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PLASMA RESOURCE RECOVERY TECHNOLOGY – CONVERTING WASTE TO ENERGY AND VALUABLE PRODUCTS

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ABSTRACT

Plasma Resource Recovery (PRR) is a revolutionary technology that can treat virtually any type of waste by combining gasification with vitrification. Vitrification produces inert slag that can be used as a construction material. Gasification produces a fuel gas containing carbon monoxide (CO) and hydrogen (H₂), used for cogeneration of electricity and steam. The plasma fired eductor which is the core technology of the PRR system is presently being used commercially on a cruise ship at a scale of 5 TPD. The capabilities of the PRR technology have been demonstrated in a pilot plant, at a rate of up to 2 TPD of various types of waste. Because of the high intensity of the plasma flame and the reduced amounts of gases produced in a gasification system, compared to traditional combustion systems, the PRR system is typically very compact. As such, the PRR technology opens the door for a decentralized, small scale approach to waste management.

INTRODUCTION

The Plasma Resource Recovery System proposed by PyroGenesis is used to convert municipal solid waste (MSW), industrial waste and even hazardous waste into commercially valuable products, including gaseous fuel for the production of electricity, gravel for construction and metal for recycling. For large systems, the economic value of the products is usually sufficient to cover most of the system's operating costs, making the system competitive with landfill and incineration options.

The PRR technology has been demonstrated technically on the pilot scale at PyroGenesis and shown to easily meet the most stringent emission requirements [1]. A similar technology is now used commercially (a 5 TPD Plasma Arc Waste Destruction System) by Carnival Cruise Lines for the treatment of waste generated onboard large ships. The first system has been installed onboard one of Carnival's cruise ships, the "Fantasy" and has been in operation since October 2003. The technology for shipboard use has been developed in

collaboration with the US Navy since 1998, with the objective of installing it onboard the next generation of aircraft carriers [2-6].

The novel approach of the PRR technology is that it combines the advanced processes of gasification and vitrification in one single system. Gasification is the process of reacting the organic fraction of the waste with water and a limited amount of air to produce a synthesis gas containing mostly carbon monoxide (CO) and hydrogen (H₂). The synthesis gas produced is cleaned and used for the production of electrical energy using gas engines. Hot water and steam can also be produced by the engines as required and be used for various purposes such as heating or cogeneration of electricity and steam. Vitrification is the process of melting all the inorganic fraction of the waste to produce a metal alloy and an environmentally safe glassy slag that is suitable for use as a construction material. As a result, the system produces virtually no secondary wastes.

The vitrification occurs in an electric arc furnace, where the inorganic portion of the waste (metals, glass, dirt, etc.) is recovered into a molten metal phase and a molten inert slag phase. The temperature of molten slag and metal is maintained above 1,550°C. Also in the graphite arc furnace, the organic fraction of the waste is separated from the inorganic fraction. The organics are basically volatilized with the addition of small amounts of gasification air into a crude synthesis gas.

The crude synthesis gas is then fed through a secondary gasifier, fired by a plasma torch, where the gas is reheated to 1,000°C by a combination of plasma and chemical energy. The patented secondary gasifier is essentially a plasma-driven eductor designed to mix the waste stream with air and moisture and expose the highly reactive mixture to the extreme temperatures of plasma. In the eductor, the gasification reactions are completed within fractions of a second. This innovation allows the Plasma Resource Recovery System to be much more compact than most other thermal treatment alternatives.

SYSTEM DESCRIPTION

The Plasma Resource Recovery System consists of four main processes (Fig. 1):

1. Waste preparation and feeding system
2. Plasma thermal treatment system
3. Synthesis gas cleaning system
4. Energy recovery system

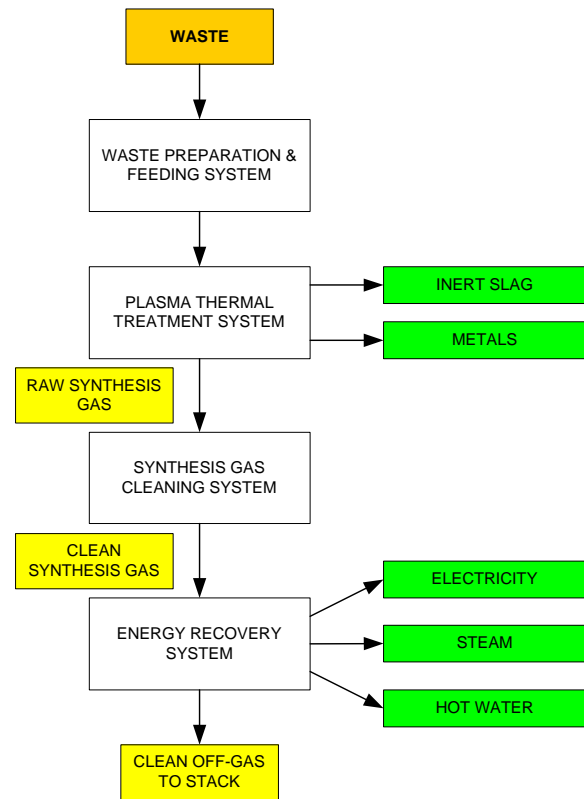


Figure 1. Plasma Resource Recovery System Schematic

Waste Preparation and Feeding System

In the waste preparation and feeding system, the waste is first shredded to make the particle size suitable for feeding into the furnace and to accelerate the gasification reactions. The shredded waste is introduced into the furnace through a series of conveyors and an airtight feeder.

Shredder

In a commercial system, it is expected that the unsorted waste from a storage pit or a storage floor would be conveyed into a large shredder where the size of waste will be reduced to small pieces, suitable for feeding to the furnace. The shredding of waste increases its surface area and thus increases the rate of gasification in the primary gasifier. Faster gasification makes the size of the gasifier smaller and increases the energy efficiency of the system. A shredder capable of reducing the size of solids into pieces of less than 2" (50 mm) in any direction is required. The shredder consists of a cutting chamber, drive system, knives, control

system, hopper and stands. An example of the shredder used on the marine system is shown in Fig. 2.



Figure 2 Example of a Shredder Used on the Marine System

Feeder

The shredded waste is then fed into the furnace through one or multiple airtight screw feeders. For large capacity systems, multiple ports ensure that the waste is evenly distributed within the furnace and provide maximum flexibility in the operation. Airtight operation ensures that the reducing atmosphere of the furnace can be fully controlled. It also ensures that no gas can escape from the furnace to the local surroundings. Screw feeders ensure that an even rate of feed is provided to the furnace, ensuring stable gasification conditions in the furnace.

Plasma Thermal Treatment System

The purpose of the plasma thermal treatment system is to convert the organic part of waste into syngas, consisting mainly of H_2 and CO and suitable for use as fuel in a gas engine and the inorganic part of waste into molten metals and inert, usable slag. This section comprises three main components:

1. A PyroGenesis patented graphite arc furnace, used to vitrify the inorganic oxides in the waste, melt the metals and convert the organic components of the waste into crude synthesis gas.
2. A hot cyclone, used to remove large solids from the synthesis gas stream. The solids are then returned to the furnace for further treatment.

3. A secondary gasifier, used to complete the gasification reactions and convert any remaining soot and complex organic molecules in the crude synthesis gas into clean CO and H_2 .

Graphite Arc Furnace

The furnace is a DC electric arc furnace, comparable to a furnace used to melt steel and other materials. In the arc furnace, two graphite rods are used to transfer electrical current through a molten slag and metal bath. The current passing through the molten metal and slag bath heats the metal resistively and provides the energy for the furnace.

In the PyroGenesis graphite arc furnace (Fig. 3), the shredded dried waste is introduced into the furnace, along with controlled amounts of air. Depending on the energy recovery requirements, pure oxygen can also be used instead of air. The molten metal and slag within the furnace are maintained at temperatures above $1,550\text{ }^\circ\text{C}$ by a combination of resistive heating through the molten slag and metal and electric arcs above the slag bath.

At the temperatures maintained within the furnace, the organic molecules are vaporized and partially react with air and water to form a crude synthesis gas, containing carbon monoxide and hydrogen, but also complex organic molecules and soot. These complex molecules and soot will be later reacted in the secondary gasifier, as described below.

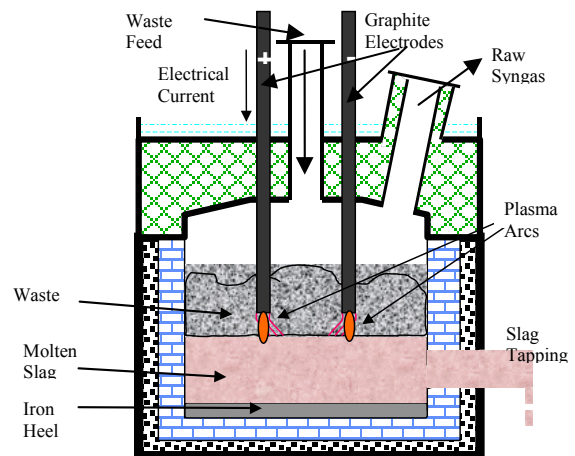


Figure 3. Graphite Arc Furnace Schematic

The inorganic components of the waste are either metal or oxides, coming from items such as glass and ash present in the organic waste. These materials melt into the molten metal bath and

separate, with the heavier metal forming a layer at the bottom of the furnace and the less dense oxides forming a separate layer on top of the metal layer. The metal layer is tapped periodically and is marketed as recycled steel.

When the oxides melt together, they form a type of glass that is extremely stable and inert. The process is called vitrification and is an excellent method of permanently trapping many environmentally hazardous materials, including heavy metals, in an inert matrix. The molten vitrified oxides are called slag and are recovered from the furnace continuously and automatically in the form of fine gravel, perfectly suited for use as construction material. Alternatively, the slag can also be cast into ingots, depending on the client's preference. PyroGenesis system produces no ash. Instead, all inorganic materials in the waste either form molten metals or stable usable slag that conforms to TCLP requirements.

Cyclone

The synthesis gas leaving the primary gasifier may carry with it a small amount of solids, primarily ash fines. A refractory lined cyclone, designed to operate at high temperatures, is used to capture these entrained solids and return them to the furnace for further treatment.

Secondary Gasifier

The synthesis gas leaving the cyclone may contain soot and complex hydrocarbons, which escaped unreacted from the furnace. In the secondary gasifier, soot and complex hydrocarbon are converted to synthesis gas (i.e. hydrogen and carbon monoxide).

The secondary plasma gasifier (Fig. 4) is essentially a nozzle in which air, moisture and the synthesis gas are mixed together with a plasma jet. The plasma jet provides the activation energy for the reaction between any hydrocarbons and other organic molecules contained in the synthesis gas with the moisture and the oxygen in the air. By controlling the chemistry in the secondary gasifier, all the organic molecules are converted to hydrogen and carbon monoxide.

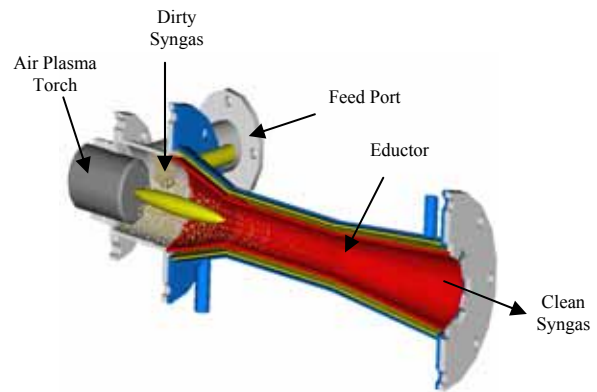
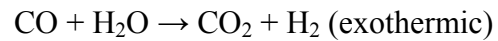
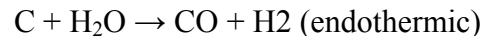
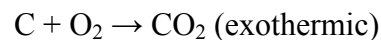


Figure 4 Plasma Eductor Schematic

The main gasification reactions occurring in the secondary gasifier are shown below:



A similar gasifier developed by PyroGenesis is used to convert pulverized solid waste into hydrogen and carbon monoxide. This patented Eductor is one of the key components of PyroGenesis' commercial shipboard Plasma Arc Waste Destruction System. A picture of the plasma eductor used for the treatment of solid waste on ships is shown in Fig. 5.



Figure 5 Example of Plasma Eductor Used on Marine System

Synthesis Gas Cleaning System

The synthesis gas leaving the secondary gasification furnace contains a number of pollutants, including fine particles, volatile heavy metals, chlorides and sulfur. In the PRR system, these pollutants are removed prior to combusting the synthesis gas in a gas engine. Furthermore, the humidity contained in the synthesis gas is also removed in order to improve its combustion properties. No further gas treatment is required at the engine outlet.

The syngas cleaning includes the following steps (Fig. 6):

- Quench chamber, used for rapid gas cooling.
- Venturi scrubber, used for particulate removal.
- Packed Bed Scrubber, used for soluble acid gases removal (for example HCl).
- H₂S absorber, used for removal of H₂S.
- HEPA filter for fine particulate removal.
- Activated carbon bed filter for removal of heavy metals.
- Induced Draft Fan, for keeping the whole system under a negative pressure.



Figure 6 Pilot PRR System Syngas Cleaning Skid

Quench

The water quench is the first step in the synthesis gas cleaning system. The quench is designed to rapidly cool the high temperature (i.e. 1000°C) gases which are essentially at thermodynamic equilibrium down to below 90°C in less than 0.5 seconds. This shock cooling of hot gases eliminates the possibility of reformation of dioxins and furans.

The quench is designed to cool the hot gases to their

saturation temperature by evaporation of an injected spray of water. Typical off-gas outlet temperatures range from 70°C to 90°C.

Venturi Scrubber

The Venturi scrubber is a simple device consisting of a duct with a constricted throat. At the throat, water is introduced, where it is atomized by the high velocity synthesis gas. Fine entrained fly ash is removed in the Venturi scrubber. Gas passing through the Venturi throat is accelerated to a velocity that fragments the water into a mass of fine droplets. Impaction efficiency is high because of high relative velocities, small water droplet size and the large number of droplets in the throat. Downstream of the throat, the cleaned gas decelerates and the water droplets agglomerate to a size easily separated from the gas stream. The droplets are separated from the gas in an entrainment separator.

Packed-Bed Scrubber

A packed-bed scrubber is used to remove acid gases (mainly HCl) from the process off-gas streams. In order to efficiently absorb contaminants such as HCl, a large surface area of contact is required to achieve interaction between the liquid and gaseous phases. Thus, the scrubber is filled with randomly oriented packing material such as saddles and rings.

The syngas enters the scrubber unit near the bottom and travels up through the bed section (where the contaminants are actually separated from the gas), where it is vigorously exposed to the scrubber solution. The scrubber solution pH is continuously adjusted using controlled amounts of caustic soda solution. The scrubber solution is also indirectly cooled using a heat exchanger, cooling down the synthesis gas and, in turn, reducing its moisture content from approximately 50% to between 5% and 10%, depending on the cooling water temperature. The condensed water is re-circulated to the quench.

H₂S Absorption

The sulfur in waste will be converted to hydrogen sulfide (H₂S) in the synthesis gas by the gasification process. Two main types of technology can be used to remove H₂S from the syngas [7]. Depending on H₂S concentration (dependant on waste sulfur

content) and syngas flow rate, either a regenerative or a non-regenerative technology can be used. In non-regenerative technology, the contaminated syngas is passed through a bed of iron oxide impregnated wood chips, where the hydrogen sulphide is converted to ferric and ferrous sulphide. These processes can achieve 90% H₂S removal. In regenerative processes, a chelated iron solution is used to convert H₂S to elemental sulfur. Its environmentally safe catalyst does not use toxic chemicals and produces no hazardous byproducts. The process units can be designed for better than 99.9% H₂S removal efficiency. The decision to select either non-regenerative or regenerative technology is also a tradeoff between higher capital costs with the later or higher operating costs with the former.

HEPA and Activated Carbon Filter

After removal of fine particles, acid gases and hydrogen sulfide, the synthesis gas may still contain traces of metals and other contaminants. In order to remove what is left of fine particles, lead, cadmium, mercury and total reduced sulfur, a deep bed gas scrubber is installed right after the hydrogen sulfide removal system.

Energy Recovery System

The clean synthesis gas will be used as fuel in a spark ignited internal combustion engine (gas engine), such as those produced by Jenbacher AG of Austria. Gas engines offer the advantage of high electrical production efficiency (35-40%), as compared to gas turbines (25%). Also, gas engines are suitable for producing electricity from low-BTU gas, such as the synthesis gas produced from the gasification of waste. Herdin et al. [8] have demonstrated the use of hydrogen containing low BTU gas in gas engines with the most extreme case at a LHV of 1.67 MJ/Nm³. Herdin et al. have demonstrated that “excellent degrees of engine efficiency have also been attained using the H₂-rich gases, in part even up to 2 percentage points better than with the use of natural gas”, estimated at 45%. In addition, Herdin et al. have reported efficiencies above 40% when using syngas from a waste pyrolysis process. Other investigators [9] have shown that the use of diesel type engines with low BTU gas could produce brake thermal efficiencies above 40%.

Because the synthesis gas has been cleaned prior to its combustion in the engine, there is no need to quench the off-gas and a heat recovery boiler can be used to recover all the sensible energy from the hot combustion gases exiting the engine in the form of steam. The sensible energy from the fluid cooling of the engine can also be recovered.

Off-gas cleaning requirements at the exit of the engine are minimal, since the fuel used has already been cleaned. The formation of NO_x can be controlled by adjusting the air to fuel stoichiometric ratio. The CO that may be produced from the engine can be controlled using a catalytic converter or a regenerator [8].

PILOT PLANT EXPERIENCE

Over the past 3 years, PyroGenesis has tested in its pilot facilities the gasification and vitrification a wide variety waste types:

- Pulp and paper boiler ash (fly ash and grate ash)
- MSW incinerator ash
- Sewage sludge incinerator ash
- Municipal Solid Waste (MSW)
- Flammable organic waste comprising variable mixtures of oil, solvent, plastics, ash and water
- ASR (automobile shredder residue) or car fluff
- Tires

The pilot facility is designed to treat between 25 and 100 kg/h of waste, depending on organic content. The pilot system uses the same approach as the commercial systems, except that the gas engine is replaced by a syngas burner.

It was found that all of the wastes listed above could be converted to syngas, suitable for use as fuel in a gas engine. Example syngas compositions are shown in Table 1 for the gasification of flammable hazardous waste (oils, solvents and plastics) and in Table 2 for the gasification of MSW. It was also found that the inorganic portion of these wastes could be converted to an inert slag, suitable for use as construction material. Typical leaching data for the slag is given in Table 3. TCLP results are typically several orders of magnitude below regulation. Atmospheric emissions from the pilot system were tested by a certified third party gas

emissions sampling firm and were found to be well below regulated levels (Table 4).

Table 1. Example syngas composition obtained from surrogate flammable hazardous waste.

Syngas	% (by volume)
CO ₂	2.1%
CO	18.8%
H ₂	28.3%
N ₂	50.8%
Gross Heating Value	6.0 MJ/m ³

Table 2. Example syngas compositions obtained from the gasification of MSW

Test no	CO ₂ (%)	CO (%)	H ₂ (%)	Gross HV (MJ/m ³)
PRR#33	8.3	20.5	11.8	4.1
PRR#32	6.0	25.6	12.0	4.8
PRR#30	8.1	28.0	8.2	4.6
PRR#30	7.7	29.0	8.8	4.8
PRR#29	4.8	27.6	13.2	5.2
PRR#29	6.4	28.4	11.6	5.1
PRR#29	6.0	26.4	14.0	5.1

Table 3. Example of TCLP (Toxicity Characteristics Leaching Procedure) obtained from pulp and paper ash vitrified to slag in PyroGenesis pilot system.

Contaminant	Canadian Regulation	Test Results
Arsenic	2.5	0.03
Cadmium	0.5	0.01
Chromium	5	0.01
Lead	5	0.01
Mercury	0.1	0.0004

Table 4. PyroGenesis' System Atmospheric Emissions processing MSW

COMPONENT	TEST RESULTS	REGULATION (MONTREAL, CANADA)	
		EXISTING	NEW
Particulate	< 3.5 mg/Rm3	< 20 mg/Rm3	< 15 mg/Rm3
HCl	0.33 mg/Rm3	< 75 mg/Rm3	< 30 mg/Rm3
HF	< 0.0065 mg/Rm3	< 2 mg/Rm3	< 1 mg/Rm3

SO ₂	18 mg/Rm3	< 100 mg/Rm3	< 50 mg/Rm3
CO	36 mg/Rm3	< 100 mg/Rm3	< 50 mg/Rm3
NO _x	124 mg/Rm3	< 300 mg/Rm3	< 200 mg/Rm3
THC	0.8 µg/Rm3	< 30 µg/Rm3	< 30 µg/Rm3
Metals	< 732 (below diction limit)	< 1000 µg/Rm3	< 500 µg/Rm3

1 Rm3 = 1 reference cubic meter at 25°C, 101.3 kPa, dry gas, 11% O₂

PROJECTION FOR COMMERCIAL SYSTEMS

The results of the pilot plant operation have been projected to commercial systems. A 3-D model of a compact commercial system for the treatment of 48 tonnes per day (TPD) of mixed waste is shown in Fig. 7. In this configuration, the system would fit in an area about one quarter to one half the size of a comparable incinerator.

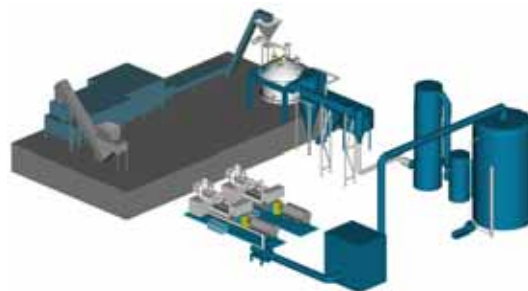


Figure 7. Example PRR System for the treatment of 48 TPD mixed waste.

This modular system can be arranged in many different ways. It is expected that a complete system with 240 TPD capacity (including pre-processing, thermal section, gas cleaning and gas engines) could fit in an area as small as 600 m². This makes the PRR system ideally suited for relatively small scale applications (50 to 240 TPD).

Example 1 – 240 TPD of MSW

An example heat and material balance is shown for a system treating 240 TPD of Municipal Solid Waste (MSW). Calculations were based on average MSW generated in the United States, removing the material that is currently recycled. The main products from the process are summarized in Table 5. The system will produce 1450 kg/h (145 kg/t) of slag, usable as construction material, 640 kg/h (64 kg/t) of metal ingots that could be used by metal

recyclers and 8,430 kW (843 kWh/t) of electricity. The system uses 3,900 kW (390 kWh/t) of electricity to operate the graphite arc furnace, the plasma eductor and the various system pumps and fans. In this system, the amount of electricity produced exceeds the amount required to operate the system by a significant margin. In fact, it is expected that the system would produce a net 4,530 kW (453 kWh/t) of electricity that could be sold to utilities. The net electrical energy for sale takes into account the energy used by the system which has been removed. It takes into account not only the electrical load of the plasma system, but all the other electrical loads as well.

In many situations, the value of the products (electricity, slag, metal) will exceed the operating costs of the plasma system.

Table 5 Selected Parameters for Processing 240 TPD of MSW.

	RATE PER HOUR
Capacity	10,000 kg/h
Inert slag (gravel) produced	1,450 kg/h
Metal produced	640 kg/h
Chemical energy available in syngas (LHV)	21,080 kW
Gross electrical energy produced	8,430 kW
Electrical energy used for the system	3,900 kW
Net electrical energy available for sale	4,530 kW
Thermal energy available in off-gas	5,270 kW
Energy available from engine water jacket	5,270 kW

Example 2 – 48 TPD of Hazardous Flammable Waste

A second example, based on the gasification and vitrification of hazardous flammable waste is shown

in Table 6. This waste is typical of that obtained by hazardous waste collectors. In that case, the amount of metal and slag produced will be, on a per tonne basis, lower than for MSW, as these wastes typically have a lower inorganic content. Since the waste being fed to the system typically has a higher calorific value than that of MSW, the net amount of electricity produced will be higher. The net electricity available for resale will be 1,940 kW, or nearly 1 MWh per tonne of waste fed to the system.

Table 6 Selected Parameters for Processing 48 TPD of Hazardous Flammable Waste.

	RATE PER HOUR
Capacity	2,000 kg/h
Inert slag (gravel) produced	100 kg/h
Metal produced	100 kg/h
Chemical energy available in waste feed (LHV)	11,368 kW
Chemical energy available in syngas (LHV)	9,100 kW
Gross electrical energy produced	3,640 kW
Electrical energy used for the system	1,700 kW
Net electrical energy available for sale*	1,940 kW
Thermal energy available in off-gas	2,280 kW
Energy available from engine water jacket	2,280 kW

Because of this high energy efficiency, as well as its clean emissions, and minimal by-products, this makes the PRR system ideally suited for recovering energy from hazardous flammable wastes.

CONCLUSION

The Plasma Resource Recovery Plasma Resource Recovery (PRR) has been demonstrated in the pilot plant for converting several waste types to inert slag and synthesis gas, containing mainly CO and H₂, suitable for the co-generation of electricity, steam and hot water in a gas engine. Projections show that a 240 TPD system processing MSW can produce

8,430 kW of electricity (4,530 kW net), and that a 48 TPD system processing hazardous flammable waste can produce 3,940 kW of electricity (1,940 kW net). PyroGenesis is currently seeking technical and financial partners for the implementation of a first small scale commercial system, of a capacity of 25 TPD.

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