Application of Plasma Gasification Technology in Waste to Energy Challenges and Opportunities

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***Abstract*—Utilization of plasma gasification in waste to energy is one of the novel applications of a technology that was introduced several decades ago. In this application, plasma arc, gasifies the carbon based part of waste materials such as municipal solid waste, sludge, agricultural waste, etc. and generates a synthetic gas which can be used to produce energy through reciprocating engine generators, gas turbines and boilers. The non-carbon based part of the waste materials form a vitrified glass and re-usable metal. The goal of this study is to describe the basics of this technology, review the challenges and opportunities for implementation of plasma gas technology in waste to energy applications in the United States, and provide a roadmap to eliminate current roadblocks for developing such projects.**

***Index Terms*—Plasma gasification technology, waste to energy, renewable energy, pyrolysis, Syngas.**

I. Acronyms and Abbreviations

Note: The singular and plural of an acronym are always spelled the same.

BDL	below detectable level
LFG	landfill gas
MSW	municipal solid waste
PGT	plasma gasification technology
PPM	parts per million
WTE	waste to energy

II. Introduction

THE instability of fossil fuels cost worldwide and adverse environmental effects of burning them, are two major contributing factors of today's energy crises. Crude oil price fluctuations, conflicts in oil producing regions, and the high cost of exploring for new oil resources, are challenging the nations to find alternate sources of energy. Additionally, the greenhouse gas emission of fossil-based fuels is believed to be a leading cause of climate change and global warming, and one of the major causes of recent catastrophic weather events.

Even though there are many disagreements among scientists and policy makers on these matters, there is, however, consensus that alternative sources of energy that are sustainable, environmentally friendly and regionally available must be found.

Municipal solid waste (MSW) is considered one source of renewable energy, and plasma gasification technology is one of the leading-edge technologies available to harness this energy. In fact, in recent years, the US government officially declared the MSW as a renewable source of energy, and power generated through the use of MSW is considered green power and qualified for eligible incentives.

Application of plasma gasification technology in waste to energy, relieves the pressure on distressed landfills, and offers an environmentally benign method of disposing MSW. Plasma technology purports to be an economic and abundant source of energy, and a reliable source of power. However, skepticism about the technology, lack of historical data, volatile price of crud oil, a mislabeling of plasma gasification technology as another type of incineration, the competing low cost of opening new landfills and a lack of government sponsored development and pilot projects, have contributed to the lack of progress in development and utilization of this technology in the US.

This study reviews the background, history, concepts and theory of utilization of plasma gasification in waste to energy application, describes some of the challenges and opportunities, specifically in the US, and suggests a roadmap to accelerate the development and implementation of this technology.

III. Background and Concept

A. Plasma

In Physics, plasma is an electrically conducting medium in which there are roughly equal numbers of positively and negatively charged particles, produced when the atoms in a gas become ionized. It is sometimes referred to as the fourth state of matter, distinct from the solid, liquid, and gaseous states [1], [2]. Lightning is a natural form of plasma. In industry, plasma is generated through plasma torches in which by heating a gas to an extremely high temperature, cause the present gas (usually air) to ionize and create plasma. The temperature outside a plasma torch can reach $7,000\,^{\circ}$F.

B. Recent Applications of Plasma Technology

To date plasma torches and plasma arc technology have been used in a variety of industrial, military, space and other applications such as:

1) Space Programs: Over forty years ago, as one of the first applications of plasma arc, NASA developed this technology to simulate the re-entry temperature and tested the space shuttles heat shield capability [3].

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2) Waste Disposal: United States Navy shipboards and a few of the cruise liners use plasma torches for destruction of their daily solid waste. In addition, several waste to energy plants are operational in Japan.

3) Remediation of Radioactive Waste: Highly radioactive waste is mixed with glass particles and exposed to plasma torches and heated to produce a molten glass. After the mixture cools, it forms a stable glass and traps the radioactive elements and prevent them from moving through the air and leaching to ground water [4].

Other applications of plasma arc technology include medical waste destruction, asbestos destruction, PCB destruction, melting incinerator ash, cutting heavy metals as well as melting scrap metals.

C. Potential Future Applications of Plasma Technology

In addition to plasma gasification technology for waste to energy, the plasma arc can be utilized in a variety of commercial and industrial applications. Among them are:

1) Animal Carcass and Animal Waste: One of the major contributors of greenhouse gases is the methane generate by animal wastes. Plasma gasification technology can be used to properly destroy the animal wastes and also generate syngas to produce electricity or heat.

2) Agricultural Waste: Wood chips and all other types of agricultural wastes can be placed in plasma reactor vessels and produce syngas to generate electricity or heat.

3) Paper and Pulp Industry Waste: Similarly, all paper and pulp industry wastes can be processed through plasma gasification method to destroy the waste and generate heat or electricity.

4) Carpet Disposal: Carpet is one of the most difficult wastes to dispose. High temperature of plasma arc can easily melt any kind of carpet. It is important to mention that the best practice is using recyclable materials to manufacture carpets and do not even create the problem, however, industry trend shows that it may take years until this practice becomes an industry standard.

5) Soil in Situ (borehole) Vitrification: For years application of high temperature for decontamination of underground waste and hazardous materials had been recognized. However, the difficulties associated with implementing it proved that the novel idea did not seem to be easy to apply. In addition it seemed even more difficult to evaluate the results. Now, with advances in plasma technology, it is possible to lower a plasma torch several feet into ground and pyrolyze the contaminated materials and melt them to shape a magma or lava material which when cools, it becomes a rock-like solid material. Experimental tests show that a 5 MW torch can be lowered in a borehole and slowly moved up to transform contaminated soil to a rock-like solid material with a diameter of 10 feet [3], [5].

The vitrified mass produced as a function of plasma torch energy can be presented as

$$M(kg) = 0.35\ P(kW.h)$$

where M is the vitrified mass produced in kilogram and P is the amount of energy used in the process [4].

Similar concepts can be applied to unstable underground layers of soil to create a more solid base. One application could be for underground leakage in dams.

6) Coal Gasification: Coal fired power plants emit large amount of sulphur (SO_x), nitrogen oxides (NO_x) and CO_2. Similar to MSW, coal can be used as feedstock to the plasma gasification to generate syngas and use syngas to generate heat or electricity. This is in opposition to burning (incinerating) coal. The same methodology can be applied in converting coal to liquid (CTL), retrofitting exiting coal fired power plants, and mix coal with MSW and gasify the mix [6], [7], [8].

D. Cost of a Typical Plant

A typical plasma gasification for waste to energy plant with a feedstock of 3,000 ton of MSW per day is estimated to cost over $400 million [9] and generate about 120 MW of electricity [10]. Another estimation for a 2,000 ton MSW per day is about $250 million [11]. It is also projected that each ton of MSW has the potential to produce 900 kWh [12]. The same plant can produce 1,200 kWh for each ton of MSW, if it is equipped with cogeneration auxiliaries.

To put these costs in perspective, it should be noted that there is not a single such plant operational in the US. This implies that similar to any other new technology, the cost will decrease significantly after the mass productions start.

IV. Application of Plasma Gasification Technology in Waste to Energy

A. History

The concept of treating MSW using plasma arc technology was first introduced by Dr. S. L. Camacho in his December 1973 patent [13]. He proposed a furnace with multiple plasma torches to continuously pyrolyze household and industrial wastes [14]. He showed that the process would produce useful gas that could be used for producing energy, and rock-like byproduct to use as aggregate for construction. He also demonstrated that gaseous emission to atmosphere were limited and very much under control. Additionally, he showed that using his methodology, all kinds of waste material would be processed without any ashes that would require to be sent to a landfill [3].

Since then, environmental regulations started to become more stringent which in turn caused to increase the cost of opening, maintaining, and operating landfills and that caused an increase in tipping fees. On the other hand, in-depth studies revealed more harmful attributes of landfills to environment. Consequently, all of the issues related to landfills, created an atmosphere for academia and industry to extend their research for new solutions.

In 1988, Resorption Canada Limited (now renamed to Plasco Energy Group) introduced their prototype plasma gasification for treatment of MSW. Their system used a 150 kW plasma torch in a furnace to pyrolyze approximately 500 pounds of MSW per hour [15].

MSW Constituents	Average Weight (%)	Ex Situ Experiment (lbs)	In Situ Experiment (lbs)
Paper	42.00	10.50	56.54
Fabric	5.20	1.30	7.00
Plastic	4.50	1.13	6.06
Food	17.90	4.48	24.10
Wood	4.50	1.13	6.06
Sweepings	1.90	0.48	2.56
Ferrous Metals	9.80	2.45	13.19
Aluminum	1.10	0.28	1.48
Non-Ferrous	0.40	0.10	0.54
Other Burnable	12.70	3.18	17.10
Rubber		1.00	10.00
Glass		1.20	5.00
Grass/Leaves		1.00	2.00
Total	100.00	25.00	134.62
Moisture Content	27.00	9.25	49.79
Total		34.25	184.40
Soil			26.92
Total			211.33

TABLE I
AVERAGE MSW CONSTITUENTS IN THE US [18], [3]

In 1992, Camacho [16] was granted another patent for his invention related to mixed refuse materials being heated by a plasma torch for the purpose of converting its organic components into fuel gases, and its inorganic components into inert solid matter. He was also granted a third patent on this subject in 1996 [3], [17].

In 1991 Georgia Institute of Technology (Georgia Tech) started a plasma arc research technology program and established Plasma Applications Research Facility (PARF) laboratory which was the largest university based research facility for plasma technology. Through the years, the lab ran several experiments and under supervision of Dr. L. J. Circeo published numerous papers and contributed to many project developments in the United States and worldwide.

B. Georgia Tech Laboratory Results

The Georgia Tech PARF lab conducted several tests using their prototype plasma gasification units. One of the units contained a 100 kW and the other a 240 kW plasma heating system. The plasma gas was mainly air; however, Argon and Hydrogen were tested too. The main supply of the furnaces were artificial combination of materials to simulate typical average constituents of MSW based on US EPA [18]. Table I shows the constituents of the materials along with the corresponding planned weight of simulated MSW for the lab experiments. For the Ex Situ experiments the MSW constituents were used and for In Situ experiments, soil was added to the MSW constituents to simulate a real landfill.

Following sections present summary of some of the Georgia Tech PARF lab experiment results.

1) MSW Weight Loss from Plasma Processing: Table II shows the percentage weight loss of the MSW after plasma processing, where in experiment 3, significant amount of soil was added to the mix and as expected, weight loss was significantly less than the other two experiments.

Experiment No.	Innitial Weight (lbs)	Final Weight (lbs)	Weight Loss (%)
1	36.1	5.9	84
2	28.5	5.5	81
3	103.8	42.1	59

TABLE II
MSW WEIGHT LOSS FROM PLASMA PROCESSING [3]

2) MSW Volume Reduction through Plasma Processing: Table III shows the percentage volume reduction of the MSW after plasma processing. Again, given that significant amount of soil was added to the mix in experiment 3, obviously, the soil was melted (vitrified) but did not gasify (pyrolyzed) and consequently the volume reduction was reasonably different comparing experiment 1 and 2.

Experiment No.	Innitial Volume (in^3)	Final Volume (in^3)	Volume Loss (%)
1	1,621	67.9	95.8
2	1,801	63.3	96.5
3	4,233	483.8	88.6

TABLE III
MSW VOLUME REDUCTION THROUGH PLASMA PROCESSING [3]

3) Toxicity Leaching Tests Results: Tables IV and V show the results of standard toxicity characteristics leaching procedure for experiment 2 and experiment 3 respectively.

Heavy Metal	Permissible Concentration (mg/l)	Measured Concentration (mg/l)
Arsenic	5.0	BDL (0.1)
Barium	100.0	0.47
Cadmium	1.0	BDL (0.1)
Chromium	5.0	BDL (0.1)
Lead	5.0	BDL (0.1)
Mercury	0.2	BDL (0.01)
Selenium	1.0	BDL (0.2)
Silver	5.0	BDL (0.1)

TABLE IV
TOXICITY LEACHING RESULTS FOR EXPERIMENT NO. 2 (W/O SOIL) [3]

Heavy Metal	Permissible Concentration (mg/l)	Measured Concentration (mg/l)
Arsenic	5.0	BDL (0.1)
Barium	100.0	BDL (0.1)
Cadmium	1.0	BDL (0.1)
Chromium	5.0	BDL (0.1)
Lead	5.0	BDL (0.1)
Mercury	0.2	BDL (0.01)
Selenium	1.0	BDL (0.2)
Silver	5.0	BDL (0.1)

TABLE V
TOXICITY LEACHING RESULTS FOR EXPERIMENT NO. 3 (W/ SOIL) [3]

4) Output Gas Composition: Table VI shows the output gas compositions for experiment 2 and experiment 3 respectively.

Output Gas	Experiment No.2 (PPM)	Experiment No.3 (PPM)
Hydrogen (H_2)	>20,000	>20,000
Carbon Monoxide (CO)	100,000	>100,000
Carbon Dioxide (CO_2)	100,000	90,000
Nitrogen Oxides (NO_x)	<50	100
Hydrogen Sulfide (H_2S)	100	80
Hydrogen Chloride (HCL)	<20	225
Hydrocarbons	>5,000	>4,500

TABLE VI
OUTPUT GAS COMPOSITION [3]

C. Current State of Practice

Besides the prototype plasma gasification units at Georgia Tech, two other similar tests have been performed and consistent results were obtained [12], [19]. In addition, two plasma gasification plants are currently in operation in Japan. Lastly, there are several projects under development in Florida, California, Minnesota and Hawaii, in US, as well as several projects in Canada, India, and Europe [10], [20].

All of these activities and prototype results clearly present an enormous opportunity in the area of waste management as well as renewable energy generation. Despite all of these evidences, still there is not enough momentum and wide acceptance of this technology. Therefore, it is the responsibility of technical community leaders such as IEEE and specifically Power and Energy Society and Industry Application Society to take charge, set the standards, advise the government and industry and eliminate the barriers with the goal of **"One Plasma Gasification Unit for Each Major Landfill in America"** and set target dates to decrease the number of landfills until total elimination.

V. Plasma Gasification Technology in Waste to Energy Roadmap: Challenges and Opportunities

Plasma gasification is a promising technology with potential to solve many complex environmental and energy challenges that many nations including the United States are facing. A detailed assessment of the state of practice, research and available technologies was conducted to identify the core research and development opportunities and challenges that exist in the field of application of plasma technology in waste to energy.

The results of these assessments are presented in three sub-groups: opportunities, which describe the obvious benefits of implementing plasma gasification technology for waste to energy application, challenges in achieving those goals, and suggested roadmap to technical community, industry and policy makers toward eliminating the current roadblocks.

A. Opportunities

1) Reducing the Need for Landfills: According to US EPA, each US resident, on average, generated approximately 4.5 pounds of daily solid waste in 2001 [21]. Also according to the same source, between 60% to 90% of American solid wastes went to landfills. This translates to over 650,000 tons of solid waste generation every day. Plasma gasification technology has the full potential to transform this huge source of energy to electricity, liquid fuels or plastic.

2) Disposal of Hazardous Waste: With proper permit and careful monitoring, almost all hazardous wastes can be fed into plasma gasification chamber and destroyed permanently without leaving ash to bury in landfills [22].

3) Syngas, A Crude Oil Replacement: Syngas leaves the plasma chamber at almost atmosphere pressure and relative high temperature (about $1,200\,^{\circ}\mathrm{C}$) and is composed of gases with varying elements depending on feedstock constituents.

Syngas can be used as the raw material to generate fuel for low BTU reciprocating engine generators, gas turbines and boilers.

Syngas can provide building blocks to generate methanol, ethanol, butanol, gasoline, diesel, plastic and many other carbon based products that traditionally are produced from crude oil [11], [23], [24], [25], [26].

4) Using Vitrified Material (byproduct) [11]: Besides the syngas that is collected from the upper part of plasma gasification chamber, there is another byproduct exiting the chamber from the lower part in the form of molten lava or magma. If naturally cooled, it forms a rock-like inert that can be used as building aggregate, ceramic tiles and bricks or in the form of gravel for road construction.

The same lava may be cooled in water to separate the nodules of metals which in turn can be recycled in metal refineries.

The molten stream can be allowed to cool down in various shapes of molds to create artificial reefs and placed in featureless parts of sea. Among many benefits of placing artificial reefs are attracting fish and other sea creatures and creating new underwater colonies [27].

B. Challenges

1) Lack of Standards: The lack of standards on plasma gasification technology endorsed by nationally or internationally known organization, is one of the most important contributing factors in project development difficulties.

2) Initial Cost and Return on Investment: Another major impediment of developing plasma gasification technology for WTE is its financial justification. Typically, the installed cost of a plasma gasification plant is approximately around $5,000 per kW. This cost is higher than the installed cost of a modern natural gas fired combined cycle power plant. For this reason, currently, a plasma gasification plant is economic only where tipping fees for MSW are high, electric rates are high, and the municipality faces an economically painful waste-management crisis.

In addition, due to relatively high cost of operation and maintenance on one hand, and the amount of syngas generated on the other, the return on investment time for these plants is considered long comparing to similar size industrial facilities.

3) Skepticism on Environmental Effects: Lack of historical data, limited number of prototype units and absence of government regulations, caused skepticism on environmental effects of plasma gasification technology. First, the generated syngas is produced at almost atmosphere pressure and that alone, causes concern on reliability of gas collection systems. The answer is simple: incorporate redundancy.

Other critique on syngas is focused on scrubbing system. It is obvious that the syngas that exits the plasma chamber needs several layers of cleansing to remove some of the unwanted elements. The distress comes on how those elements are stored, transported and disposed.

Finally, there are questions on slag exiting from the bottom of the chamber. Several independent tests on prototype units had been performed and level of toxics in inert material seemed to be several folds less than permitted level in some cases, and below detectable level in other cases. Europlasma [28] as part of *Vivaldi Programme* provided similar test results which they were validated by French Nuclear Agency. However, given that there is no certifying or monitoring agency in the United States dedicated to this task, it is typically difficult to convince skeptics.

4) Confusion between Plasma Gasification and Incineration: There is a great deal of misunderstanding (or deliberately misstating) between incineration and plasma gasification.

Incineration in short is simply burning the garbage, which comes with toxic fumes and toxic ashes. There are ways to scrub the fumes, however their effectiveness rely on technology, proper maintenance and regular monitoring. The toxic ashes remain toxic forever and need to be buried somewhere, most likely, in a landfill. Obviously there is always the risk of contaminating underground water, or exposure to natural disasters such as hurricane, and flood.

While in plasma arc chamber, the solid waste is gasify or instantly melted and the sludge is almost a rock-like inert material.

C. Suggested Roadmap

1) Establish Standard Organization: Initiate a standard group within the technical community. If concentrating on renewable energy benefits of plasma gasification, IEEE Power and Energy Society and IEEE Industrial Application Society can form a joint technical committee. Suggested title could be: "Plasma Gasification for Waste to Energy (PGWTE) committee." This technical committee can be in charge of developing standards for design, manufacturing and safe operation of plasma gasification plants. They will also be the voice of technical community to advise the government agencies and set the standards for the near future mass production of these plants.

This committee may become the leader of a forum for government agencies, technical community, industry, waste management community and others to set up regular conferences and invite the entire community for sharing their thoughts, concerns and new ideas.

Several sub-committees can be formed to be responsible for a variety of challenges. One may take responsibility for gathering data on pilot plants as well as operational plants on continues basis to create a data base and use is as a guide for improving the technology. Another, may focus on reliability of these plants, etc.

2) Certifying the Plasma Gasifying Plants: Similar to other industries that affect the environment, such as landfills, create a task force at government level (i.e. US EPA) and regulate the design, installation and operation of plasma gasification plants. This process will legitimize the existence of these plants and would assure the public that these plants will be built under stringent regulations and will be monitored accordingly. This will also help the counties to have a guideline for issuing permits to these facilities.

3) Certifying the Vitrified Materials: Establish criteria and test methods to evaluate the composition of slag exiting the plasma gasification chamber. This can be initiated at the government level (i.e. US EPA) and used as a guideline for states and counties who are responsible for issuing permits for plasma gasification plants.

4) Government Intervention: Given that as of the end of year 2008, there was not a single plasma gasification plant for waste to energy, operational in the United States, almost thirty years after it was introduced, implies that there are roadblocks to overcome.

Significant initial costs, lack of standards, lack of community awareness and lack of historical data, to name a few, caused the slow progress of this technology in the United States.

Impediments associated with landfills, energy crises and adverse environmental effects of current power generation practices are all national matters touching every citizens' daily life. Consequently, government can declare the development and implementation of plasma gasification for waste to energy infrastructures a national priority and similar to construction of roads and bridges, take part and assist in development. This technology has the potential to generate more than 5% of the United States electricity [29], more than all wind turbines, biogas, solar and geothermal sources combined; reduce the need for landfills and ultimately clean all the existing landfills and eliminate the need for future; create jobs and alleviate some of the environmental problems.

This is an enormous task and needs a massive response and support.

VI. Conclusion

The background and basic concepts of plasma gasification technology is reviewed. A history of the origin and inventors of the technology for application of plasma gasification in WTE presented. Potential future applications, challenges and opportunities are discussed. Finally, a roadmap to industrialize and commercialize the technology is presented.

Studying the results of several prototype operation in US and Canada as well as commercial operations in Japan, prove that plasma gasification is a promising technology in WTE applications and could be one of the best methods to eliminate the landfills in the US. It will alleviate the greenhouse gas emission problems and save underground water too.

A high level roadmap to achieve these initiatives has been presented which include formation of technical committees, seminars, and cooperation among government organizations.

It is unprecedented to see thirty years after invention of the technology, several pilot projects in North America and a couple of commercial operation in far east, two plants under construction in India and another two in Turkey [20], to name a few, still major US government agencies such as US Department of Energy (DOE) do not recognize the plasma gasification technology, and in one of their latest reports "Gasification World Database 2007, Current Industry Status" [30], the plasma gasification has not been even mentioned as one of the available gasification technologies.

ACKNOWLEDGMENT

The author would like to thank Dr. Louis Circeo for providing invaluable resources on plasma gasification technology and its applications, and Mr. Mark Sindeband for his constructive suggestions.

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