CHAPTER 1

Introduction to Gasification/Pyrolysis and Combustion Technology(s)

HISTORICAL BACKGROUND AND PERSPECTIVE

Archeological studies demonstrate that Trash-Garbage-Waste was generated by Native Americans in Colorado about 6,500 BC in North America. Based upon archeological assessment of the waste site, the Native Americans in that ancient clan generated 5.3 pounds of waste per day as compared to 2.5 pounds per day for middle-class Americans today. The first municipal dump in the Western world is credited to the Athenians of Greece about 500 BC. In Jerusalem/Palestine, the New Testament of The Bible mentions Sheol was likely a dump outside the city of Jerusalem and became synonymous with "Hell." In 1388, the English parliament barred waste disposal in public waterways and ditches. Recycling was mentioned in 1690 when Rittenhouse Mill, Philadelphia, made paper from recycled fibers of waste paper and rags. In Nottingham, England about 1874, a new technology known as "the Destructor" was used to manage garbage; it involved systematic burning, i.e., incineration. The first garbage incinerator was built in the United States on Governor's Island, New York about 1885. It was reported in 1889 around Washington, D.C., that there was lack of places for refuse. Also, the first recycling/sorting of rubbish in the United States occurred in New York around 1898.[1]

Landfills became popular in the 1920s as a means of reclaiming swampland while disposing of trash. Then in 1965, the Federal government of the United States enacted the first Federal solid waste (SW) management laws. In 1976, the Resource Conservation and Recovery Act (RCRA) was created for stressing recycling and hazardous waste management, which likely was instigated by the discovery of Love Canal.[1]

This proves that since the creation of mankind, humans have generated waste. But waste disposal was not a problem when we had a nomadic existence; mankind simply moved away and left their waste behind. In addition, populations concentrating in urban areas necessitated better methods for management of waste. With the initiation of the industrial revolution, waste management became a critical issue. The

Municipal Solid Waste to Energy Conversion Processes: Economic, Technical, and Renewable Comparisons By Gary C. Young

population increase and migration of people to industrial towns and cities from rural areas resulted in a consequent increase in the domestic and industrial waste (IW), posing threat to human health and environmental issues of water quality, air pollution, and land toxicity issues. As the American population grew and people left the farms for life in the city, the amount of waste increased. But the method of getting rid of the waste needed to improve. We continue to dump it. Today, about 55% of our garbage is hauled off and buried in sanitary landfills.

Municipal solid waste (MSW) is garbage that comes from homes, businesses, and schools. Today, this garbage is disposed of in "municipal solid waste landfills" so the garbage does not harm the public health, or land, water, and air environment. MSW landfills are not dumps for the new landfills are required to have liners, leachate collection systems, gas collection equipment, groundwater monitoring, and environmental reporting requirements so as to protect the health and welfare of the community.

Our population is still growing and we are producing more garbage, even with the recycling efforts in full operation. We have come to the "place in time" where the momentum of TECHNOLOGY can help "protect human health and welfare," and thus the environment, by creating an infrastructure design, creation and building of sustainable MSW processes that can turn our WASTE PROBLEM into useful GREEN ENERGY for the betterment of ALL.

INTRODUCTION

The management/treatment of SWs by thermal pyrolysis/gasification technology is increasingly viewed as the best suitable and economically viable approach for the management of wastes such as: residential waste (RW), commercial waste (CW), IW, and MSW, which can be a mixture of these wastes. Various types of Thermal Processes using pyrolysis/gasification technology will be discussed and also why plasma arc gasification process was selected as most attractive for commercial viability.[2–4] The various types of thermal processes based upon pyrolysis/gasification technology are pyrolysis, pyrolysis/gasification, conventional gasification, and plasma arc gasification. One additional thermal process was also considered, which is based upon combustion technology and is known as mass burn (incineration). The key product from these thermal gasification technologies is the conversion of MSW into synthesis gas (syngas), which is predominantly carbon monoxide (CO) and hydrogen (H_2), which can be converted into energy (steam and/or electricity), other gases, fuels, and/or chemicals, and will be discussed in detail throughout this book.

One approach or option for the use of the key product from the conversion of MSW into syngas by a thermal process is for generation of steam and/or electricity in a powerhouse. This approach or "Power Option" will be discussed later in Chapters 2, 4, 5 and 7.

Another approach to the management of MSW is the "BioChemistry Option" (biochemical or biological technologies), which by necessity operates at conditions appropriate for living organisms/microbes. Consequently, the reaction rates are lower and these technologies require feedstock that is biodegradable. One, therefore, could conclude that these biochemical technologies have limitations for applicability for treating MSW compared to the thermal processes. Thermal processes are brute force chemical reaction approach to the management of MSW feedstock in comparison to the finesse of biochemical/biological reactions and consequent limitations of feedstock acceptance. However, the real niche for biochemical processes is to take the syngas (predominantly, CO and H_2), produced by a thermal process, and have the biochemical process (bacteria/microbes) convert the syngas into products such as fuels and chemicals, for example, ethanol, methanol, etc.[5,6] This approach or "BioChemistry Option" will be covered in Chapter 3 with a case study.

Another approach could be labeled the "Chemistry Option," which converts syngas into fuels and chemicals by catalytic chemistry. A catalyst that is used typically is called Fischer–Tropsch catalyst. Thus, a thermal process can be used to produce syngas from MSW and then convert the syngas into chemicals by Fischer–Tropsch chemistry. This "Chemistry Option" is also covered in Chapter 3 with a case study.

Lastly, one could consider landfill gas (LFG) as an approach, which involves the use of microorganisms to produce LFG *in situ* within the landfill. LFG is predominantly methane (CH_4) and carbon dioxide (CO_2) gas, i.e., approximately 50% CH_4 and CO_2. LFG is extracted from landfills with a system typically comprising gas collecting from wells at the landfill to a central point, a gas processing plant, and a gas delivery pipeline to customer(s). LFG could be used in a boiler, dryer, kiln, greenhouse, or other applications. A basic drawback of LFG facility is that the microorganisms producing the LFG leave behind *in situ* landfill leachate as a by-product of the microbiological process that can contaminate soil and groundwater. Even with the latest designs and use of liners in landfills, no LFG system is fail-safe. Another negative factor is that an LFG facility just depletes the energy value of the landfill wastes by using up the most easily biodegraded organics in the MSW. Thus, a lesser energy value of MSW remaining in the landfill after an LFG facility will make it more difficult economically to justify a future MSW management system to eliminate the landfill. In summary, an LFG process just skims off the energy leaving a degraded MSW mess behind to be dealt with later at a much greater cost to any future management system. Thus, this approach is not discussed further as a suitable approach both economically and environmentally.[7,8]

These basic approaches for the management of MSW are schematically shown in Fig. 1.1, whereby the options for the syngas are numerous.

Key Thermal Processes will be discussed next with emphasis upon the conversion of MSW to syngas and an assessment of each process with a thorough technical and economic analysis.

WHAT IS PYROLYSIS?

Pyrolysis can be defined as the thermal decomposition of carbon-based materials in an oxygen-deficient atmosphere using heat to produce syngas.[9] No air or oxygen is present and no direct burning takes place. The process is endothermic.

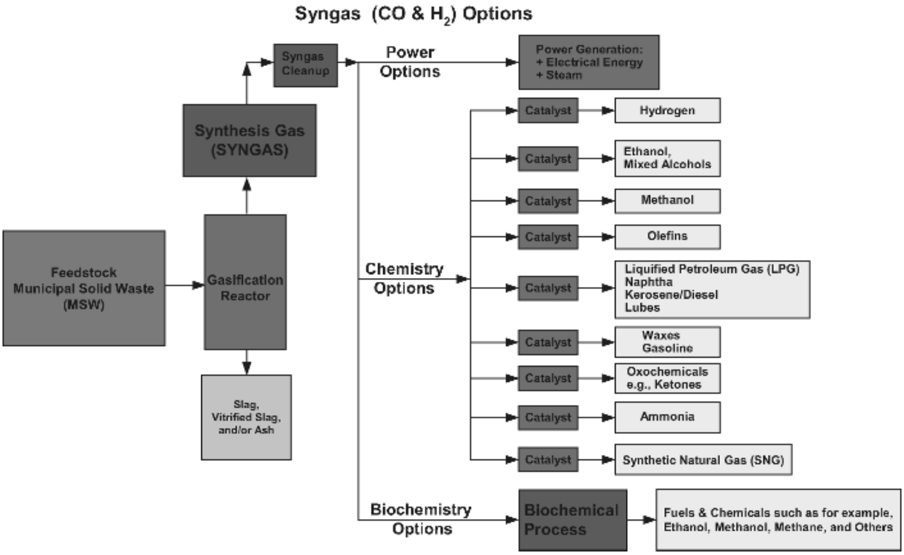

FIGURE 1.1 MSW to Energy, Gases, Fuels, and Chemicals.

Typically, most organic compounds are thermally unstable, and at high temperatures, the chemical bonds of organic molecules break, producing smaller molecules such as hydrocarbon gases and hydrogen gas. At high temperatures, the gaseous mixture produced comprises predominantly the thermodynamically stable small molecules of CO and H_2. This gaseous mixture of CO and H_2 is called “syngas.” This latter stage of the thermal process is known as gasification.

A typical pyrolysis process is illustrated in Fig. 1.2.

As illustrated in Fig. 1.2, feedstock as MSW is preprocessed to remove profitable recyclables. Then the preprocessed material is fed into the pyrolysis reactor where an indirect source of heat elevates the contents to a temperature between 1,200 and 2,200°F to produce raw syngas overhead and a bottom ash, carbon char, and metals from the reactor. Some report the pyrolysis process to occur at a reactor temperature between 750 and 1,650°F.[9] The pyrolysis process occurs in an oxygen-deficient (starved) atmosphere.

The syngas cleanup step is designed to remove carry-over particulate matter from the reactor, sulfur, chlorides/acid gases (such as hydrochloric acid), and trace metals such as mercury.

Syngas is used in the power generation plant to produce energy, such as steam and electricity, for use in the process and export energy. The export energy is typically converted into electricity and supplied/sold to the grid.

The bottoms from the reactor are ash, carbon char, and metals. The carbon char and metals have use as recyclables in industry. However, the ash from the pyrolysis process is usually disposed of in a landfill, which is one of the major environmental shortcomings of the pyrolysis process when used for MSW management.

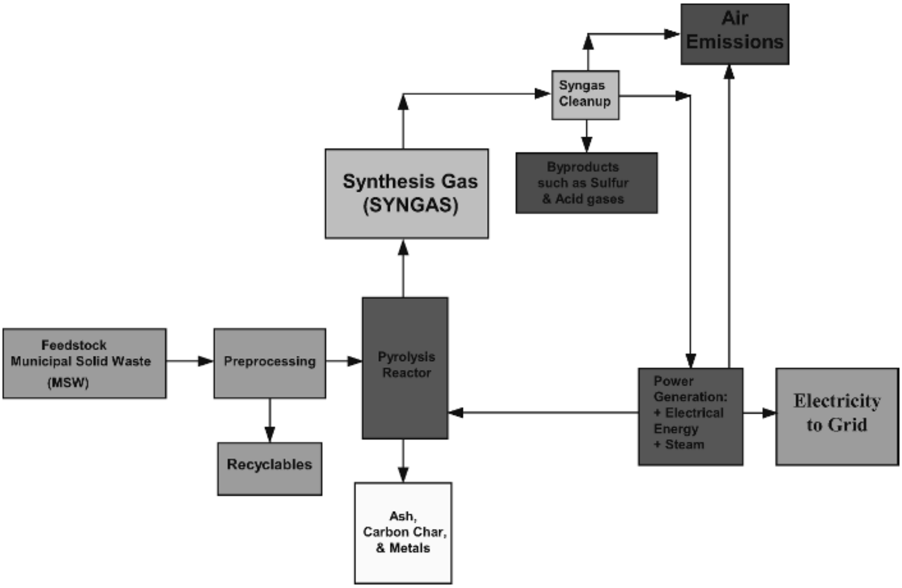

FIGURE 1.2 Process Schematic, MSW to Electricity via Pyrolysis.

WHAT IS PYROLYSIS/GASIFICATION?

Pyrolysis/gasification is a variation of the pyrolysis process. Another reactor is added whereby any carbon char or pyrolysis liquids produced from the initial pyrolysis step are further gasified in a close-coupled reactor, which may use air, oxygen, and/or steam for these gasification reactions. As shown in Fig. 1.3, a controlled amount of air/oxygen is fed into the pyrolysis/gasification reactor whereby some of the char and pyrolysis liquids react, i.e., there is combustion with oxygen. The combustion reactions (exothermic reactions) are controlled so as to supply sufficient heat for the pyrolysis reactions (endothermic reactions), yielding a temperature typically between 1,400 and 2,800°F. Sometimes the pyrolysis/gasifier conditions are stated as 750–1,650°F for the pyrolysis zone and 1,400–2,800°F for the gasification zone. In addition, steam is supplied to the reactor for the chemical reactions that yield CO and H_2.[9]

Pyrolysis/gasification reactor operates predominantly in an oxygen-starved environment, since the combustion reactions (exothermic reactions) quickly consume the oxygen producing heat sufficient for the pyrolysis reactions (endothermic reactions), resulting in a raw syngas exiting the reactor. The raw syngas is cleaned up of carry-over particulate matter from the reactor, sulfur, chlorides/acid gases (such as hydrochloric acid), and trace metals such as mercury. Syngas is used in the power generation plant to produce energy, such as steam and electricity, for use in the process and export energy. The export energy is typically converted into electricity and supplied/sold to the grid.

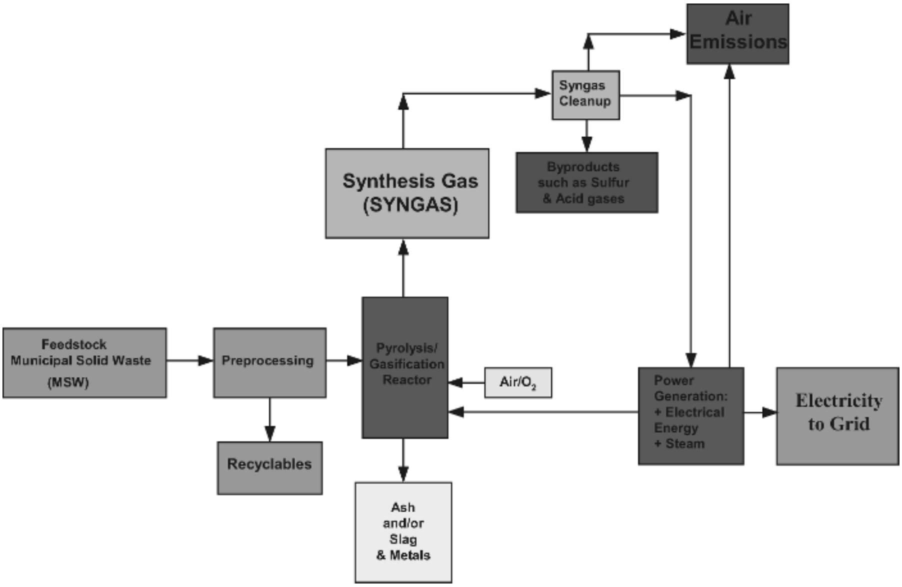

FIGURE 1.3 Process Schematic, MSW to Electricity via Pyrolysis/Gasification.

The bottoms from the reactor are typically ash, slag, and metals depending on the temperature of the pyrolysis/gasification reactor. The metals find use as recyclables in industry. However, the ash and/or slag is typically disposed of in a landfill, which is one of the major environmental shortcomings of the pyrolysis/gasification process when used for MSW management.

WHAT IS CONVENTIONAL GASIFICATION?

Conventional gasification is a thermal process, which converts carbonaceous materials, such as MSW, into syngas using a limited quantity of air or oxygen.

The conventional gasification conditions are sometimes between 1,450 and 3,000°F. Steam is injected into the conventional gasification reactor to promote CO and H_2 production.

For simplicity, some basic chemical reactions in the gasification process are:

$$C + O_2 \rightarrow CO_2 \tag{1.1}$$

$$C + H_2O \rightleftharpoons CO + H_2 \tag{1.2}$$

$$C + 2H_2 \rightleftharpoons CH_4 \tag{1.3}$$

$$C + CO_2 \rightleftharpoons 2CO \tag{1.4}$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \tag{1.5}$$

$$C_nH_m + nH_2O \rightleftharpoons nCO + (n + \tfrac{1}{2}m)H_2 \tag{1.6}$$

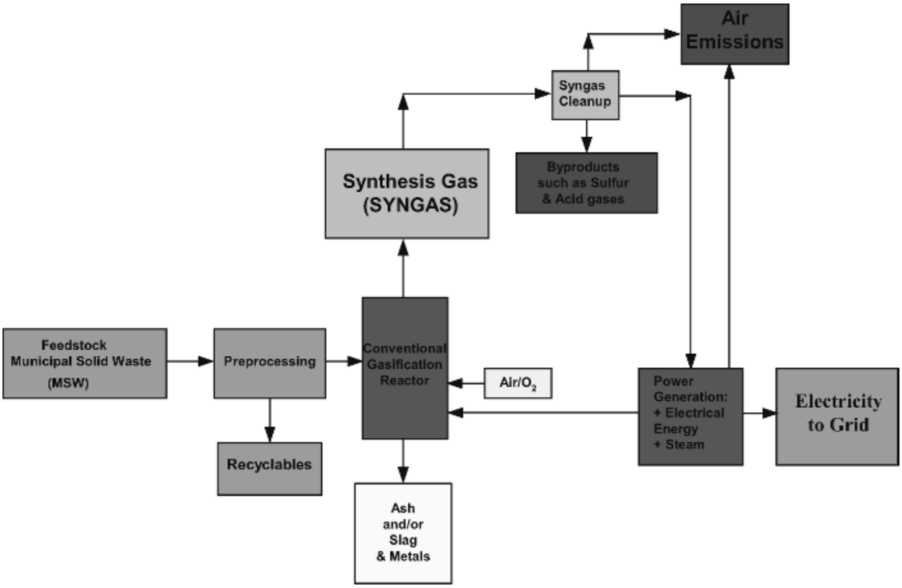

FIGURE 1.4 Process Schematic, MSW to Electricity via Conventional Gasification.

Thus, CO, H_2, and CH_4 are the basic components of the gasification process producing the gaseous mixture. Of these components, the gaseous mixture comprises predominantly of CO) and H_2. Equation (1.1) shows the carbonaceous components of the MSW as carbon (C) that reacts with oxygen (O_2) to produce limited combustion but with the necessary heat for the syngas reactions (Eqs. (1.2–1.5 and 1.6)).

Figure 1.4 illustrates a typical conventional gasification process. As shown, a controlled amount of air/oxygen is fed into the conventional gasification reactor whereby some feedstock material reacts, i.e., there is combustion with oxygen. The combustion reactions (exothermic reactions) are controlled so as to supply sufficient heat for the predominantly syngas reactions (endothermic reactions), yielding a temperature typically between 1,450 and 3,000°F. The raw syngas exits the reactor and is cleaned up of carry-over particulate matter from the reactor, sulfur, chlorides/acid gases (such as hydrochloric acid), and trace metals such as mercury. Syngas is sent to the power generation plant to produce energy, such as steam and electricity, for use in the process and export energy. The export energy is converted to electricity and supplied/sold to the grid.

The bottoms from the conventional gasification reactor are ash and/or slag and metals depending upon the temperature of the conventional gasification reactor. However, the ash and/or slag from the reactor bottoms is usually disposed off in a landfill which is one of the major environmental shortcomings when used for MSW management.

WHAT IS PLASMA ARC GASIFICATION?

Plasma arc gasification is a high-temperature pyrolysis process whereby the organics of waste solids (carbon-based materials) are converted into syngas and inorganic materials and minerals of the waste solids produce a rocklike glassy by-product called vitrified slag. The syngas is predominantly CO and H_2. The high temperature during the process is created by an electric arc in a torch whereby a gas is converted into a plasma. The process containing a reactor with a plasma torch processing organics of waste solids (carbon-based materials) is called plasma arc gasification. The plasma arc gasification reactor is typically operated between 7,200 and 12,600°F. A process schematic of a typical plasma arc gasification process is shown in Fig. 1.5.

In commercial practice, the plasma arc gasification process, as shown in Fig. 1.5, is operated with an injection of a carbonaceous material like coal or coke into the plasma arc gasification reactor. This material reacts quickly with oxygen to produce heat for the pyrolysis reactions in an oxygen-starved environment. Equation (1.1) shows the carbonaceous materials as C that reacts with the O_2 to produce limited combustion but with the necessary heat for the syngas reactions (Eqs. (1.2–1.5 and 1.6)). In addition, steam is added to the plasma arc gasification reactor to promote syngas reactions. The combustion reactions (exothermic reactions) supply heat with additional heat from the plasma arc torches for the pyrolysis reactions (endothermic reactions), yielding a temperature typically between 7,200 and 12,600°F.

The inorganic minerals of the waste solids (MSW) produce a rocklike by-product. Since operating conditions are very high (7,200–12,600°F), these minerals are

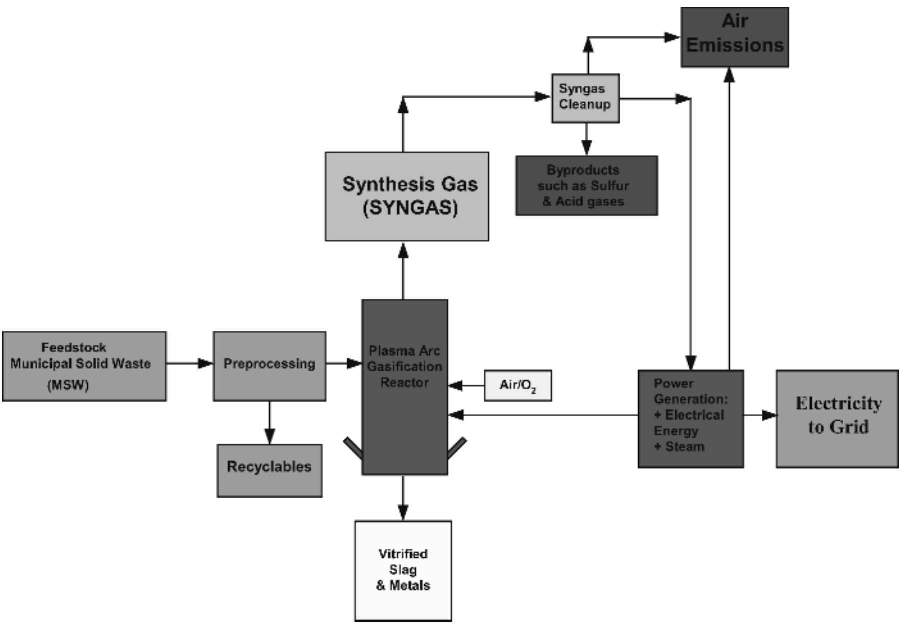

FIGURE 1.5 Process Schematic, MSW to Electricity via Plasma Arc Gasification.

converted into a vitrified slag typically comprising metals and silica glass. This vitrified slag is basically nonleaching and exceeds EPA standards. Metals can be recovered from the slag and the slag can be used to produce other by-products such as rock wool, floor tiles, roof tiles, insulation, and landscaping blocks, to mention a few.[5,10] The vitrified slag, being environmentally acceptable as a recyclable by-product, is one of the more positive attributes of plasma arc gasification process for the management of MSW.

Another positive attribute of the plasma arc gasification process is that developments in the design of plasma arc gasification reactor have improved and lessened the need for pretreatment/preprocessing.[2–4,10]

WHAT IS MASS BURN (INCINERATION)?

Mass burn (Incineration) is a combustion process that uses an excess of oxygen and/or air to burn the SWs. The mass burn process operates with an “excess of oxygen” present and is therefore a “combustion” process as illustrated in Fig. 1.6. It is “NOT” a pyrolysis process.

Feedstock as MSW is preprocessed to remove saleable recyclables for the marketplace and remaining MSW may be shredded. MSW is fed into the fluid bed boiler with operating temperatures between 1,000 and 2,200°F. Excess air/O_2 is used for combustion of the combustibles in the MSW. High-pressure steam produced in the fluid bed boiler is sent to the power plant for energy generation. Hot exhaust gases from the fluid bed boiler are sent for gas cleanup and heat recovery sent to the power plant for generation of energy.

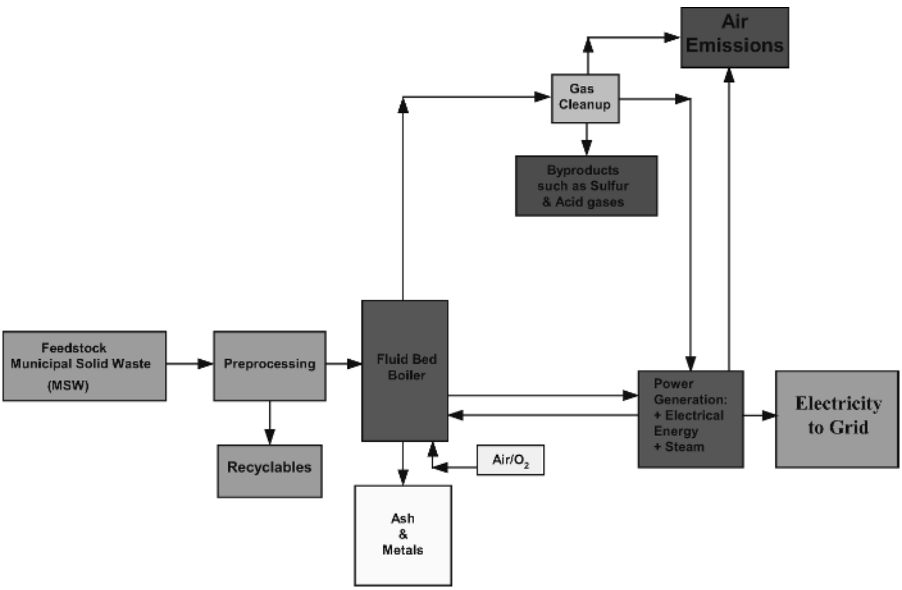

FIGURE 1.6 Process Schematic, MSW to Electricity via Mass Burn (Incineration).

The power plant produces electricity using steam turbines and saleable excess electricity to the grid.

One of the biggest drawbacks or negative environmental aspects of the mass burn process is the production of ash from the grate of the fluid bed boiler. This ash is typically sent to a landfill for disposal.

WHICH THERMAL PROCESS TECHNOLOGY IS THE MOST EFFICIENT AND ECONOMICAL?

Five Thermal Processes have been discussed so far but which process should be selected based upon the highest thermal efficiency and the best economics? To answer this question, the thermal efficiency and economics of the five technologies will be determined and compared.

Performance/Thermal Efficiency of Technologies

For the thermal process technologies discussed, the typical range of process operation is presented in Table 1.1 for comparison.[9]

The thermal efficiency of each thermal process technology previously discussed was determined by URS Corporation, which reported the net energy production of electricity to the Grid (area electrical distribution system) per ton of MSW, as shown in Fig. 1.7 and Table 1.2.[9,11]

On reviewing the net energy production to the grid for various types of thermal process technologies, plasma arc gasification produces about 816 kWh/ton MSW compared to only about 685 kWh/ton MSW for a conventional gasification technology. Thus, plasma arc gasification could be considered the most efficient thermal gasification process.

What is the Economic Comparison Between the Thermal Processes?

However, before concluding that plasma arc gasification process is the best approach to management of MSW, a preliminary economic analysis is performed for each of the thermal processes discussed previously. Then, a process economy and a process efficiency comparison can be shown for all of the thermal processes discussed.

TABLE 1.1 Thermal Process Technology(s)

Thermal Process Technology/Typical Range of Process Operation:	
Plasma Arc Gasification	7,200–12,600°F
Conventional gasification	1,400–2,800°F
Pyrolysis gasification	1,400–2,800°F
Pyrolysis	1,200–2,200°F
Mass burn (incineration)	1,000–2,200°F

Note: Except for plasma arc gasification, these processes have environmental issues for disposal of ash and slag.

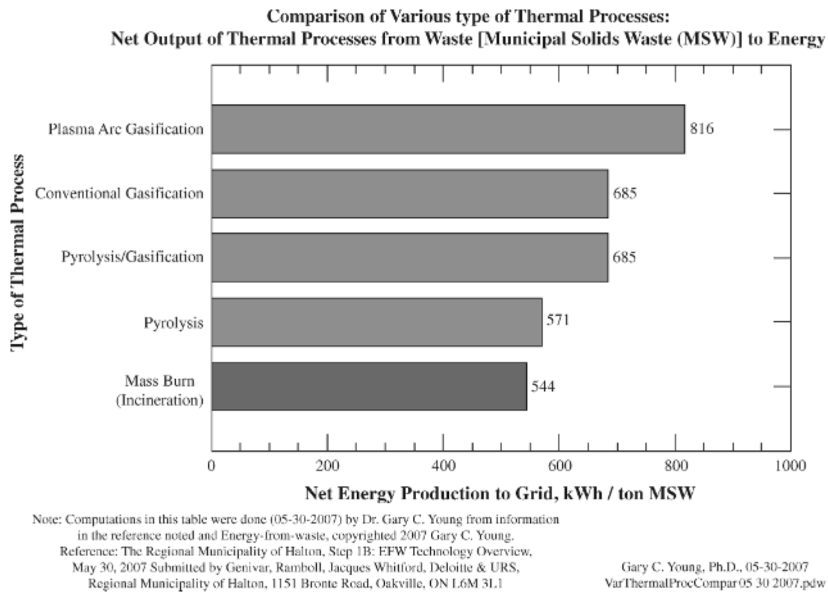

FIGURE 1.7 Comparison of Various Types of Thermal Processes.

A preliminary economic analysis was completed on the five thermal processes. Parameters used in this economic evaluation are shown in Table 1.3 and were estimated from the available literature.[2–6,10]

Economic analysis with these parameters allows computation of the net revenue (before taxes) of each thermal process as shown in Fig. 1.8.

Mass burn shows negative net annual revenue (before taxes) while pyrolysis, pyrolysis/gasification, conventional gasification, and plasma arc gasification indicate positive net annual revenue (before taxes). Plasma arc gasification process has the highest net annual revenue. In addition, it should be pointed out that plasma arc gasification process produces vitrified slag that is an environmentally acceptable by-product with revenue as a road material at typically $15.00/ton.

On reviewing process characteristics of the thermal processes discussed, mass burn, pyrolysis, pyrolysis/gasification, and conventional gasification all typically produced ash as a by-product, which is not environmentally friendly since it must be disposed of in

TABLE 1.2 Thermal Process Technology and Net Energy to Grid

Type of Thermal Process Technology	Net Energy Production to Grid
Mass burn (incineration)	544 kWh/ton MSW
Pyrolysis	571 kWh/ton MSW
Pyrolysis/gasification	685 kWh/ton MSW
Conventional gasification	685 kWh/ton MSW
Plasma Arc Gasification	816 kWh/ton MSW

Source: Ref. (4).

TABLE 1.3 Parameters for the Economic Assessment of the Thermal Processes

Parameter	Mass Burn (Incineration)	Pyrolysis	Pyrolysis/ Gasification	Conventional Gasification	Plasma Arc Gasification
Capital investment at 6%, 20 years	$115,997,700	$86,936,900	$102,593,400	$80,337,800	$101,583,800
Plant capacity (tons MSW/day)	500	500	500	500	500
Energy production (kWh/ton MSW)	544	571	685	685	816
Operation and maintenance, capital budget, cost of ash disposal ($40/ton)[12] ($/year)	$8,216,600	$7,193,700	$7,711,100	6,871,800	$7,483,400
Tipping fee ($/ton MSW) (revenue)	$35.00	$35.00	$35.00	$35.00	$35.00
Green tags (revenue)	2 ¢/kWh	2 ¢/kWh	2 ¢/kWh	2 ¢/kWh	2 ¢/kWh
Production energy sales (revenue)	6.50 ¢/kWh	6.50 ¢/kWh	6.50 ¢/kWh	6.50 ¢/kWh	6.50 ¢/kWh
By-product	0.2	0.21	0.2	0.2	0.2
Residue (tons/ton MSW)	Ash	Ash/Char	Ash	Ash/Slag	Vitrified slag

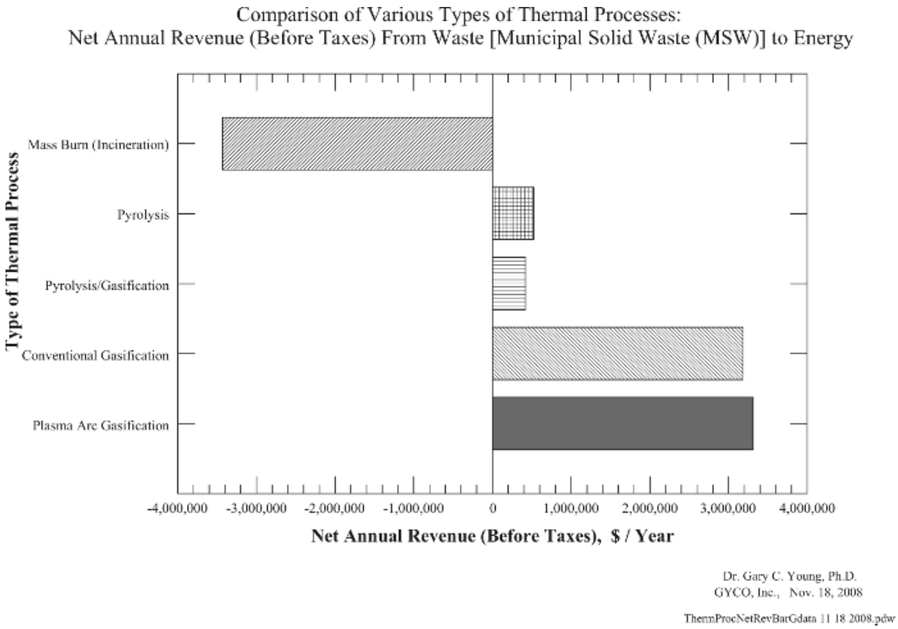

FIGURE 1.8 Comparison of Various Types of Thermal Processes.

a landfill or other depository isolated from the environment. The plasma arc gasification process produces a "vitrified slag" as by-product. The vitrified slag is environmentally sound, since it is basically nonleaching and exceeds EPA leach test standards. Therefore, it can be used to produce other by-products such as rock wool, floor tiles, roof tiles, insulation, and landscaping blocks, or recycled as a road aggregate material.[2,4]

Toxicity leaching tests were conducted on the vitrified slag produced from MSW using a plasma arc gasification reactor.[4,10] Standard toxicity characteristics leaching procedure (TCLP) tests were conducted on vitrified sample materials from experiments. The results are shown in Table 1.4.

TABLE 1.4 Toxicity Leaching Test Results on Vitrified Slag

Heavy Metal	Permissible Concentration (mg/l)	Measured Concentration (mg/l)
Arsenic	5.0	<0.1
Barium	100.0	0.47
Cadmium	1.0	<0.1
Chromium	5.0	<0.1
Lead	5.0	<0.1
Mercury	0.2	<0.1
Selenium	1.0	<0.1
Silver	5.0	<0.1

Source: Ref. (4,10).

From the analysis above, it was concluded that plasma arc gasification process would be the most attractive process for handling solid wastes in general due to the following characteristics:

- thermal efficiency
- process variety of different solid wastes
- minimal pretreatment/presorting of solid wastes
- production of "syngas" for conversion into a variety of energy sources such as steam, electricity, and/or liquid fuels
- environmentally sound, since the solid by-product, vitrified slag, can be used as a construction material
- environmentally sound, since the "syngas" can be used to produce various energy products and any discharged gaseous effluents treated by currently acceptable environmental processes
- ability to minimize if not eliminate the need for a landfill
- can be used to process wastes in an existing landfill and eliminate the old landfill.

The plasma arc gasification process can be described as a "technologically advanced and environmentally friendly method of disposing of waste, converting it into commercially usable by-products. This process is a drastic nonincineration thermal process that uses extremely high temperatures in an oxygen-starved environment to completely decompose input waste material into very simple molecules. The intense and versatile heat generation capabilities of plasma technology enable a plasma gasification/vitrification facility to treat a large number of waste streams in a safe and reliable manner. The by-products of the process are a combustible gas and an inert slag. Plasma gasification consistently exhibits much lower environmental levels for both air emissions and slag leachate toxicity than other thermal technologies."[13]

Thus, the following Chapters 2, 3, 4, 5 and 7 are devoted to an estimate of the commercial economics and viability of plasma arc gasification. Chapter 6 presents the economic facts about cash flows from curbside pickup of garbage to landfill and the net cash revenues generated by the business segment of MSW management.

Chapter 2 How Can Plasma Arc Gasification Take Garbage to Electricity and a Case Study?

Chapter 3 How Can Plasma Arc Gasification Take Garbage to Liquid Fuels and Case Studies?

Chapter 4 Plasma Economics: Garbage/Wastes to Electricity, Case Study With Economy of Scale

Chapter 5 Plasma Economics: Garbage/Wastes to Power Ethanol Plants and a Case Study

Chapter 6 From Curbside to Landfill, Cash Flows as a Revenue Source for Waste Solids-to-Energy Management

Chapter 7 Plasma Economics: Garbage/Wastes to Power, Case Study With Economics of 94 ton/day Facility

Chapter 8 Plant Operations: Eco-Valley Plant in Utashinai, Japan; an Independent Case Study

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