cities such as Beijing and Shanghai the figure is higher at an estimated 70% [11]. However, despite these improvements, a SEPA report found that over 70% of the water in five of China's seven major river systems was unsuitable for human contact.

9.4 Air Pollution

Without a doubt, the air pollution problems in China are the worst in the world, mainly due to industrial emissions but also to increasing motor vehicle usage. Zhu Rongji, the former prime-minister of China stated that "I would shorten my life by at least 5 years if I worked in Beijing". The level of particulate matter (PM_{10}) concentrations in the Beijing air hovers around 3 times the acceptable limits given by the U.S. Environmental Protection Agency for ambient air quality. These levels have already improved slightly since 1997 when SEPA began to monitor air pollution in major cities and found annual average total suspended particulate (TSP) levels in Chinese cities varied from 32 to 741$\mu g/m^3$ per cubic meter compared to the EU air quality standard of 80 $\mu g/m^3$. In the northeast where the air pollution is worst, these levels equate to an amount of over 20 tons of dust falling on each square kilometer per month [12].

According to the World Bank, China has 16 of the 20 most polluted cities in the world and World Health Organization estimates suggest that 300,000 people die prematurely in China each year due to respiratory diseases. The main reason for the poor air quality is that around 70% of China's mushrooming energy needs are supplied by coal-fired power stations (compared to 50% in America). Compounding these problems is the fact that China's coal is of poor quality, with high sulfur and mercury levels, and many power stations are not equipped with air pollution control equipment. Air emissions from rocketing car ownership are also becoming an issue.

9.5 Economic Impact of Pollution

Pollution costs the Chinese economy somewhere from 3 to 12 percent of GDP each year, according to estimates of various Chinese and Western scholars. Ecological damage potentially costs another 5 to 14 percent [13]. Estimates on the cost of environmental damage include crop damage due to acid rain, lost income due to desertification, medical bills, lost work due to illness, and money spent on disaster relief due to resource depletion. Even at the low end of these estimates, the environmental damage is roughly equivalent to China's annual economic growth, meaning that the Chinese economy is producing little or no new net national wealth.

9.6 Ecological Impacts

There is a huge amount of anecdotal evidence regarding the environmental destruction occurring in China at the present time but little is reported in the international media, or the local media for that matter. Reliable figures are very hard to find, because of the low level of regulation and a severely under-funded and under-resourced State Environmental Protection Agency as previously mentioned.

However, some figures are beginning to be released, such as the fact that over 23 million tons of soot and particulate are released into the air every year which successfully manages to block the sun on most days on the Eastern coast as well as reducing crop yields by 5-30% over 70% of the land in China according to a Georgia Tech Study [14]. Also, 180,000 hectares of farmland is salinized each year due to draw downs on the water table, and an additional 200,000 hectares turn into desert partly due to the over 5 billion tons of topsoil that are eroded away from deforested land annually. Millions of dollars of damage are also caused to local fisheries by industrial pollution: giving rise to events such as the algal blooms in Bohai Sea in northern China that destroyed over $US120 million worth of fish, or the wash-up of over 2000 tons of fish in Anhui province [13]. Fish kills occur regularly in China due to extremely high nutrient levels which remove dissolved oxygen, as well as the problems of toxic pollution in some areas.

9.7 Health Impacts

In addition to the serious environmental impacts, health impacts on local people are also severe. More than 80 percent of children aged 5-7 tested in Guangzhou in early 2000 had unhealthy levels of metallic lead in their blood; studies in other cities have also shown rates exceeding 50 percent [15]. Lead has been shown to retard children's physical and mental development and damage the nervous system. In the same region in southern China are the so called "cancer villages" where over half the deaths are due to cancer. This is attributed to the high level of toxic metals in waste water being emitted from mines and factories into local waterways. When examining health effects of air pollution, it is shocking to note that chronic obstructive pulmonary disease is the leading cause of death in China; the rate of death from such disease is twice the average for developing countries and is roughly equal for men and women, even though few women smoke; the American Chemical Society estimated that more than a million Chinese deaths a year or one-eighth of total deaths were attributable to air pollution between 1990 and 1995.

10. Solid Waste Management in China

Figure 12: *A "Landfill" in the village of Taipingzhuang in Liaoning province*

10.1 Introduction to Waste Management in China

In all of history, no country has ever seen as large or as rapid an increase in solid waste generation as China is seeing at the present time. Last year China produced over a billion tons of solid waste ranking it as the global leader - even surpassing the USA [16]. The solid waste includes coal ash, mine tailings, construction waste, and a recorded 190 million tons of Municipal Solid Waste (MSW). China is set to produce 490 million tons of MSW per year by 2030 according to a World Bank report released in May 2005 [4]. It is estimated that China will need to develop an additional 1400 landfills during this time period. Up to the present time, an estimated 6 billion tons of MSW have accumulated in areas around China's cities occupying an area of over 500 square kilometers [17]

10.2 Rural Solid Waste

Urban residents make up only 28% of China's population; the remainder live in villages and farms in China's vast rural countryside. These residents, for the most part, receive no refuse collection service. It is common for refuse to be dumped on any unused piece of land, or directly into a river. While most rural waste in non-toxic, the main problems are bacteria which cause a high incidence of gastric disease in the summer, and non-biodegradeable plastic bags that clog waterways and are blown in the wind. Unlike the U.S., where littering is socially unacceptable, in China people seem unaware of the health hazards related to garbage and are not averse to washing in the same river which they dump garbage into. Finding solutions is difficult due to the lack of funding for local municipalities to spend on waste management, and the corollary lack of access to technical alternatives. A typical scene of a local river in the rural village of Taipingzhuang, population 1800, is shown in *Figure 12*.

10.3 Municipal Solid Waste

Waste collection is sufficient in most of China's big cities with daily MSW collection and street sweeping although disposal is still a problem. China's cities are dense, with almost the entire urban population living in low rise apartment buildings. The most common method of waste collection in China is a central drop-off scheme for each neighborhood or building. Drop off points may be as simple as a designated spot to pile garbage, sometimes with the use of barrels or bins, or even refuse sorting centers in some cases. Collection spots are normally odorous and attract insects and rodents in the summer.

In general, Chinese urban MSW collection systems are reliable and provide a similar level of sanitation to those in North America. However, transfer and disposal systems are not well developed, and do not adequately protect the environment. MSW generation rates for Chinas 21 largest cities, with populations over 2 million people, are shown in *Table 5*.

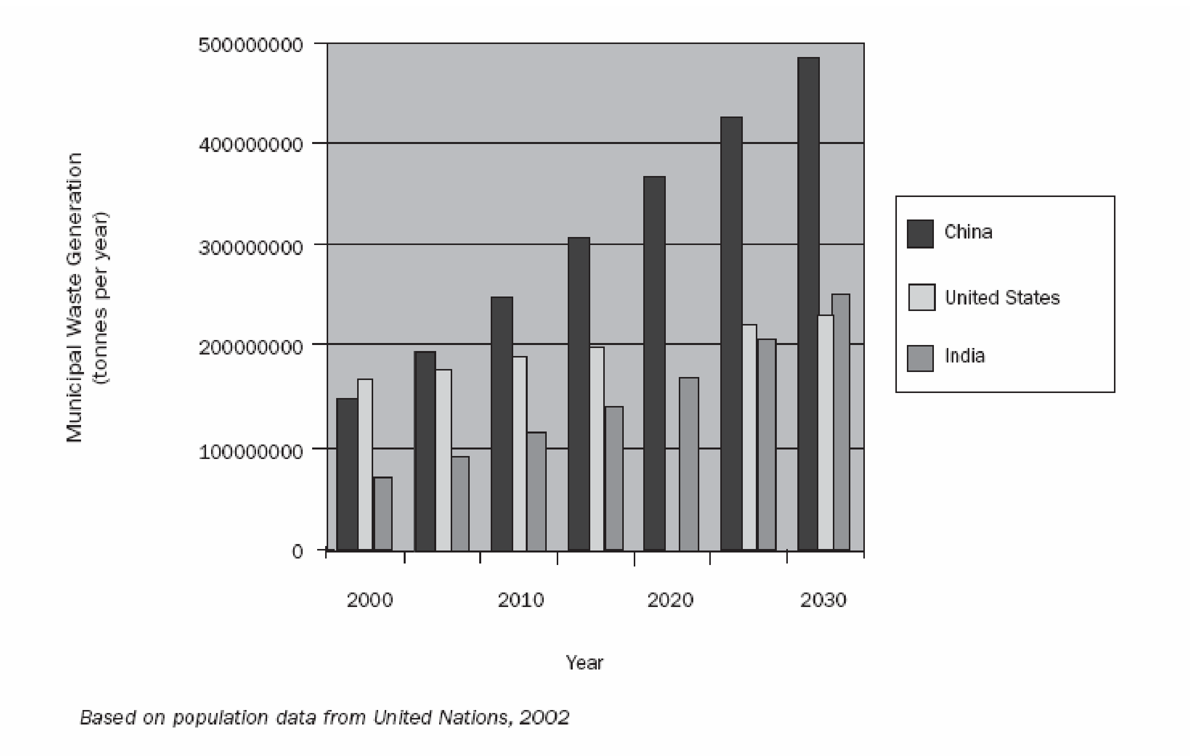
Table 5: *MSW generation in China's Largest Cities [7]*

City	Province	Population (2000)	MSW generation Tons per Year	TPD
Shanghai	Shanghai	12,887,000	4,233,000	11,597
Beijing	Beijing	10,839,000	3,561,000	9,756
Tianjin	Tianjin	9,156,000	3,008,000	8,241
Wuhan	Hubei	5,169,000	1,698,000	4,652
Chongqing	Chongqing	4,900,000	1,609,000	4,408
Shenyang	Liaoning	4,828,000	1,586,000	4,345
Guangzhou	GuangDong	3,893,000	1,279,000	3,504
Chengdu	Sichuan	3,294,000	1,082,000	2,964
Xian	Shaanxi	3,123,000	1,026,000	2,811
Changchun	Jilin	3,093,000	1,016,000	2,784
Harbin	Heilongjiang	2,928,000	962,000	2,636
Nanjing	Jiangsu	2,740,000	900,000	2,466
Zibo	Shandong	2,675,000	879,000	2,408
Dalian	Liaoning	2,628,000	863,000	2,364
Jinan	Shandong	2,568,000	844,000	2,312
Guiyang	Guizhou	2,533,000	832,000	2,279
LinYi	Shandong	2,498,000	821,000	2,249
Taiyuan	Shanxi	2,415,000	793,000	2,173

Qingdao	Shandong	2,316,000	761,000	2,085
Zhengzhou	Henan	2,070,000	680,000	1,863
ZaoZhuang	Shandong	2,048,000	673,000	1,844

Current levels of MSW generation in China are 0.4 kg/person/day on average, but as high as 0.9 kg/p/day in cities, compared to 1.1 kg/p/day and 2.1 kg/p/day in Japan and the USA respectively [4]. However, the World Bank estimates that due to increases in living standard, the Chinese average figure will surpass 1kg/p/day by 2030. The effect of the increased per capita rate is compounded by the huge predicted increase in urban population, expected to almost double from 456 million people in 2000 to 883 million in 2030. This gives rise to the high predicted growth rates of MSW in China shown in *Table 6*.

Table 6: *Projected MSW Generation for China, India and the USA.*



10.4 MSW Composition

China's MSW contains a large amount of waste ash (approximately 25 million tons per year or 13%) as well as high levels of organic waste (40-65%) [18]. China's waste stream is growing fastest in paper, plastics, and multi-laminates such as tetra-pak or plastic coated paper. Developed countries such as those in the E.U. or the U.S. have about 10 times more paper in MSW than China does, although this disparity is slowly eroding as living standards improve. A general comparison between MSW composition in the USA and China is shown in *Tables 7 and 8.*

***Table 7**: MSW Composition in China compared to the USA*

Geographic Area	New York	USA	General	Qingdao, China	Chinese City
Source	SCS Engineers	EPA Report	Tchobanoglous	Henderson et al [19]	Rissanen et al [18]
Year of publication	1992	2000	1990	1997	2004
Paper	31	37.4	40	3.1	2.5
Plastic	9	10.7	7	4.5	4
Food-waste	13	11.2	9	60	50
Yard waste	4	12	18.5	n/a	n/a
Misc. Organics	25	12.5	8	n/a	n/a
Glass	10	5.5	8	0.8	2.9
Iron	4	6	6	0.3	5.1
Other Metals	1	1.8	3.5	0	1
Fines/other	3	2.9	n/a	31	35

***Table 8:** MSW Characteristics in Chinese Cities and New York* [21,22]

City Name	Moisture Content %	Density (kg/m3)	Paper %	Plastic %	Glass %	Metal %	Food / Organic waste	Inorganic/Ash
Changzhou	48.47	450	3.56	7.95	3.5	1.04	44.4	34.6
Hangzhou	53.6	360	3.68	6.62	2.09	0.98	58.19	24
Guangzhou	50.12	250	5.4	8.99	3.37	0.49	60.17	17.12
New York	21	550	26.6	8.8	5	4.8	16.8	12.3

10.5 Legislation for MSW

In China, the State Environmental Protection Agency (SEPA), which forms part of the People's Congress, and the Ministry of Construction (MoC) are presently sharing the role of making MSW management legislation and this results in a complex system for municipalities to follow as shown in the partial list of laws and regulations in *Table 9*. These laws create a set of technical standards for comprehensive waste management which has been in operations since at least 1996, but in reality enforcement is lax and very few municipalities come close to achieving these standards [4].

The most recent changes occurred at the 13th session of the Standing Committee of the 10th National People's Congress (NPC) which amended the law on solid waste pollution prevention to encourage the recycling of solid waste, clarify the responsibilities of polluters and regulate the import of waste from overseas [20]. This is seen by observers as a move towards a polluter pays system.

***Table 9:** Summary of National Chinese Laws and Regulations on MSW [4]*

Law or Regulation	Brief Description	Issuer	Effective Date
Regulations Regarding Municipal Residential Solid Waste	Regulations for management of collecting, transferring, and treating residential solid waste	The Ministry of Construction, PRC	September 1, 1993
Low on Prevention and Control of Environmental Pollution Caused by Solid Waste of PRC	First law to regulate the management of MSW	The Standing Committee of the National People's Congress(including SEPA)	April 1, 1996
Technical Policies on the Disposal of Domestic Waste and the Prevention of Pollution	Guidance and standards of the technologies applied in MSW treatment	The Ministry of Construction, PRC	June 1, 2000
Law for Environment Impact Assessment of PRC	Emphasize the importance of preventing environmental pollution from source and regulate EIA approval permitting process	The Standing Committee of the National People's Congress(including SEPA)	September 1, 2003

10.6 Collection and Disposal

It is estimated that only 20% of MSW generated in China is properly collected and disposed of despite the fact that the government spends around 30 billion Yuan ($US3.7 billion) on solid waste management per year [4]. The remaining waste is released into rivers, burned in heaps, or dumped without containment or treatment.

However, significant improvements have been made in the waste sector over the last ten years, with most of the larger cities aggressively moving towards sanitary landfills and more recently combustion technology. In the late 1990s, The World Bank stated that unmanaged land-fills are China's most acute solid waste management problem due to their uncontrolled release of methane and other greenhouse gases, release of carcinogenic chemicals, toxic leachate seeping into groundwater, and other health and environmental hazards, and this is still largely true today. *Table 10* gives some idea of the methods of waste management in China's large cities.

Table 10: *Treatment methods of Collected MSW in 6 Metropolitan Cities in China* [21]

%	Simple Landfill	Sanitary	Incineration or

		Landfill	**waste-to-energy facilities**
Beijing	73	24	3
Tianjin	73	27	0
Shanghai		95	5
Chongqing	74	13	13
Wuhan	13	84	3
Guangzhou		95	5

10.7 Recycling

China's overall waste management system includes a high degree of sorting and recycling carried out with the manual labor of garbage pickers. Official estimates show that around 1.3 million people work in the waste collection industry, including street sweepers paid by local governments. An additional 2.5 million people make their living as "scavengers" on the waste stream – generally very poor and disadvantaged people [19]. There is no official sorting or separation system. The cost of living is so low in China (generally $US1 can satisfy daily nutritional requirements), that it is possible to make a living collecting bottles, paperboard and cans for many. Some typical prices can be seen in *Table 11*. Note that one U.S. dollar is equal to approximately eight Chinese Renminbi (RMB).

Table 11: *Price of Recycled MSW materials in Shanghai, January 2004* [4]

Material	**RMB/kg**
Newspaper	0.95
Plastic Bottles	0.22/each
Other Plastic	0.8
Waste iron	0.9
Aluminum Cans	0.11/each
Aluminum metal	10
Beer Bottle	0.1
Cotton/clothing	0.7
Television	5-280/each
Refrigerator	30-150/each
Air Conditioner	110-800/each

10.8 Composting

Composting is a viable option in China because over 50% of the waste stream consists of bio-degradable organics. However, composting efforts have been hindered by improper separation of glass, plastic and other chemicals from the compost feed. In small operations that have been experimented with so far, the compost product has been of limited value, discouraging further composting activities. However, the majority of rural food waste is recycled as pig feed or fertilizer.

10.9 Landfilling

Landfilling is the most common method of solid waste disposal in China. China's 660 cities now have about 1000 major landfills taking up aver 50,000 hectares of land, and will require an estimated additional 100,000 hectares over the next 30 years for new landfill space [4] . As noted earlier, China has only started to develop modern sanitary landfills in the last decade, and the majority of solid waste still causes severe environmental problems. Generally, the quality of Chinese landfills does not come close to the standards set in the West: Every dump has scavengers (human and animal) on site, typically there is no leachate collection system or treatment, no capping or cover, limited or no compaction, and no gas control system. However, in the next 10 years, it is expected that all major cities with a population of over 1 million will have modern sanitary landfills and that simple landfills will slowly be phased out.

China has very good legislation regarding the construction of sanitary landfills provided by the 1989 *Urban Municipal Solid Waste Landfilling Technical Standard*; however enforcement lags behind the ideals set out in this legislation. The standards require similar levels of design to those of American standards for example an impermeable liner, distancing from the water table, buffer zones, low-permeability final cover, leachate collection and treatment, and gas control systems. However the problem runs deeper than a lack of enforcement, as most municipalities simply do not have the cash or technical knowledge to construct these kinds of facilities. Enforcement of the standard is left to municipal environmental protection bureaus, which have little power or financial resources.

However, a few of the largest landfills constructed in recent years in wealthier cities such as the Shanghai and Guangzhou have reached excellent environmental standards.

10.10 Waste-to-energy (WTE) in China

As land surrounding large cities becomes increasingly scarce, the combustion of MSW in waste-to-energy (incineration, WTE) facilities has become the preferred disposal option in many Chinese cities. Incineration has several benefits such as great volume reduction and destruction of pathogens, but is constrained by high capital cost and potential toxic air emissions if poorly designed.

MSW incineration began in China in the late 1980s and developed rapidly in the 1990s. The most accurate figures identified for the number of WTE combustors in China showed the existence of 19 facilities in the year 2003, with a total capacity of 7000 tons per day (TPD) [18]. This is a very low number for such a large country – the small island of Taiwan exceeds this figure with 21 facilities serving 22 million people, while the U.S. has over 50 [22]. Although relatively recent, this figure will have increased substantially since published and the more recent World Bank Report released this year states that over 30 large and middle size cities have constructed or are constructing WTE plants as of May 2005, with four in Shanghai alone.

Many Chinese WTE plants are set up with technology provided by foreign companies such as Mitsubishi, Ahlstrom, Novel etc. (see *Appendix A* for a list of Waste Management companies in China). However, an increasing number of municipalities make use of locally developed technologies from research institutions such as Zhejiang University where over 90 Ph.D. students are working in the area, and a research WTE unit is in operation. As of 2002, more than thirty enterprises, research institutes and universities were concentrating on research and development associated with incineration technology and equipment [21].

10.10.1 The Economics of WTE in China

Due to a number of factors such as the low cost of land, commodities and labor the capital cost of WTE in China are significantly lower than overseas. International average costs for landfilling and incineration are $30 and $150 respectively which clearly reflects the high capital cost of WTE facilities – generally over $US100,000 per daily ton. However, the capital cost of WTE construction in China has been as low as $31,000 per daily ton [8] and may decrease further. This may make general wisdom about the affordability of WTE held in the USA and Europe non-applicable to China.

Although scanty information is available, a list of a few of China's WTE plants and costs where available are shown in *Table 12.*

Table 12: *Some of China's WTE plants and Statistics*

Name	Province	TPD	Power (MW)	Designer	Technology	Year built	Capital Cost (US$m)	APC	Notes
Shenzhen	Guangdong	450		Mitsubishi (Japan)	Martin grate	1988		ESP and Scrubber	First modern incinerator in China
Pudong	Shanghai	1000	17	Alstorm(France)	Stoke grate	1999	84	fabric filter	Requires auxiliary oil injection
Ningbo	Zhejiang	1050		Novel (Germany)	Stoke grate	2001		fabric filter	Requires auxiliary oil injection
Longgang	Guangdong	300		Richway (Canada)	Rotary Kiln	1999			5T of diesel added per day
Hangzhou	Zhejiang	800	12	Zhejiang University	Fluidized Bed	2002	24.4	Scrubber and fabric filter	Auxiliary coal is added (20% weight); over 10 incinerators of this design made so far in china
Shaoxing	Zhejiang	400		Chinese Academy of Social Sciences	Fluidized Bed	2001	16.9	semi-dry scrubber and fabric filter	Uses co-fired coal
Haerbin	Heilongjiang	200.0		Ebara (Japan)		2002	18		
Laogang	Shanghai	1000		Onyx			61		
Changzhou	Jiangsu	450		JFE Holdings (Japan)		2000			
Minhang	Shanghai	3000				2005	180		Largest in Asia
Chongqing	Sichuan	1000							
Suzhou	Jiangsu	1000		Everbright International					
Huizhou		600	12	Enersave (Singapore)					

10.10.2 Types of Technology

MSW combustion technologies in China can be classified into three main types: Mechanical stoker grate, rotary kiln and fluidized bed. The first is the mass-burn technology that is used predominantly in the West. The rotary kiln type furnace is also used in some WTE combustors in developed countries, mostly for medical waste incinerators. Although fluidized bed reactors are rarely used for modern WTE combustors in the West, a local variety of this technology has been developed by the Academy of Sciences and Zhejiang University in China. Experience has shown that fluidized bed combustion is more suitable for the treatment of high moisture content Chinese MSW than foreign developed technologies. One advantage is the ease of addition of an auxiliary fuel such as coal or diesel oil, which is necessary to maintain combustion due to the low heating values of most Chinese MSW. Additionally, the fluidized bed combustors are suitable for high moisture content wastes such as those in China.

10.10.3 Heating Value of Chinese MSW

Due to the high food and inorganic waste content of Chinese MSW, its heating value is much lower than that of North American or European garbage, although it has increased in recent years. In the year 2002, the average calorific value of Chinese MSW was about 3300MJ/kg, but ranged from as low as 2000MJ/kg up to 7000MJ/kg. This value varies significantly with city size, standard of living, season as well as the type of fuel used locally for heating (coal results in high ash content in MSW and hence lower heat content). U.S. MSW generally has a heating value between 11-12 MJ/kg. The World Bank specifies the "Autogenic limit" for WTE fuel is 6MJ/kg. This means that most Chinese MSW cannot sustain combustion without an auxiliary fuel.

10.10.4 Air Emission Standards for WTE

Emission standards in China did not exist until the year 2000, and even now most incinerators do not have air pollution monitoring or control systems. In fact it is very difficult to buy monitoring equipment in China, and international certified laboratories must be used to get reliable environmental testing done as domestic operations are not well developed. Only the newest incinerators, designed by international companies, have such monitoring systems and reach the SEPA emission standards shown *in Table 13*. Even if these standards were reached, it can be seen that the SEPA national emission standards are significantly more lenient than the American EPA ones, especially for the acid rain causing compounds such as SOx and HCl.

Table 13: *SEPA National Emission Standards for Incineration, 2000*

Name	Unit	Limit	EPA limit
Particulate	mg/m3	80	34
SO2	mg/m3	260	55
NOx	mg/m3	400	250
CO	mg/m3	150	40
HCl	mg/m3	75	15
Hg	mg/m3	0.2	0.55
Cd	mg/m3	0.1	0.04
Pb	mg/m3	1.6	0.07
Dioxin	TEQ ng/m3	1.0	0.6

10.10.5 The Future of WTE in China

Ten years ago there were no modern municipal solid waste incinerators operating in China, but there were many small and highly polluting manually loaded incinerators without air pollution control equipment. However in recent years, incineration started to be looked on favorably by many cities due to the small land requirements and potential for electricity generation. WTE was identified as an "encouraged technology" by the People's Congress and recorded in the 10^{th} fifth year plan (2000-2005). This has seen every major city (over 600 in China) begin to consider investing in a WTE technology to prepare to reach the target of 30% of MSW being treated by incineration by the year 2030 described in the same plan.

10.11 Waste Management in the Capital City

Beijing, China's capital city, has struggled with waste management problems and already has over 70 small and poorly managed landfills scattered along the city outskirts. However, these operations are still insufficient to cope with the almost 10,000 tons of MSW the city produces per day. With the approach of the 2008 Olympic games, the city is working hard to solve its garbage problem and recently the municipal government released plans to spend up to $US400 million to build the following waste management facilities by 2008: 7 Integrated waste processing where waste is sorted for recycling, WTE or landfilling, 3 more incineration facilities, 2 waste transfer stations and 3 sanitary landfills. After these facilities are completed, Beijing will be able to cope with about 12,500 tons of rubbish on a daily basis.

11. CONCLUSIONS

Although the environmental situation in China is dire, and without a doubt the worst in the world at the present time, increasing public expectations and economic wealth have led to tightening legislation and the stabilizing of environmental conditions at the present time. *The Economist* noted hopefully that the environmental situation in China had "past its nadir", although admitting there was still a long way to go [23].

Waste management is one of the most important facets of this puzzle, and the Chinese government seems to have realized this by aiming to push up environmental spending to 1.5% of GDP (to $US16.5 billion) from around 0.5% presently. The People's Congress has also passed numerous articles of legislation in recent years to clearly define responsibilities of polluters and to reduce pollution of air and waterways.

Although the low heating value of Chinese MSW affects adversely the economics of WTE incineration in China, the last few years have seen an increasing demand for WTE technology supplied by both domestic and international firms. The reasons are the environmental benefits, energy recovery, shortage of land, and the lower capital cost of WTE in China. The Chinese government has been strongly promoting WTE technology and has set a goal for 30% of MSW to be treated by WTE by the year 2030. This represents a capacity of over 400,000 TPD or 400 large scale WTE combustors.

Whatever happens in the future, it is clear that China cannot continue to pollute the environment at the present rate, and that standards of technology, policy, and education need to be improved together to ensure that MSW is managed safely and appropriately.

APPENDIX A: LIST OF WASTE MANAGEMENT COMPANIES IN CHINA

Alstrom (French)
AMEC Environmental Consultants
Asia Base
Basic-Energy
China Everbright Technology (HK)
Cleanaway
Environmental Resources Management (ERM)
Enersave (Singapore)
GolderAssociates
Hangzhou Boiler Works (HBW)
Hudson Electek (US)
Impreglio (Italy)
Ingerop (French)
Intercedent
InterChina consulting
IT Power
JFE Holdings Inc. (Japan)
Meisheng International Group (HK)
Mitsubishi (Japan)
Novel (German)
Onyx (French)
Richway (Canada)
Sembcorp
Shanghai Chengtou Environmental Industries Development Co.
Shanghai Huancheng Waste-to-Energy Co.
Sinosphere
Swire Sita
URS

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