Comparative Assessment of Gasification and Incineration in Integrated Waste Management Systems

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Executive Summary

Several recent studies have compared the relative environmental and economic impacts of landfill, incineration and gasification for municipal solid waste (MSW) treatment and disposal. Such studies, including those carried out by the USEPA (*1996*) and USDOE (*2002*), as well as reports from Los Angeles (*URS, 2005*), Victoria, BC (*Stantec, 2011*), BPA (*2009*), and a large study from Europe (*Munster, 2009*), show that properly designed and operated air fed gasification systems are, by far, the most efficient and cleanest thermal technology for converting solid waste to energy.

Zaman *(2009)* provided a comparative life cycle assessment comparing landfill, incineration and gasification as primary technologies for treatment and disposal of MSW. Again, gasification ranked highest overall when considering the combined characteristics of conversion efficiency, cost per unit of power generated, and favorable environmental impact. Specifically, these published studies and reports have shown that gasification technology is inherently:

- **more thermally efficient** than incineration (by as much as 18%);
- **cleaner** than incineration, with fewer air emissions including less entrained particulate, less CO_2, and lower emissions of nitrogen and sulfur oxides (NOx and SOx), as well as lower concentrations of other pollutants in the flue gas;
- **less expensive** than incineration to build and operate;
- **capable of producing commercially beneficial by products**. In addition, MSW gasifiers can be designed to produce a low carbon, inert and non-leachable slag or vitreous frit instead of a leachable bottom ash (as is produced by incinerators). Residual slag or vitreous frit can be beneficially used in cement making, or as an aggregate for cement blocks or for fill materials. As such, gasification adds an additional sources of potential revenue to the operator through the sale of this material.

Emissions from gasification are lower than from incineration, whether calculated on the basis of per ton of waste treated, or per MWh of energy generated. Gasification technology offers greater flexibility in design and layout and requires less heavy construction and civil work onsite than incineration, resulting in shorter construction times (and lower costs). A great advantage of adopting air fed gasification for conversion of MSW to energy is that these plants can be built in distributed systems allowing them to be closer to the source of waste, as well as to the end users of the power they generate. This reduces transportation and waste hauling costs while at the same time facilitating transition to a more robust distributed grid, and eventually smart grid technology.

Like incinerators, gasifiers have a history of safe and dependable operation and can be used for reliably firing steam boilers to generate electrical power, as well as for combined heat and power application. Modern air fed gasifiers operating on various forms of biomass, as exemplified by a new (2014) system that operates on 70% MSW in France, have an outstanding performance record, some having been in operation for more than 30 years.

Background

Thermal treatment of municipal solid waste (MSW) is a well proven technology for producing renewable energy, while greatly reducing waste volumes going to landfills. A further environmental advantage of thermal treatment is that residual materials, such as the residual ash or slag that are eventually placed in landfill, are inert and do not cause odors or generate greenhouse gasses. In this regard, the USEPA has recently concluded that landfills are the major source of methane gas in North America (*Thorneloe, 2012*). Methane is more than 20 times as harmful as a greenhouse gas than is carbon dioxide. Thermal processing of waste has the net effects of reducing carbonaceous waste to landfill, thereby reducing overall greenhouse gas equivalent emission (CO_2 equivalent emission).

In sustainable waste management systems, resource recovery is a prime objective. Thermal treatment allows for recovery of the chemical energy represented by the combustible residue remaining in the waste stream after the recyclable materials have been removed. In the most efficient thermal conversion systems, incoming raw waste is sorted to remove recyclable materials, which are sold. Non-combustible materials such as rock, metals and glass, and hazardous materials such as batteries, fluorescent light bulbs and e-waste, which could introduce toxic metals into the system, are also removed. The remaining combustible residue, designated as refuse derived fuel or RDF, is then thermally converted in an incinerator or gasifier.

Traditionally," mass burn" incineration has been the most widely deployed thermal technology for treatment of MSW to generate renewable energy. As described above, several recent assessments from governmental and academic institutions, both in Europe and the US, have shown that air fed gasification is generally better suited than incineration for thermal conversion of MSW to electrical power, as well as for use in combined heat and power systems.

This is especially true when gasifiers are operated on RDF instead of in mass burn mode (see below). Unless otherwise indicated, the term *gasification,* as used in this document, will refer to conventional air fed gasification, and more specifically, to air fed gasification as optimized for the thermal conversion of MSW to renewable energy.

Below are descriptions of the incineration (combustion) and gasification processes, as well as additional detail as to the above listed advantages of gasification, as applied to treatment of municipal solid waste at the scale of approximately 300 to 3000 Tonnes per day (Tpd).

Comparison of Gasification to Incineration for Treatment of MSW

Incineration is a thermal process wherein the combustible components of a solid waste stream are thermally oxidized to produce heat energy that can be used to create steam for use in generating electrical power, for industrial processes, or for district heating. In addition to thermal energy, products of the incineration process include bottom ash, fly ash, and flue gas, in which are found a number of regulated pollutants. The combustion of carbonaceous materials, including those containing sulfur and nitrogen, can be characterized by the following well known summary oxidation reactions (some of which may have several intermediates).

1. $C + O_2 \Rightarrow CO_2$	Oxidation of Carbon
2. $1/2\ O_2 + H_2 \Rightarrow H_2O$	Oxidation of Hydrogen
3. $N + O_2 \Rightarrow NO_2$ (NOx)	Oxidation of Nitrogen (from intermediate reactions)
4. $S + O_2 \Rightarrow SO_2$ (SOx)	Oxidation of Sulfur (from intermediate reactions)

Oxides of nitrogen (NOx) formed during combustion are associated with increased ozone levels and are otherwise major contributors to air pollution. Oxides of sulfur (SOx), as well as NOx, react with water in the atmosphere to form acids that lower the pH of rain water, forming acid rain. Not shown among the equations for combustion are reactions involving chlorine (such as that found in waste paper), which can also be of significance in incineration processes because they contribute to the formation of hydrochloric acid, another harmful acid gas. These acid gas pollutants are important contributors to the environmental damage that results from combustion of fossil fuels, and the inadequately controlled thermal conversion of MSW.

Bottom ash is that component of the fuel that is not converted to gas or to entrained particulate. This material is comprised mainly of inorganic materials, including metal oxides and unburned carbon, and remains in the char bed until it is removed from the bottom of the combustor. Smaller ash particles, known as fly ash, may become entrained in the flue gas of an incinerator or gasifier and must be removed, along with volatile organic compounds and other acid gas constituents.

Several processes are in current use for removal of SOx, NOx, particulates, and other pollutants from the flue gas before it is released into the atmosphere. Flue gas clean-up units commonly found in MSW incineration plants include either a dry or wet acid gas removal unit and a bag house. For additional clean-up of the flue gas, carbon and/or lime can be injected into the gas stream in the bag house. Air pollution control units, including wet and dry scrubbers, selective catalyst reduction units, electrostatic precipitators, and baghouses, as well as flue gas recirculation, can be used in both incineration and gasification systems. However since gasification systems are inherently cleaner that incineration, use of these units results in much lower emissions from a gasifier than from an incinerator of comparable capacity.

Mass burn incineration is the term used to designate a system wherein solid waste is burned as received, after removal of hazardous waste and items that will not physically pass into the incinerator. This approach requires essentially no labor for sorting and is cost effective when electrical rates are low and waste volume reduction is a main objective. Mass burn incineration is characterized by lower thermal efficiency as well as more bottom ash and increased concentrations of toxic materials in the flue gas stream. To generate power, thermal energy from the furnace flue gas is recovered by a steam boiler and used to produce steam that drives a steam turbine generator.

RDF burn incineration, as the name implies, refers to the practice of sorting the incoming waste stream by removal of recyclables and hazardous materials and non-combustibles such as metals, glass, rock, concrete, and sheet rock. In RDF facilities, wet and low BTU materials such as green waste are processed separately. With this minimal sorting, the average calorific values of the RDF is higher, and the ash production lower, than in mass burn mode, all other factors being equal. At a 3,000 Tpd incinerator in South Florida, for example, the average calorific value of the RDF is 6,500 BTU per pound with some seasonal variation in moisture content.

Gasification is a process wherein organic carbonaceous materials are dissociated at high temperatures in an oxygen-starved thermal reactor to form a fuel gas known as synthesis gas (also designated as syngas, or producer gas). The syngas is composed of mainly, carbon monoxide, carbon dioxide, hydrogen, methane, and water vapor. If the thermal reactor is air fed (as opposed to oxygen fed only), the syngas stream also contains nitrogen gas. This latter form of syngas, which includes di-molecular nitrogen in relatively large quantities, is more correctly referred to as producer gas. However, in accordance with common usage, the fuel gas from the air fed gasifier will be referred to as syngas in this document.

Gasification has been used to convert mixed solid waste materials for more than 30 years, and for the present purposes can be divided into three main categories:

1. **Pyrolysis,** which is carried out in a low to nil oxygen partial pressure environment operating at temperatures between approximately 600 and 800 °C;

2. **Air Fed gasification** systems, which typically operate at temperatures ranging between approximately 800 and 1,800 °C; and

3. **Plasma or plasma arc gasification**, which employ plasma torches that can increase chamber temperatures to 2,000 to 2,800 °C with higher local temperatures.

As discussed elsewhere, pyrolysis and plasma arc gasification are not suitable for commercial scale MSW treatment for a number of reasons having to do with thermal efficiency and the environment.

While gasification processes can vary considerably, typical air fed gasifier reactors operate at temperatures between approximately 800° C and 1,000° C and can use air, oxygen, and hydrogen, or steam, as reactants. When used for MSW, they are best operated on RDF that has been finely shredded after sorting to reduce moisture and create a more uniform fuel. The initial step in gasification, de-volatilization, is similar to the initial step in pyrolysis. However, because of the higher temperatures involved, thermo-chemical reactions associated with gasification are more energetic than those in pyrolysis, resulting in a cleaner syngas fuel.

Chemical reactions involved in gasification vary in rate and relative importance, depending on the process conditions and the gasification agent (air, oxygen, steam, carbon dioxide, or hydrogen). A listing of some of the more important gasification reactions for MSW, and in particular the carbonaceous char that remains after the volatilization step in the process, are shown in equations 1–9 below. Gasification of carbonaceous materials can be characterized by the following summary chemical reactions:

1. $C + CO_2 \Rightarrow 2CO$	Gasification with Carbon Dioxide
2. $C + H_2O\ (g) \Rightarrow CO + H_2$	Gasification with Steam
3. $C + 2H_2O\ (g) \Rightarrow CO_2 + 2H_2$	Gasification with Steam
4. $C + 2H_2 \Rightarrow CH_4$	Gasification with Hydrogen
5. $CO + H_2O\ (g) \Rightarrow CO_2 + H_2$	Water Gas Shift Reaction
6. $C + 1/2\ O_2 \Rightarrow CO$	Gasification with Oxygen
7. $CO + 3H_2 \Rightarrow CH_4 + H_2O\ (g)$	Gasification with Hydrogen
8. $S + H_2 \Rightarrow H_2S$	Gasification with Hydrogen
9. $C + O_2 \Rightarrow CO_2$	Gasification with Oxygen

Note that, according to equation # 8 fuel bound sulfur is converted to hydrogen sulfide in an exothermic reaction instead of SO_x as in combustion. Likewise, chlorine can be converted to hydrochloric acid (H + Cl = HCl). Both hydrogen sulfide and hydrochloric acid are a strongly acidic and react readily with alkaline materials in the acid gas removal units or scrubbers which are very effective in removing acidic compounds from the flue gas stream. As a result, the following benefits occur with gasification compared to incineration:

1. Less oxidation of fuel bound sulfur and nitrogen to form SOx and NOx;
2. Little or no formation of dioxins and furans in gasifiers compared to incinerators.
3. Little or no "thermal NOx" is generated by properly operated gasifiers;
4. Some of the moisture in the fuel is converted to hydrogen (eqn.2) in the reducing atmosphere, which enhances the calorific value of the clean burning syngas fuel.

More specifically, and as stated by the *Gasification Technologies Council* with regard to formation of toxic organic compounds, one of the concerns with incineration of MSW is the formation and reformation of toxic dioxins and furans, especially from PVC-containing plastics and other materials that form dioxins and furans when they burn. These toxins end up in exhaust steams by three pathways:

- By decomposition, as smaller parts of larger molecules,
- By "re-forming" when smaller molecules combine together; and/or
- By simply passing through the incinerator without change.

Incineration does not allow control of these processes, and all clean-up occurs after combustion. In the high temperature, low oxygen, environment of the gasifier, however:

- Larger molecules such as plastics are completely broken down into the components of syngas, which can be cleaned and processed before any further use,
- Dioxins and furans need sufficient oxygen to form or re-form, and the oxygen-deficient atmosphere in a gasifier does not provide the environment needed for dioxins and furans to form or reform,

Furthermore, dioxins need fine metal particulates in the exhaust to reform. Syngas from gasification is typically cleaned of particulates before being used, (See **Figure 2** below). In gasification facilities that use the syngas to produce downstream products like fuels, chemicals and fertilizers, the syngas is quickly quenched, so that there is not sufficient residence time in the temperature range where dioxins or furans could re-form. When the syngas is primarily used as a fuel for making heat, it can be cleaned as necessary before combustion; this cannot occur in incineration.

The ash produced from gasification is different from what is produced from an incinerator. While incinerator ash is considered safe for use as alternative daily cover on landfills, there are concerns with its use in commercial products. In high-temperature gasification, the ash actually flows from the gasifier in a molten form, where it is quench-cooled, forming a glassy, non-leachable slag that can be used for making cement, roofing shingles, or used as an asphalt filler or for sandblasting.

Some gasifiers are designed to recover melted metals in a separate stream, taking advantage of the ability of gasification technology to enhance recycling *(Gasification Technologies Council).*

The incinerator and gasifier diagrams on the following page (**Figure 1** and **Figure 2**, respectively) illustrate the essential differences between the two processes. Incinerators are designed to accomplish complete combustion in a single unit. As shown in **Figure 1** incineration operates at an air to fuel ratio of approximately 6.25:1 in order to accomplish complete combustion

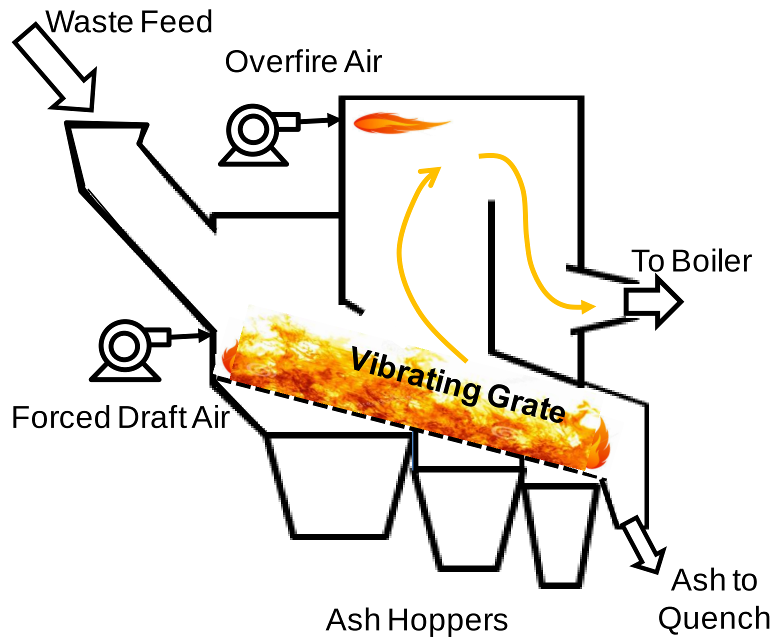

Figure 1. Simplified depiction of a vibrating grate MSW incinerator

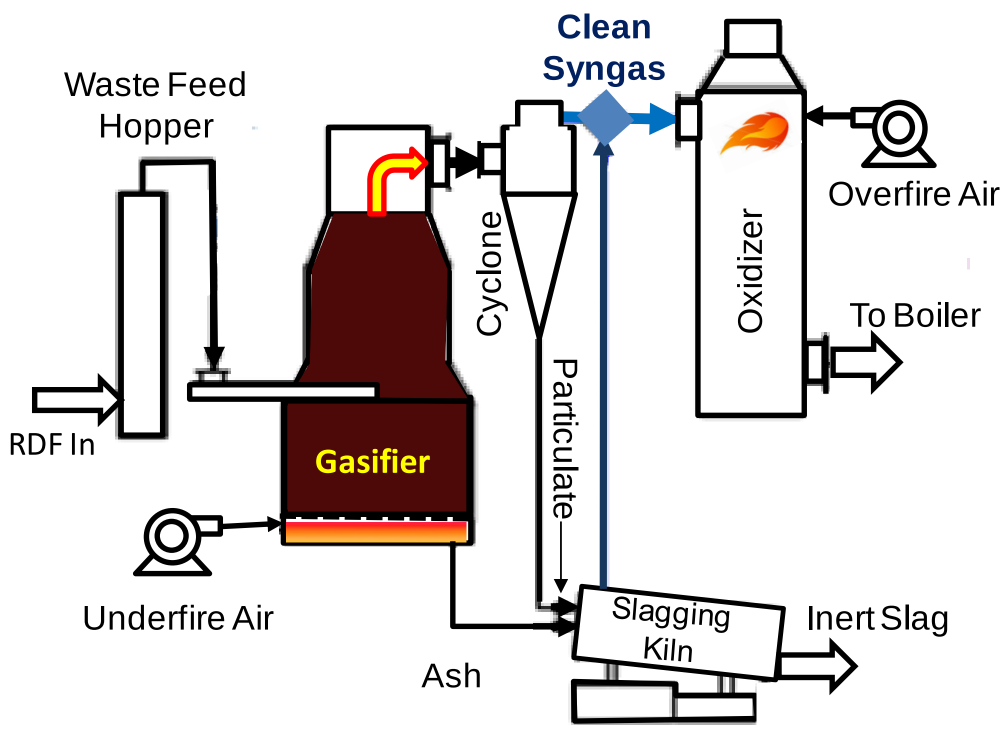

Figure 2. Simplified depiction of an air fed gasification system for the treatment of MSW

Excess air available to the solid fuel is provided via a forced draft air system or damper. The fuel forms a char bed that progresses along the length of the grate. This design results in the near complete oxidation of combustible components in the fuel, as well as more entrained particulate in the hot gasses entering the boiler, as compared to the gasification system shown in **Figure 2**. The additional entrained particulate is due, in part to the greatly increased volume of gas moving through the combustor as compared to the primary reactor of the gasification system for a given amount of fuel.

This is because the initial step in the gasification process is carried out at an air to fuel ratio of approximately 3:1. This means that a lower volume of gas comes in contact with the solid fuel and therefore less particulate and ash is entrained in the syngas flow. Since the gasification and oxidation (combustion) stages of the process are carried out in separate chambers, it is also possible to install a hot cyclone between the gasification and combustion chamber (as shown in **Figure 2**) to remove entrained particulate from the syngas.

This means that for a given amount of RDF, the hot combustion exhaust gas entering the boiler from a gasifier has inherently less particulate than it would from a comparably fueled incinerator. In addition, the oxygen starved conditions in the reaction chamber result in fewer oxidation products such as NOx and SOx, as well as less CO_2 as compared to incineration.

Because of the need to maintain uniform temperature and oxygen partial pressure control in the gasification reactor, there is a practical limit to the size of the reactor chambers. For the fluidized bed systems depicted in this document, the individual reactor vessels vary in diameter from about 18 feet to 24 feet. For this reason, each gasifier line is equipped with two gasifier reactors that are running at approximately 45% of volume capacity during normal operation.

This design allows for a rapid increase in the feed rate or amount of RDF going into reactor in case of a reduction in RDF calorific value. The design of the PRME fluidized bed gasifiers used for MSW allows these systems to be deployed in 300 - 350 Tpd, 12 MW (nameplate) modules that can be built with a minimum of civil works and onsite steel fabrication, as compared to incinerators of the same waste processing and power generation capacity. The latter require individually tailored design and engineering work resulting in higher overall construction costs.

Lower calorific value or higher moisture content of the waste is likely to require that a conventional incinerator use natural gas available as a source of auxiliary fuel for co-firing. Gasification systems such as the one illustrated in **Figure 2** can be designed so that no auxiliary fuel is needed to thermally convert high moisture waste.

If needed (usually with waste having more than 50% moisture content) low temperature steam, or waste heat, can be used to bring the moisture content of the RDF down to the range of 20% or so.

These dryers can be installed for each gasifier line, or in certain lines designated for high moisture waste, as required. Savings in natural gas costs gained by using waste heat for RFD drying in gasification can be substantial.

Table 1 below compares the thermal treatment technologies evaluated in terms of cost and thermal efficiency at the 250 Tpd scale. **Table 2** below compares fuel processing capability, service life and availability for the same technologies. Incineration and air fed gasification processes shown in **Table 1** and **Table 2** are compared based on the production of steam to drive a steam turbine generator for production of electricity.

Table 1. Cost and thermal efficiency comparisons for 250 Tpd solid waste thermal processing facilities using various technologies

Performance Parameter	Incineration*	Pyrolysis**	Plasma Arc Gasification**	Air Fed RDF Gasification***
Capacity in Solid Waste Tpd	250	250	250	250
Conversion Efficiency (MWh/ton @ 8000BTU/lb)	0.7	0.3	0.4	0.9
Cost of Construction (Rounded to $10 MM)	60	40	100	30
Generating Capacity MWh / Day	172	180	108	224
Unit Cost /kWh Generating Capacity	$348.00	$222.00	$1,000.00	$125.00
Unit Cost (US$K / Ton Capacity / day)	240	160	960	120

*Numbers are derived from new Babcock-Wilcox/KBR 3000 Tpd facility in Palm Beach Florida, USA. **Numbers are estimated and included for comparison only, since no commercial facilities at this scale are in operation. *** Numbers based on operating Facilities with certain design modifications.

Table 2. Fuel processing capability, service life and availability for various solid waste processing technologies

Performance Parameter	Incineration	Pyrolysis	Plasma Arc Gasification	Air Fed Gasification	Anaerobic Digestion/ Co-Gen	Aerobic Digestion / Gasification
Availability (%) (Est.)	92%	85%	80%	95%	85%	90%
Service Life (yrs)	30+	20?	20?	30+	20	20-30
Max Fuel Moisture (%)	40-50	10	10	40 -50	Up to 95	Up to 85
Low BTU & Wet Waste	Limited	No	No	Drying Req.	Yes	Yes
High BTU & Tire Waste	Up to 10%	Yes	Yes	Up to 20%	No	No

References

BPA (2009) Evaluation of Emissions from Thermal Conversion Technologies Processing Municipal Solid Waste and Biomass: Final Report (2009) Bioenergy Producers Association
http://socalconversion.org/pdfs/UCR_Emissions_Report_62109.pdf

Gasification Technologies Council http://www.gasification.org/

Münster, M (2009) Energy Systems Analysis of Waste to Energy Technologies by use of Energy PLAN, Danish Technical Research Counsel; ISBN 978-87-550-3719-9
http://orbit.dtu.dk/fedora/objects/orbit:81741/datastreams/file_4069900/content

Stantec (2011): Waste to Energy: A Technical Review of Municipal Solid Waste Thermal Treatment Practices Final Report (2011) Environmental Quality Branch Victoria BC
http://www.env.gov.bc.ca/epd/mun-waste/reports/pdf/BCMOE-WTE-Emissions-final.pdf

Thorneloe, SA (2012) U.S. Trends in Solid Waste Management and GHG Emissions Health and Environmental Concerns for Landfills ,Berlin Germany
http://www.umweltbundesamt.de/sites/default/files/medien/421/dokumente/us_epa_swm_and_ghg_emission.pdf

USDOD (2004) US Department of Defense: Solid Waste Incineration UFC 3-240-05A

USDOE (2002): Gasification Markets and Technologies – Present and Future: An Industry Perspective USDOE Report DOE/FE-0447

USEPA (2009) Gasification and Renewable Energy
http://www.epa.gov/osw/hazard/wastemin/minimize/energyrec/renew.htm

URS (2005): Summary Report: Evaluation of Alternative Solid Waste Processing Technologies. City of Los Angeles Dept of Public Works. Prepared by URS Corporation, Los Angeles, CA.
http://www.lacitysan.org/solid_resources/strategic_programs/alternative_tech/PDF/summary_report.pdf

Zaman, A U (2010) Comparative study of municipal solid waste treatment technologies using life cycle assessment method Int. J. Environ. Sci. Tech., 7 (2), 225-234, Spring 2010 ISSN: 1735-1472 http://link.springer.com/article/10.1007%2FBF03326132#page-1