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SUSTAINABLE ENERGY RECOVERY FROM WASTE THROUGH PLASMA GASIFICATION: EVOLUTION OF PLASMA TORCH TECHNOLOGY FROM RESEARCH APPLICATIONS TO GASIFICATION OF WASTE TARGETING ZERO WASTE TO LANDFILL

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ABSTRACT: Westinghouse plasma technology has evolved from its genesis producing super high temperature energy for testing the heat shields on space shuttles to application in gasification reactors for the destruction of a wide range of waste materials and the production of renewable energy. A Westinghouse plasma gasification plant is ideally suited to help Malta achieve its waste treatment objectives, move toward eliminating its dependency on landfill, increase its energy self-sufficiency, reduce its carbon footprint, and become a global leader in waste management.

Keywords: Plasma, Gasification, Energy from Waste

1 HISTORY OF PLASMA DEVELOPMENT

Westinghouse Plasma Corporation's (WPC) plasma technology was developed over a period greater than 30 years and with over $100 million in Research and Development funding. The WPC technology was initially developed in collaboration with NASA for use in the Apollo space program to simulate space vehicle re-entry conditions of over 5,500°C (10,000°F). Between 1983 and 1990, Westinghouse and the Electric Power Research Institute (EPRI) developed a reactor using plasma for reclaiming fragmented scrap metal. Between 1988 and 1990, Westinghouse extended the plasma cupola technology for the treatment of hazardous wastes including contaminated landfill material, PCB-contaminated electrical hardware, transformers and capacitors, and steel industry wastes.

In the mid-1990s WPC, in cooperation with Hitachi Metals, completed a R&D program and pilot testing program to confirm the capability of the plasma cupola to treat municipal solid waste (MSW) and other waste materials to produce a syngas, which could be used in a power plant for the production of steam and electricity. A series of tests were completed at the WPC Plasma Center in Madison, Pennsylvania using a variety of feed materials and at varying moisture contents. The success of these tests provided the technical basis for the design and installation of a pilot scale 24 ton/day MSW gasification plant in Yoshii, Japan.

Hitachi Metals and WPC's combined efforts culminated in the demonstration to the Japanese government that the Yoshii WTE facility was capable of using plasma energy to reliably and economically gasify waste materials for energy production. In September 2000, the Japanese Waste Research Foundation awarded a process certification of the technology and the Westinghouse plasma gasifier was born.

2 PLASMA

At the most rudimentary level, plasma is just very high temperature thermal energy. In nature, plasma is produced by lightning when it superheats the air around the lightning bolt converting the air to plasma with a temperature of about 20,000 °C. Because plasma behaves differently than the three common states of matter; solid, liquid and gas, plasma is sometimes referred to as the fourth state of matter.

3 PLASMA TORCH SYSTEMS

WPC creates plasma with its plasma torch systems. WPC creates electric arcs, similar to lightning, inside its plasma torches and air is pushed through the arcs to create plasma. The plasma, with temperatures close to 5,500°C, is controlled and directed into a gasifier.

A plasma torch system comprises the following components:

- plasma torch
- arc igniter
- power supply
- torch air system
- de-ionised cooling water system

Figure 1 shows a cutaway of a WPC plasma torch. Each torch includes two closely spaced electrodes across which an arc is created when current is applied. When a gas, such as air, is forced through the arc, plasma is created. The arc dissociates the gas into electrons and ions enabling the gas to become electrically and thermally conductive. The conductive properties of the ionized gas stream in the arc region provides a means to transfer energy from the arc to the process gas. The plasma state exists in the immediate confines of the arc within the torch. By the time the gas stream exits the torch it will be recombined into a neutral (non-ionized) superheated gas stream.

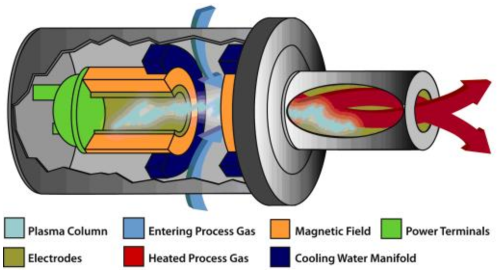

Figure 1: Plasma torch cut-away.

The WPC plasma torch is capable of superheating the process gas (air) to temperatures in excess of 5,500 ºC. The plasma torch system is capable of increasing the specific energy of the process gas to between two and ten times higher than conventional combustion equipment. It has the capability of greatly increasing the temperature of the gas coupled with the ability to maintain control over process variables, gas operating temperature, and amount of energy supplied to the system.

The high voltage arc igniter is coupled to the plasma torch to provide sufficient energy to break down the electrode gap during torch ignition. The igniter is connected directly into the arc current path from a DC power supply to the plasma torch.

The plasma torch power supply converts the incoming AC power to DC open circuit power.

The plasma torch air supply system provides instrument quality air to the torches as process gas for plasma generation.

The plasma torch system requires cooling water to maintain the electrodes, both anode and cathode, at safe operating temperatures. De-ionized (DI) water is used to cool the plasma torch, power supply, arc igniter, and power cables.

4 PLASMA GASIFIER

A plasma gasifier is an oxygen starved vessel that is operated at the very high temperatures achievable with plasma. Because the environment inside the vessel is deprived of oxygen, feedstock that is processed in the gasifier is not combusted. Rather, the heat breaks the feedstock down into elements like hydrogen, carbon monoxide and other simple compounds. The gas that is created is called synthesis gas or “syngas”.

Most feedstocks, including MSW, contain both organic and inorganic components. The organic components are converted into syngas. The inorganic components, like glass, metal and concrete, are melted inside the reactor and flow out of the bottom as a non-toxic vitrified molten slag which can be used safely as aggregate.

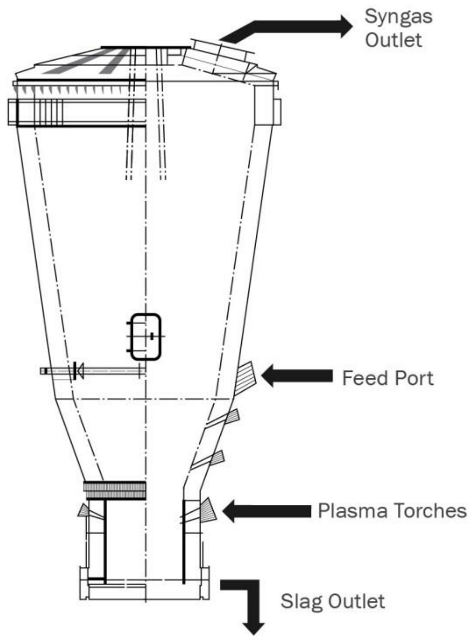

Figure 2: WPC plasma gasifier.

The heat from the plasma torch systems and the relatively long residence time in the gasifier ensures complete destruction of the feedstock and allows for the processing of high moisture feedstock or feedstock containing high levels of inert materials like glass and metals.

During the gasification process, the principle chemical reactions are those involving, carbon (C), carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), water (H_2O) or steam, and methane (CH_4). These include [1]:

Combustion reactions:

$$C + \frac{1}{2}O_2 \rightarrow CO \quad (1)$$
$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \quad (2)$$
$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad (3)$$

The Boudouard reaction:
$$C + CO_2 \leftrightarrow 2CO \quad (4)$$

The carbon-steam reaction:
$$C + H_2O \leftrightarrow CO + H_2 \quad (5)$$

The water gas shift reaction:
$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (6)$$

The methanation reaction:
$$C + 2H_2 \leftrightarrow CH_4 \quad (7)$$

The syngas created in the gasifier will initially contain dust (particulates) and other undesirable elements like mercury, sulphur and chlorine.

The syngas then undergoes a clean-up process to make it suitable for conversion into other forms of energy including power, heat and liquid fuels. The syngas clean-up process is tailored to meet the requirements for each application. But in most cases, especially where MSW is the feedstock, the syngas clean-up will include particulate removal, sulphur removal and mercury removal.

The interior of the plasma gasifier is lined with refractory. The bottom section of the gasifier endures the highest exposure to heat and slag erosion/corrosion, while the top gasification and freeboard sections of the gasifier are exposed to corrosive gases. The WPC gasifier includes slag resistant, conductive refractory at the bed section of the reactor in order to eventually achieve a frozen slag layer as additional protection, and castable refractory in the freeboard to mitigate cost.

Plasma gasification differs from non-plasma gasification in one key area – temperature. Non plasma gasifiers typically operate between 800 and 900 °C. The temperatures inside Westinghouse Plasma's gasifier reach over 1600 °C. The higher temperatures inside the WPC plasma gasifier result in the complete destruction of tars, something that is not achievable with non-plasma technologies. It is difficult to remove tars downstream of the gasifier and therefore the utility of the syngas produced by non-plasma gasifiers is very limited. It can be burned immediately but it is extremely difficult to condition the syngas for use in gas turbines, reciprocating engines or for conversion into liquid fuels.

5 COMMERCIAL EXPERIENCE

The WPC plasma gasification technology is used in three commercial facilities which are described below. The technology will be used in three facilities, also described below, which are under construction.

5.1 Mihama Mikata

The Mihama-Mikata plant processes 20 tonnes per day (tpd) of MSW from the towns of Mihama and Mikata in Japan. It also processes four tpd of sewage sludge. The syngas is used to produce heat which is then used to dry the sewage sludge so it can be gasified.

All of the slag from the Mihama-Mikata plant, which has been operating since 2002, is used beneficially as aggregate for concrete or paving stones.

5.2 Maharashtra Enviro Power Limited ("MEPL")

The MEPL plant, located in Pune, India, processes up to 70 tpd of hazardous wastes from over 30 industries in India and produces electricity.

WPC has access to the operational data and the operating staff at the plant which started operations in 2008. SMSIL also makes the plant available to WPC customers for pilot tests and optimization tests.

A partial list of materials destroyed at MEPL is shown below:

- paint sludge from automobile industry
- Pharmaceutical process residues, off specification products and wastes
- Expired drugs and medicines
- Pharmaceutical organic solvents
- Cosmetics solvents, wastes and residues
- Pesticide residues and wastes
- Incinerator flyash
- Pesticide chemical sludge
- Chemical residues from textile industry
- Spent carbon
- Used/spent oil
- Waste residues containing oil
- Cotton waste containing oil
- Oily sludge/emulsion
- Adhesives
- Resins
- Laboratory chemicals

5.3 GTS Shanghai ("GTS")

In 2014, GTS, a Chinese company, completed construction of a hazardous waste plasma facility at Shanghai Chengtou (Shanghai Environmental) in Jiangding. The plant uses the WPC plasma technology including WPC plasma torch systems. The project processes a combination of medical waste and incinerator fly ash and is focused on the effective and efficient disposal management of medical waste and its potential environmental hazards and public health risks.

The facility is located adjacent to an existing incinerator, is designed to process 30tpd of medical waste, incinerator ash and other difficult, hazardous feedstock. The facility produces steam for use throughout the balance of the process facility, and also converts hazardous incinerator flyash into an environmentally friendly slag, which reduces fly ash disposal costs and increases overall efficiency.

5.4 Tees Valley Renewable Energy Facility ("Tees Valley")

Air Products is currently commissioning the Tees Valley #1 facility which is scheduled for commercial operation in 2015. Air Products is constructing a second plant, the Tees Valley #2 facility, adjacent to the first project and plans to enter that plant into commercial operation in 2016.

Each Tees Valley facility will process approximately 1000 tpd of Refuse Derived Fuel (RDF), which is a pre-sorted MSW with the recyclables removed, and produce electricity through a combined cycle power island configuration. A combined cycle power island is the combination of a gas turbine(s), a heat recovery steam generator(s) and a steam turbine(s) and is considered the most efficient commercial technology for converting gas to power.

The facility will employ sophisticated syngas clean-up technology to ensure the syngas meets the demanding specifications of the gas turbines.

The emissions from the power island will be similar to those from a traditional natural gas fired combined cycle power plant. Air Products has received its environmental approval from the UK government.

5.4 Wuhan Kaidi (Kaidi) Wood Waste Plant

In December of 2011, Kaidi, a large Chinese energy company, developed a new technology park in Wuhan, China. The facility includes a 150tpd plasma gasifier purchased from WPC. The Kaidi facility will process waste biomass, and potentially MSW or RDF, for conversion to power and liquid fuels.

Kaidi recently purchased the assets of Rentech, a Fischer Tropsch (FT) Liquids technology company, and plans to install the Rentech technology at the Kaidi Wood Waste Plant. FT technology converts syngas to liquid fuels.

The Kaidi plant includes sophisticated syngas clean-up equipment and will be the first commercial scale reference plant that converts wood waste to FT liquids.

5.4 EcoValley Plant - retired

The EcoValley plant, which was located near the small town of Utashinai in a rural area on the island of Hokkaido, could process up to 220 tpd of pre-sorted MSW. The plant, originally built by Hitachi Metals, had two gasifier trains each capable of processing 110 tpd.

The plant, which started operations in 2003, was closed in 2012 due to lack of feedstock.

5.5 Commercial Designation

In December of 2012, WSP, a design, engineering and management consultancy, included the information in Table 1 in a presentation summarizing WSP's findings in relation to a report for the Government of Western Australia [2].

Table 1: Process status of plasma technologies.

Company	**Process Status (MSW/RDF)**
Advanced Plasma Power	Demonstration
AlterNRG (Westinghouse)	Commercial
EER	Demonstration
Europlasma	Demonstration
InEnTec	Demonstration
Plasco	Demonstration
Pyrogenesis	Pilot
Solena	Concept
Startech	Concept

As can be seen in Table 1, Westinghouse plasma gasification technology is the only plasma technology that is "commercial" for the treatment of MSW and RDF.

6 PLASMA GASIFICATION VS. INCINERATION

Plasma gasification is often compared to incineration technology, which has been used for decades and is the most widely used thermal treatment technology for waste.

The primary differences are described in this section.

6.1 Feedstock Flexibility

A WPC plasma gasification plant can process a much wider range of feedstocks compared to incineration, as shown in Table 2.

Table 2: Feedstock flexibility.

WPC Gasification	**Incineration**
• MSW • RDF • Commercial and Industrial Waste • Hazardous Waste • Abattoir Waste • Waste Tires • Animal Waste • Waste biomass • Sewage sludge	• MSW • RDF

6.2 End Product Options

While an incineration plant can produce electricity and steam, a WPC plasma gasification plant can be configured to produce those two products and numerous additional high value products such as those presented in Table 3.

Table 3: Energy product options.

WPC Gasification	Incineration
• Electricity via Gas Turbine, Gas Engine, Steam Cycle • Electricity via Fuel Cell • Replacement Fuel for Natural Gas or Fuel Oil • Diesel and Jet Fuel • Steam • Hydrogen • Fertilizer • Chemicals	• Electricity via Steam Cycle • Steam

6.3 Residues Requiring Further Treatment

Incineration plants produce significant quantities of bottom ash which has very limited or no commercial value and must typically be deposited in landfills. The quantity of bottom ash depends on the composition of the waste being burned but is typically between twenty and thirty percent by weight of the waste being incinerated.

A WPC plasma gasification plant produces an inert slag instead of bottom ash. The quantity of slag produced will be approximately the same as the quantity of ash produced by an incineration plant assuming the plants process the same waste feedstock. The slag is inert and can be used as construction aggregate. One WPC customer, Bijie City Green Environmental Energy Limited, plans to produce a high value foam insulation product from the molten slag that exits the WPC plasma gasifier.

Incineration plants also produce flyash, a hazardous waste stream, in addition to bottom ash. The amount of flyash produced is typically equal to about 3% by weight of the waste incinerated and must be specially treated before disposal in a landfill.

In a WPC plasma gasification plant, the amount of residues that will require disposal will be lower than the amount of flyash generated by an incineration plant.

6.4 Dioxins and Furans

The presence of oxygen, chlorine, and particulate inside an incineration plant create the right conditions for the formation of dioxins and furans.

By contrast, the high operating temperature (>1000°C) inside a plasma gasifier in conjunction with an oxygen starved environment destroys any dioxins/furans that may be present in the feedstock, and eliminates the potential for the creation of dioxins/furans. Rapid syngas cooling via water quench prevents de-novo synthesis of dioxins and furans.

7 MALTA'S WASTE AND RENEWABLE ENERGY RELATED OBJECTIVES

7.1 Waste Feedstocks for Malta EfW Facility

Malta is considering the treatment of the following waste streams in an Energy-to-Waste Facility [3];

i) Mixed Municipal Solid Waste (mixed stream pre-treated in other facilities)
ii) Commercial and Industrial mixed waste
iii) Bulky Waste
iv) Refuse Derived Fuel (RDF)
v) Clinical Waste
vi) Pharmaceutical Waste
vii) Waste Oils and Sludges
viii) Abattoir waste (including animal carcasses) that can't be treated in biological treatment facility
ix) Sewage Sludge
x) Landfill leachate concentrate
xi) Other stabilised hazardous solid, liquid or sludge wastes
xii) Any other organic/non-organic waste as shall be permitted by MEPA

7.2 Malta Waste Treatment Goals

With respect to waste treatment, the aims of the Maltese government include [4];

- Minimising as much as possible all landfilling of non-inert wastes.
- Increasing as much as possible usable energy recovery. Low grade waste heat should only be included in the computation of energy recovered only if such waste heat is utilised in an economically viable and feasible manner.
- Ensuring emissions and environmental impacts are in conformity with the strictest standards and likely future standards. Particular attention should be given to the risk of adverse impacts or emissions in the event of malfunction and/or mis-operation and such risk should be low enough to be considered tolerable.
- Lowest processing cost per ton of waste.
- Good tolerance to contaminants in feed stock.
- Low mean time between failures, low down time and avoidance of extended periods when waste cannot be processed.

The government would also like to reduce landfill volumes to 35% of 1995 levels by 2020 [5].

7.3 Malta's Renewable Energy Related Goals

The government wants to achieve a 10% renewable energy share of final energy consumption by exploiting solar energy, waste-to-energy conversion plants and biofuel blending substitution obligation.

The government also wants to reduce CO_2 emission by 2020 to be approximately 80% of 1990 levels. [6]

8 APPLICABILITY OF PLASMA GASIFICATION FOR MALTA

8.1 Processing Malta's Waste Feedstocks

A WPC plasma gasification facility can process all 12 waste streams as listed in Section 7.1. The only waste stream listed in Section 7.1 that has not been treated at a commercial scale by WPC plasma gasification technology is abattoir waste. However, abattoir waste will present little or no technical challenge for plasma gasification.

8.2 Achieving Malta's Waste Treatment Goals

A plasma gasification plant will allow the Maltese government to achieve all of its waste related objectives as listed in Section 7.2.

All non-inert wastes can be processed into energy and inert slag through plasma gasification.

A plasma gasification plant configured with a combined cycle power island has high energy efficiency. The same plant can be configured to produce both electricity and heat to meet local needs.

A plasma gasification plant will meet all of the strictest emissions standards. The emissions of a plasma gasification plant configured with a combined cycle power island, the same configuration as the Tees Valley facilities, will produce emissions that are very similar to those of a power plant that burns natural gas.

When the cost of processing a large number of the varied waste streams listed in Section 7.1 is considered, a plasma gasification plant will be cost competitive. Other treatment technologies will process only a small subset of the listed waste streams and will need to be combined with other technologies and facilities to process the entire list of waste streams. One plasma gasification facility will do the complete job using a lower land footprint. Some technologies, such as incineration, will create residues that need further treatment and landfilling, further increasing costs.

One of the major strengths of plasma gasification is its high tolerance to contaminants. Any waste streams that are put into a plasma gasifier will be destroyed.

WPC does not expect the next two to five installations of its technology to achieve, at least initially, the same operating availability as more established technologies like incineration. That being said, WPC does expect high availability that will increase over the next few years and become similar or even better than established technologies.

A WPC plasma gasification plant will work in harmony with Malta's MSW sorting plants. The feedstock for the Tees Valley facilities is sorted waste, which will be very similar to the output of the Maghtab and Sant Antnin sorting facilities.

The scale of the plasma plant that would treat all of Malta's requirements (~150,000 tonnes per annum) is about 50% of the size of one of the Tees Valley facilities. Most other non-incineration technologies have not been commercially proven at 150,000 tonnes per annum.

The electric output from a 150,000 tonnes per annum plasma plant treating primarily sorted waste will be about 17-19 MW or about 136,000-152,000 MWh per year, which represents about 6-7 percent of Malta's annual electricity consumption [7]. Certainly, the energy produced at a plasma gasification plant can help Malta reach its 10% renewable energy share target by 2020.

Converting waste to energy instead of landfilling that waste and allowing it to decay and produce methane will also contribute positively toward Malta's 2020 CO_2 target.

9 ADDITIONAL OPPORTUNITIES FOR MALTA

In addition to helping Malta solve its waste treatment and renewable energy challenges, a plasma gasification facility could open up several additional green economy and employment opportunities focused on plasma gasification related technology development.

As mentioned in Section 6.2, syngas can be used to produce energy in forms other than electricity through combustion. For example, syngas can be converted to diesel and jet fuel. It can be used as fuel for a fuel cell for the production of emission free electricity. The government of Malta might investigate the opportunity to create, in partnership with Maltese universities (MCAST Institute of Applied Science & UoM Institute for Sustainable Energy), a research and development technology center in conjunction with a plasma gasification energy from waste plant. One exciting opportunity would be universities and private business working in partnership to create intellectual property for the efficient production of electricity through fuel cells. Another exciting opportunity relates to creating high value products, such as the insulation product mentioned in Section 6.3, using the slag bi-product of a gasifier.

A research and technology center, in conjunction with an operating plasma gasification plant and perhaps a fuel cell and/or FT pilot plant could provide teaching and vocational work experience within the EU / Schengen zone.

If the facility were to be oversized significantly, then Malta could become a waste processing service provider to other European nations that are struggling with waste management. There are pros and cons to processing waste from outside Malta. The pros include

- additional revenues which could offset the cost to treat the island's waste,
- the reduction of imported electricity and/or fuel required to produce electricity on the island,
- increased renewable energy for Malta, moving Malta closer to its target,
- a positive change in Malta's balance of payments

The cons include managing the safe transport of waste streams from other countries.

As a densely populated island, land is at a premium in Malta. The current landfills occupy valuable land. Plasma gasification could conceivably be used to reclaim current landfills returning the land to productive purposes.

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