

NAWTEC18-35, &

ANALYSIS OF THERMAL PLASMA – ASSISTED WASTE-TO ENERGY PROCESSES

Caroline Ducharme, Nickolas Themelis

Earth and Environmental Engineering and Earth Engineering Center,
Columbia University, New York, NY 10027, USA

Abstract

Thermal plasma torches convert electricity to high-temperature thermal energy by applying a high voltage across a flowing gas stream. Plasma torches are used extensively for producing metallic and ceramic coatings and also for vitrifying hazardous materials, such as asbestos-contaminated wastes. In the last decade, several thermal plasma processes have been proposed for treating municipal solid wastes (MSW). This research is based on a critical analysis of previous work by the Earth Engineering Center and on published reports and examines the possibilities for the proposed thermal plasma (TP) processes to be recover energy from MSW as an alternative to the conventional waste-to-energy (WTE) by grate combustion. In particular, this study will investigate two prominent thermal plasma technologies that are presently under development: The Alter NRG "Westinghouse" process in the U.S. and the Europlasma process in France. The environmental impacts and the technical economic aspects of plasma-assisted WTE processes will be compared to the traditional process of MSW combustion on a moving grate.

Background

MSW is a heterogeneous fuel containing a very wide variety of solid wastes. Due to the presence of some post-recycling materials, such as paper fiber and plastics, its heating value can be high and plasma-assisted gasification proposes to take advantage of this.

The description of this fuel will be based on past work by Columbia University that indicates that the typical U.S. MSW stream contains approximately 60% combustible, 20% moisture and 20% non-combustible materials (metals, etc.). The combustible fraction consists of both fossil and biogenic organic compounds that collectively can be described by the approximate chemical formula $C_6H_{10}O_4$. This mixture has the calorific value of about 18 MJ/kg but, because of its moisture and inorganic content, the as-received MSW stream has a calculated calorific value of about 11 MJ/kg, corresponding to about 3.16 MWh of contained thermal energy per metric ton.

In the U.S., the post-recycling MSW is mostly landfilled (64% of the total MSW generated) or combusted with energy recovery on a moving grate (7-8%). Current waste-to-energy plants have a thermal efficiency of about 20% and are principally financed by gate fees paid by the neighboring communities and the sale of the produced electricity to the grid.

Plasma processes have been widely used for the destruction of hazardous waste, such as asbestos, but this requires a high consumption of electricity. The high temperatures generated by plasma torches have the unique ability to melt and destroy any chemical bond and reduce it to gas and vitrified ash.

Gasification

Plasma-assisted gasification volatilizes MSW in an oxygen-starved environment and decomposes waste material into the basic molecules of CO, H₂, H₂O. It combusts the organics fraction of the MSW only partially and

converts it into a synthetic gas (or syngas) that contains most of the chemical and heat energy of the waste. The inorganic fraction of the waste is converted into an inert vitrified glass so that there is no ash remaining to be landfilled. Furthermore, the plasma reactor can treat all waste materials, as the only variable is the amount of electric energy needed to melt the waste. Any feedstock, other than nuclear waste, can be processed.

A process that depends only on full use of thermal plasma (waste “zapper”) will not be able to compete with conventional WTE because of the high input of electricity needed per ton of MSW processed (estimated at about 0.8 MWh of electricity/ton). Therefore, this study concentrated on processes that use a combination of partial combustion and plasma-assisted gasification, such as the Alter NRG process, based on the Westinghouse Plasma Technology, and the Europlasma process developed in France.

Thermal Plasma Torches

Plasma is a mixture of ions, electrons and neutral particles and is often called the “fourth state of matter”. It is created by the ionization of a gas due to the formation of a sustained electric arc by an electric current flowing through a gas stream. The gas molecules collide with charged electrons and this creates charged particles. When enough charged particles are created, both positive and negative, the gas starts to conduct electricity. Collisions between charged particles also occur giving off heat and forming an arc of light that is called plasma.

Thermal plasma is close to local equilibrium as the electrons, due to their high mobility, maintain the heavy particles – ions, molecules – at the same temperature as themselves; the energy given by the plasma is captured by the electrons and transferred to the heavy particles by elastic collision. The ionized carrier gas is projected at high velocity beyond the end of the electrodes as a result of the high-density electric fields, creating a plasma jet.

The gas jet issuing from a plasma torch is at temperatures up to 5,000°C or higher and is capable of vaporizing materials and destroying any chemical bonds. This has led to many efforts to utilize it for the processing of waste materials. The main advantages of plasma jets are their higher energy densities and temperatures allowing high heat and reactant transfer rate, smaller size of the installation, and rapid start-up. The use of

electricity as input is also very interesting as it decouples the heat generation from the oxygen potential, permits a better control of the processing unit. However the use of electricity is also a main drawback as it is the most expensive form of energy. Also, in terms of carbon footprint, E.U. regulations equate the use of 1 MWh of electricity to the use of 2.6 MWh of electricity.

Plasma can be generated by DC or AC electricity (RF, microwave, etc.). For the treatment of waste, plasma is preferentially generated by DC electric discharge and two kinds of devices can be used: transferred and non-transferred arcs. Non-transferred arc is the one mostly used for waste treatment. Electricity is transformed into thermal energy by means of electric discharges from cathode to anode within a water-cooled torch and the hot plasma jet issues from the torch (Figure 1). The arc is established between an axial cathode and an annular anode. The gas crosses the boundary layer between the gas column and the anode inner surface and is pushed downstream by the pressure of the gas flow. The electrodes are large components able to tolerate the gradual erosion and are water-cooled to handle the high excursion of temperatures. They have low efficiencies and their power output can be as low as 50% of the power input, for small torches, and as high as 75% for MW-scale torches. This means that one quarter to one half of the electricity of the torch is dissipated to the cooling water. The main fabricators of transferred arc plasma torches for waste treatment applications worldwide are Europlasma and Westinghouse Plasma Corp (WPC).

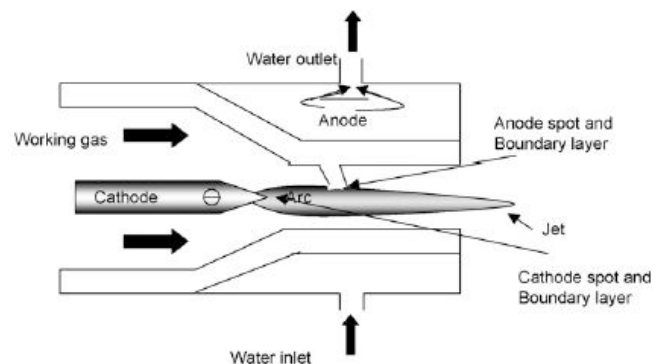


Figure 1. Non-transferred arc plasma torch (J. Heberlein, Thermal Plasma processes)

In the transferred arc torch, the cathode is usually a graphite cylinder through which flows a gas. The anode is the metal or slag bath below the cathode (Figure 2). Electricity is transformed to

heat in the gas flow between cathode and anode. This device is characterized by a relatively large physical separation between the anode and the cathode that ranges from a few centimeters to one meter. Since the plasma flow is generated below the electrode the device allows for very high thermal fluxes and is more efficient than the non-transferred arc torch as radiant heat transfer losses to the cold torch body are minimized. In fact, the cathode can be constructed by either a water-cooled metal or, more usually, by a refractory material that is consumed slowly by sublimation. In this case, the thermal losses are thus greatly reduced but the cathode needs to be replenished. The anode is made from metal with high thermal conductivities and the key aspect is to provide sufficient water cooling on the back face of the anode to prevent melting as it is the receiver of all the heat.

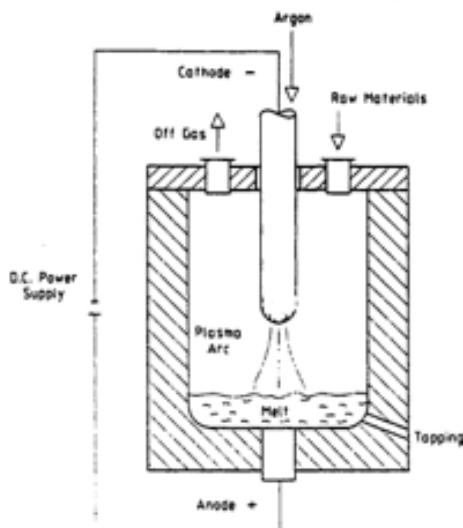


Figure 2. Transferred Arc Plasma torch

Plasma-assisted Gasification Processes

The most advanced companies are currently Alter NRG that has taken over the plasma technology developed by Westinghouse Plasma Corporation (WPC), InEnTec LLC, now called S4 technologies, and Plasco Energy Group. A few other companies such as Solena, Europlasma are also developing plasma-assisted processes for processing solid wastes and MSW. The Westinghouse technology has been tested in Japan for several years with Hitachi Metals whereas Plasco is running a pilot plant in Ottawa, Canada. The goal of this paper is to understand the material and energy balances of these processes

and their attributes with regard to competing with grate combustion technology.

The overall idea of the process is to use partial oxidation of the waste followed by a thermal treatment done by small plasma torches. The design varies with WPC using the plasma torch in the gasification chamber while Europlasma and Plasco use traditional gasification technique in a starved in air environment with recycled heat and two plasma torches for cracking the gasification products and vitrifying the ash, respectively (Figure 3).

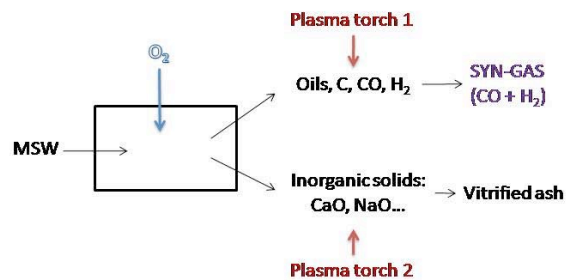


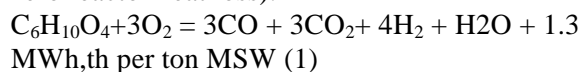
Figure 3. Schematic diagram of plasma-assisted gasification process with partial combustion followed by gas cracking (PT1) and ash vitrification (PT2)

The most valuable product of this process is the syngas that has to be cleaned through an Air Pollution Control (APC) system and then fired in a gas turbine in order to produce electricity. If the vitrified ash passes the leachability tests of the EPA (TCLP), this product can be sold and used in road construction or other applications.

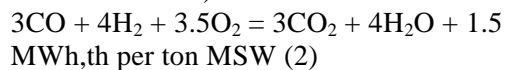
Material and energy balance in gasification

The fraction that is gasified is the organic materials in the MSW. If we assume that bulk oxygen is used in the gasifier instead of air and that the solids are brought to the gasification temperature by some means, the process involves the following stages:

- Gasification by means of partial combustion with oxygen and, for the time being, assuming zero reactor heat loss):



- Gas turbine combustion (again assuming no turbine heat loss):



At an assumed 50% of thermal efficiency for the gas turbine, the electricity generated is:
 $1.5 \text{ MWh}_{th} \times 50\% = 0.75 \text{ MWh}_{el}$

Furthermore, heat may be recovered from the high-temperature syngas as well as from the exhaust gas of the turbine. This heat can be used to produce steam, and the steam used to generate more electricity or to heat water for district heating. In the case of the steam turbine generator (with assumed thermal efficiency of 32%), and also now assuming 10% heat loss in the gasifier and 10% heat loss in the steam boiler, the maximum amount of additional electricity that may be generated from the syngas flow is:
 $1300 \text{ kWh} \times 80\% \times 32\% = 332 \text{ kWh}$ per ton of waste processes.

It will also be necessary to produce industrial oxygen for such a process and use some of the power generated to power the plasma torches. The production of one ton of industrial oxygen (95% O_2) requires about 0.25 MWh of electricity. The above equation of gasification (Eq. 1) shows that one mole of combustible corresponds to 3 moles of oxygen. On the basis of their respective molecular weights, we calculate that to gasify 148 kg of $C_6H_{10}O_4$ it will take $3 \times 32 = 96$ kg of oxygen. Moreover, as stated earlier, there is 60% combustible material ($C_6H_{10}O_4$) in the waste stream.

Thus, the amount of oxygen required to gasify one ton of MSW is $1000 \times 60\% \times 96/146 = 304$ kg of oxygen and the electricity needed to produce enough oxygen to gasify one ton of MSW is:

$304/1000 \times 0.25 \text{ MWh}_{el} = 0.075 \text{ MWh}_{el}$ per ton of MSW gasified. This amount must be provided by the electricity output of the syngas turbine.

The electricity needed for the plasma torches that will crack the syngas and vitrify the ash depends on the capacity and the number of plasma torches used in the plasma-assisted process. They will be studied individually for each process later on.

The Europlasma process

Figure 4 shows the gasification process developed by Europlasma. It uses an auto-thermal gasifier, comprised of a stoker grate auto-thermal gasifier, based on design already in use in Germany. The syngas is then heated to over 1200°C with a plasma torch and prepared for

electricity production in a gas turbine. At this stage, all organics free radicals are destroyed.

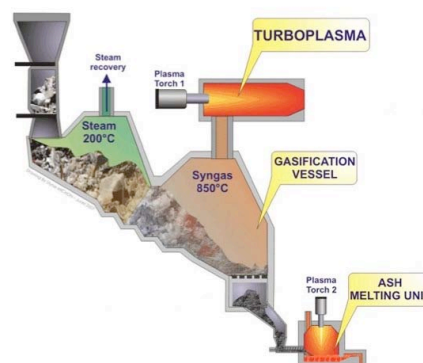


Figure 4. Europlasma gasifier (Europlasma)

Furthermore, because of the rapid cooling, dioxins and furans are not reformed. Lastly, a second plasma torch to produce an inert material that can be used in construction vitrifies the ash, consisting of metals and minerals.

The industrial process uses dried MSW mixed with scrap tires to boost the overall calorific value.

The Alter NRG/WPC process

Another plasma-assisted process uses plasma torches to provide the heat of gasification while at the same time it melts the ash into vitrified products. This is the plasma-assisted gasification process developed by Alter NRG/Westinghouse. The same syngas is generated as in the Europlasma process but in a different gasification reactor. In this case, the plasma jet is at the bottom of the gasifier. Up to six plasma torches are used at the bottom of the gasifier to provide sufficient heat for the gasification to take place. A bed coke is created within the cupola by feeding metallurgical coke (met coke) to absorb and retain the heat energy from the plasma torches and provides the environment for melting the inorganic materials into a vitrified slag. The coke is fed through the same inlet as the MSW feedstock.

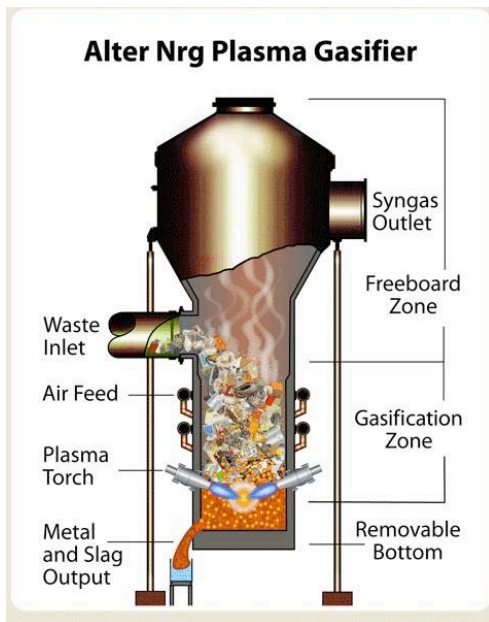


Figure 5. Alter NRG plasma gasifier (Alter NRG website)

InEnTec (which stands for Integrated Environmental Technologies, LLC) is an American company founded in 1995 after plasma research, which led to a patented Plasma Enhanced Melter (PEM), the combination of plasma and glass melter technologies.

The PEM technology has been used in the only two commercial facilities using plasma arc within the whole U.S. The first one was in Richland, Washington, and was the property of Allied Technology Group and it closed due to operational problems with the plasma arc equipment.

Their system is combining the use of plasma arc with graphite electrodes and a Joule Heating System (JHS) to keep the temperature of the molten bath high. This allows decreasing the power needed from the plasma torch but at the same time adds the electricity consumption of the JHS. The plasma torch energetic consumption is 74-86% of the energy input while the JHS is 14-21%. Its goal is, just like the gasification island of WPC, to gasify the organic compounds to a high quality syngas while at the same time vitrify the organics to a glass-like material. The main reaction going on is a steam reforming reaction:

$$C + H_2O(g) + \text{heat} \rightarrow CO(g) + H_2(g)$$

As it is an endothermic reaction, the plasma arc will provide the energy to make it happen.

The plasma arc is created by DC current going through three 3 in diameter graphite arcing electrode. An AC current going through three graphite electrodes creates the JHS.

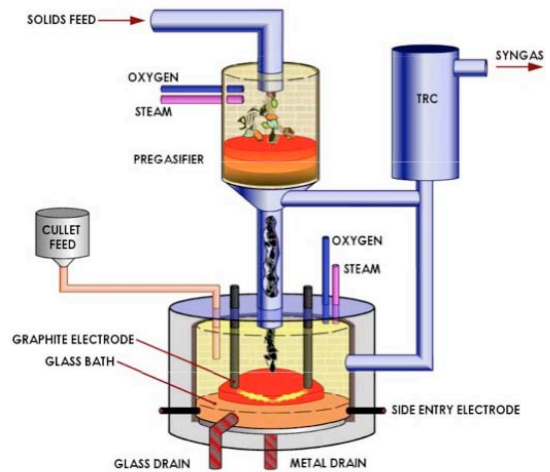


Figure 6. Plasma Enhanced Melter (InEnTec)

As shown in Figure 6, the MSW is gravity fed, and the plasma arc is created with the graphite electrodes right after. The JHS is created of the two side entry electrodes and keeps the glass bath at a constant temperature while the melted solids are going out at 1,000°C.

The interesting aspect is that there is a pre-gasifier before the PEM, allowing gasifying a first part of the organics and thus reducing the energy needed from the plasma arc.

Current research

Both the material balances and the economic analysis are in progress. Due to the confidential aspect of some data, we were not able to describe every detail in this review.

A classic Waste-to-Energy plant can be assumed to produce 500 kWh net of electricity per ton of waste. The analysis is based on the case of a 750 tons per day plant. The capital costs associated to such a plant are about \$50/ton of MSW processed. The labor costs are considered to be the same for both a classic combustion and a plasma gasification plant and represent \$10/ton of waste for a plant of the size studied.

Capital costs for the latter are expected to be higher than the grate combustion plant, but the production of electricity is also much higher. The investigation is to see whether this increased production of electricity is able to cover the difference in capital costs and aliment the intern electricity demand for the plasma torches.

The revenues of these plants will be based on the gate fees – assumed to be \$65/ton of waste for NY State –, the sale of the electricity and the one of slag and metals coming out.

Another interesting aspect could be the fewer off-gases generated by the gasification plant compared to the combustion one. It could give a more compact design and save money on the capital costs. This aspect is still studied.

References

Themelis N.J. and Y.H. Kim, Energy recovery from New York City Waste, ISWA journal: Waste management and Research, 2002:20, 223-23.

J. Heberlein, New approaches in thermal plasma technology, Pure Appl. Chem., Vol 74, No 3, pp. 327-335, 2002.

J. Heberlein, A. B. Murphy, Thermal plasma waste treatment, IOP Publishing, 2008.

E. Gomez D. Amutha Rani, C.R. Cheeseman, D. Deegan, M. Wisc, A.R. Boccaccini, Thermal plasma technology for the treatment of wastes: A critical review, Journal of Hazardous Materials 161 (2009) 614–626

Alter NRG/Westinghouse Plasma Corp

<http://www.alternrg.ca/>

Europlasma <http://www.europlasma.com/>

Plasco Energy Group

<http://www.plascoenergygroup.com/>

EPA, waste reports <http://www.epa.gov/>

Charles H. Titus, Jeffrey E. Surma,

Integrated Environmental Technologies, LLC, Enhanced Tunable Plasma-Melter Vitrification Systems, Patent number 5,811,752, Date of Patent: Sep 22, 1998.

InEnTec, Environmental Technology Verification Report for the Plasma Enhanced Melter.

Juniper Consulting, Independent waste technology report, the Alter NRG/Westinghouse plasma gasification process, November 2008.