

## A PLASMA-ARC-ASSISTED THERMAL TREATMENT SYSTEM FOR SHIPBOARD WASTE

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### ABSTRACT

A plasma arc assisted thermal treatment system for combustible shipboard solid waste has been developed as part of the U.S. Navy's Advanced Technology Demonstration (ATD) program. This novel system combines a simple milling process for converting waste into a uniform and highly combustible fuel with a plasma-arc-assisted compact combustor that burns the fuel rapidly and cleanly.

In the process, combustion occurs in two stages, in which the first stage gasifies milled combustible waste using the patented, plasma-fired eductor (PFE) and the second stage fully combusts the synthesis gas generated by the PFE. The system is compact and lightweight, since it does not use refractory materials, has the advantage of being modular to ease shipboard installation and has quick startup and shutdown capabilities. In addition, the system has been demonstrated to treat all types of combustible waste, such as food, paper, cardboard, plastics, wood and textiles.

This paper describes the plasma-arc-assisted thermal treatment for combustible shipboard solid waste and reports on its operation in terms of performance, compliance to MARPOL requirements, mass & energy balances and mechanical integrity.

### INTRODUCTION

A plasma arc assisted thermal treatment system for shipboard solid waste has successfully been developed as part of the U.S. Navy's Advanced Technology Demonstration (ATD) program. The approach used to develop the system has been to create a design that takes advantage of the inherent benefit of ultrahigh temperatures for waste destruction while remaining compatible with the ship's mission requirements. Some of these mission constraints are: restrictions on system size and weight, reduced labor requirements, reduced skill level of operators, high system reliability and availability, equipment operational safety, tolerance to mechanical shock and vibration, minimal electromagnetic interference (EMI) and rapid startup and shutdown.

On board Navy aircraft carriers, solid waste is typically managed by using a variety of equipment. Shredders and pulpers are used for food, paper and cardboard, while plastic waste processors are used for plastics. Incinerators are also used on board some ships, however they face a variety of problems. Incinerators, which are refractory-lined vessels, are very large and heavy, which is undesirable for aircraft carriers given the high premium on deck space. In addition, incinerators are problematic when operated with high concentrations of food, having a high moisture content, or plastics, due to their high fuel value. In addition, the refractory lined incinerators have very long startup and shutdown times, a factor which is undesirable for operation on board Navy ships which require rapid shutdown in cases of emergency. Because of all the equipment used on board Navy ships today, to meet the various discharge regulations, shipboard waste management is very labor intensive. Furthermore, in environmentally sensitive areas, the U.S. Navy is required to comply with the International Maritime Organization standards, in particular MARPOL Annex VI standards. The U.S. Navy desires to be a good world citizen while minimizing the total ownership cost for waste management and providing an increasing quality of work and life.

The plasma-arc-assisted thermal treatment system for shipboard solid waste has many advantages over conventional incinerators. Using this technology, all waste, including food and plastics, can be treated without segregation. The ATD system, which requires only two operators, is extremely compact (650 ft<sup>2</sup>), occupying only one deck of a ship and weighing less than ten tons. Also, because of the novel construction of the wall of the combustion section, start-up and shutdown is achieved in less than five minutes.

The central element of this thermal destruction system is the plasma-fired eductor, shown in Figure 1. Internal to the water-cooled jacket shown in the schematic is an air-cooled metallic liner. This innovative wall construction, also used for the Secondary Combustion Chamber (SCC), allows the eductor to operate at high temperature, without requiring the use of a refractory liner, thus eliminating the need for slow heat-up and cool-down times. The air-cooled liners are relatively inexpensive, easy to install and are expected to have a lifetime in excess of six months during normal use. The eductor shape forces the mixing of the milled waste with the plasma plume. In order to

achieve rapid thermal destruction, the waste must be sized so that its internal temperature is driven above gasification levels during the short time (less than 0.1 second) that it resides in the plasma-fired eductor.

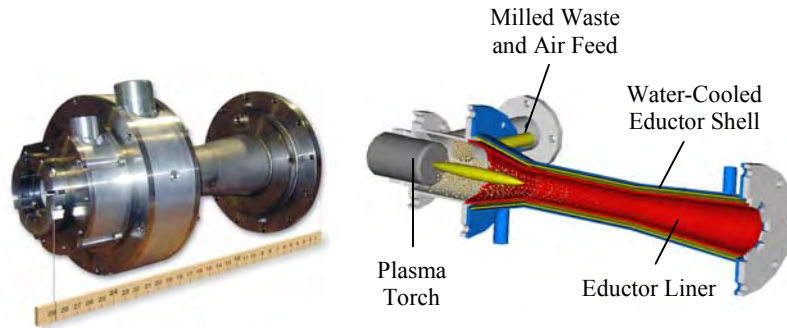


Fig. 1. Photograph and Schematic of Plasma-Fired Eductor

### TEST FACILITY

A full-scale, plasma-arc-assisted thermal treatment system for shipboard solid waste has been built and tested in the pilot lab of PyroGenesis Inc., located in Montreal, Canada. The system has been greatly simplified since its original installation, as reported in earlier work (1,2), to increase its reliability and also to decrease its overall size. A three dimensional representation of the ATD system may be seen in Figure 2.

In the system, mixed combustible waste is first pretreated through a series of size reducing equipment. The pretreatment dramatically increases the surface area to mass ratio of the waste particles, thus allowing them to gasify rapidly when exposed to extreme heat. Effectively, the pretreatment converts a waste stream into a fuel stream. The finely pulverized combustible waste is then introduced into the PFE where the waste particles and the entrained air mix with the plasma jet and quickly heat up. At high temperatures, the particles react with the air and gasify to form CO, H<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>O, ash and other simple molecules. The resulting products leave the PFE and enter the SCC where the CO, H<sub>2</sub>, and other hydrocarbon molecules react with additional air to form CO<sub>2</sub> and H<sub>2</sub>O. A water quench and Venturi scrubber are used at the exit of the SCC to cool the off-gas and remove the ash. The facility is also equipped with acid gas scrubbers, which would not be required for shipboard use, but are required to meet local environmental regulations.

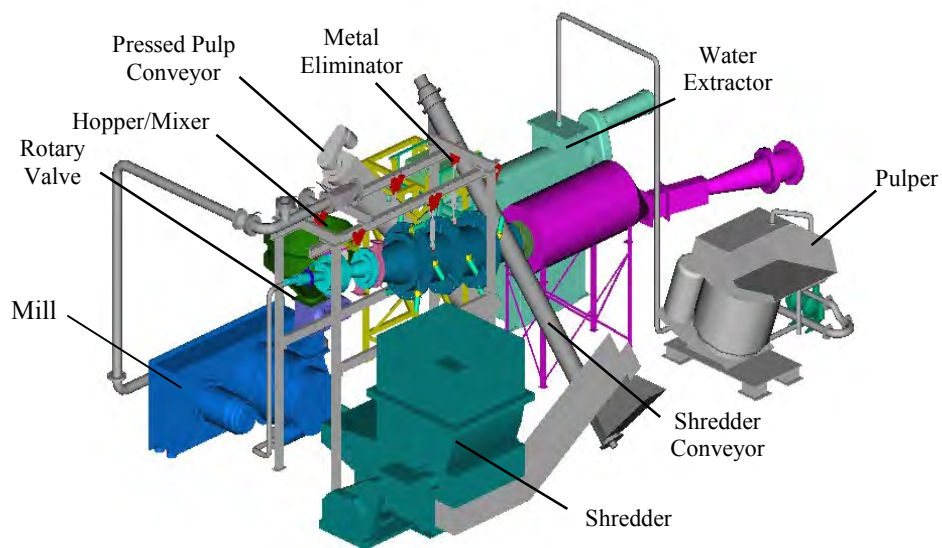


Fig. 2. Overall Layout Drawing of ATD System

### **Feed Preparation System**

The Feed Preparation System was designed to reduce the size of waste, namely food, paper, cardboard, wood, textiles and plastics, into a suitable feed for the PFE. Waste is introduced into the process either by being fed into the pulper or shredder. The Navy pulper processes food, paper and cardboard, whereas the shredder may handle all types of waste. In the pulper, the size of the waste particles is reduced to less than ¼ inch, and the waste leaves the pulper as slurry, consisting of approximately 1% solids. The slurry enters a water extractor, where water is mechanically removed to yield an extracted product containing approximately 50% solids by weight. The extracted waste is then fed to the hopper/mixer via the pulp conveyor. In the shredder, waste is reduced to pieces that are typically less than one-inch in any dimension. The shredded waste is then conveyed via the shredder conveyor to the metal extractor, where any fugitive metallic items present in the shredded waste are removed. Leaving the metal extractor, the shredded waste is fed to the pulp conveyor where it is mixed with the pulped waste from the water extractor. The two waste streams are further mixed in the hopper/mixer prior to further processing. The mixed waste is metered from the hopper/mixer via the weighbelt feeder (not shown) and then fed to the mill via the rotary valve, which acts as an airlock for the system. In the mill, the size of the waste is reduced to fine fibers approximately 15 µm in diameter, which resembles lint from a household dryer. In addition to pulverizing the waste, the mill also dries the waste, resulting in particles with a moisture content of 4% by weight. Drying of the pulped material is accomplished by the mechanical work performed by the mill grinding the waste particles. A known quantity of air is fed into the mill to carry the fine particles to the eductor and to partially oxidize the waste in the PFE. The dried waste, along with the air and generated water vapor, is then fed to the PFE for thermal treatment.

### **Thermal Processing System**

The PFE serves as the first-stage of a two-stage combustion system for combustible solid waste. In the PFE, the amount of oxygen (air) is controlled to provide less than the theoretical amount necessary for full combustion; i.e. fuel rich. A small amount of air is also used as the plasma forming gas for the plasma torch. The thermal energy supplied by the plasma plume breaks apart the complex molecules resulting in the production of syngases, primarily CO and H<sub>2</sub>. When the high temperature syngases (> 1100 °C) exit the PFE, they flow into the SCC, where additional air is added for complete combustion. The gas temperature in the SCC is typically about 1,000 - 1,100°C. To ensure complete combustion in the SCC, the quantity of process air is controlled to maintain an oxygen concentration of 6-12% by volume in the off-gas.

Air-cooled liners, similar to the liner used in the plasma-fired eductor, are used in all four sections of the SCC, thus allowing the SCC to operate at high temperature without the use of refractory liners. Furthermore, since the wall is maintained at a temperature above 750°C during operation, the formation of dioxins or furans is prevented. In addition, the cooling air from the wall is injected into the SCC and is used as the process air, thus improving the overall energy efficiency of the system and lowering the amount of total air required by the process.

Upon exiting the SCC, the gases are rapidly quenched with a water spray to prevent the trace formation of unwanted complex molecules (dioxins and furans). The Off-Gas Treatment System consists of a quench, where water is sprayed to reduce the temperature of the gas to less than 100°C (373°K), and a Venturi scrubber for particulate removal. An induced draft blower (not shown in Figure 2) is used to maintain a negative pressure in the PFE, SCC and Off-Gas Treatment System. After the quench and Venturi scrubber, an oxidation tower, which oxidizes NO to NO<sub>2</sub>, and an absorption tower, which removes acid gases, were added to the system to meet local municipal regulations, but are not needed to meet shipboard regulations.

### **Control and Instrumentation System**

A control and instrumentation system for the process was designed to provide either automatic or manual control of all components of the thermal treatment system, as well as on-line monitoring of process parameters such as temperatures, flows and pressures. In addition, electronic and mechanical interlocks ensure safe operation of the set-up.

A Continuous Emissions Monitoring System (CEMAS) was used to monitor the composition of the combustion gases exiting the SCC and the final system emissions at the stack.

**Waste Composition**

The plasma-arc-assisted thermal treatment system processed all the major waste components generated on board ships. The categories of wastes included in this study and their processing rate are listed in Table I. The amounts listed represent half of the 95<sup>th</sup> percentile U.S. aircraft carrier waste generation rates. The notional carrier system has a dual PFE process.

Table I. Categories and Processing Rate of Combustible Solid Waste

Waste Component (as received)	Process Rate (kg/hr)	Weight %
Food (Except for Non-Pulpable Items)	38.3	23.5%
Paper (White Paper, Wax-Paper)	60.9	37.2%
Cardboard (Light, Heavy, Wax-Coated)	36.1	22.0%
Plastics (Sheets, Bottles, Kimwipes)	16.6	10.1%
Wood (Pallets, Dunnage)	3.3	2.0%
Textiles (Rags, Clothing)	8.5	5.2%
Total	163.7	100.0%

**RESULTS AND DISCUSSION**

**Process Performance**

The process has been tested with a variety of mixtures of waste types, listed in Table I under different modes of operation. The process can be operated under the following modes:

- Pulper only (food, paper, cardboard)
- Shredder only (paper, cardboard, plastics, wood, textiles and some food)
- Pulper and Shredder (all types of waste)

Under all three modes, the process was found to comply with MARPOL Annex VI standards. Table II shows a comparison of typical experimental results with the MARPOL limits.

Table II. Comparison of Experimental Results to MARPOL Limits

Type of Emission	MARPOL Limit	Typical Experimental Results
O <sub>2</sub> , dry basis	6-12%	9.0%
CO	200 mg/MJ <sup>1</sup>	40
Soot Number	Bacharach 3 or Ringleman 1	Not measured
Flue gas temperature in combustion chamber	850-1200 °C	950 – 1100 °C
Unburned components in ash residues	10%	<3%
Flue gas temperature	200 °C max.	<100 °C

The only element that has not been tested to date is the soot number (or opacity). However, based on visual inspection of the stack gases emitted and the high combustion efficiency of the process, it is expected that the process is well within MARPOL limits.

The nominal feed rate of the process during the study was 163.7 kg/h (6 lb/min), with the composition presented in Table I. The process was found to be very flexible in terms of accepting a wide range of waste materials. In the Pulper only mode of operation, pulp was fed to the mill at 50% moisture content. By comparison, in the Shredder only mode, the waste material was significantly dryer (15% moisture). Because the mill also dries the waste, in addition to pulverizing it, the plasma torch does not have to provide the energy required for vaporizing the water. As such, the combustion process is not affected by the moisture content of the waste, as is the case with conventional incinerators.

Of all the process parameters studied (torch power, air distribution (PFE versus SCC), waste composition and waste feed rate), the strongest effect on the process in terms of emissions resulted from waste feed rate variations. Although an on-line measurement of the feed rate was not possible, instantaneous changes in the waste feed rate were observed by monitoring the electric current draw of the mill. As the feed rate increases, the work done by the mill increases, thus resulting in a higher electric current draw. During operation, the CO<sub>2</sub> concentration in the off-gas was found to be proportional to the mill electric current draw, confirming that the mill current varies as a result of waste feed rate. Drops in the waste feed rate below 3 lb/min) resulted in peaks in the CO concentration and also in lower combustion gas temperatures in the SCC (<1000 °C), thus showing lower combustion efficiency. As such, it is evident that for maximum combustion efficiency, steady feeding of waste into the PFE at the nominal feed rate is required.

Although the operation of the system meets MARPOL requirements, it was deemed important to compare the experimental results with theoretical mass and energy balance calculations. Such a comparison allowed for an estimation of the combustion efficiency of the process.

### Mass and Energy Balance

Given the nominal feed rates and composition shown in Table III, mass and energy balance calculations were performed for the ideal operation of the PFE and SCC. The calculated values were then compared with the actual values obtained during operation of the system, and an estimate of the efficiency of combustion was made. Because food waste adds variability in the feed due to its varying moisture content, it was excluded from the waste stream for these comparisons so that the composition of the waste can be more accurately determined.

<sup>1</sup> Conversion based on 0.23 m<sup>3</sup> of evolved combustion gas per MJ of energy (Hot Test No. 98B).

Table III. Feed Rate, Composition and Heating Value of Shredded Waste Stream

Waste Composition	As Received Feed Rate (kg/h)	Moisture Content (%)	% by Mass (Dry Basis)				Heating Value (dry basis) (kJ/kg)
			C	H	O <sub>2</sub>	Other	
Paper	64	15	38.0	5.1	39.0	17.9	15427
Cardboard	38	15	44.0	5.7	44.9	5.4	17283
Plastics	16	5	60.0	7.2	22.8	10.0	33631
Textiles	9	5	48.0	6.4	40.0	40.0	18693
Wood	4	15	49.5	6.0	42.7	42.7	18671

Mass Balance

The results of the mass balance calculations are shown in Figure 3 for the PFE and the SCC. Based on this analysis, a comparison was made between the calculated off-gas composition and the actual composition as measured by the Continuous Emissions Monitoring System. The comparison is shown in Table IV. For simplicity, only CO<sub>2</sub>, O<sub>2</sub>, H<sub>2</sub>O and N<sub>2</sub> have been included, because all other components are present in such small quantities that their contribution to the mass balance is negligible.

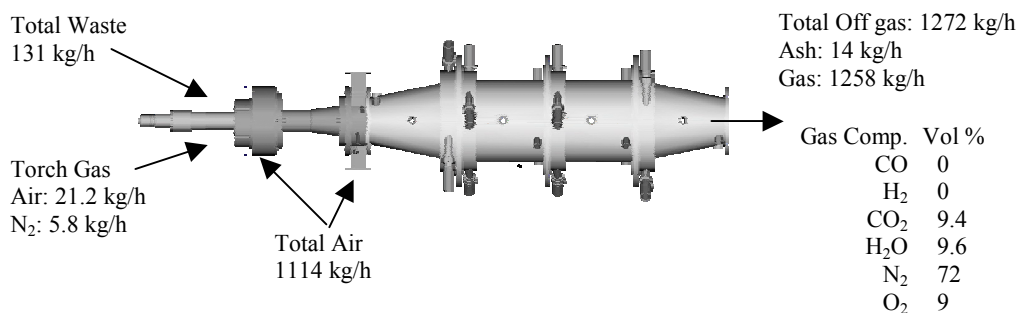


Fig. 3. Summary of Theoretical Mass Balance Calculations

Table IV. Comparison of Calculated and Experimental Mass Balance Results

Composition	% vol (wet basis) (ideal)	% vol (wet basis) (actual)	mol/h (ideal)	Calculated mol/h (actual)
CO <sub>2</sub>	9.4	9.3	4092	4141
O <sub>2</sub>	9.0	10.8	3919	4809
H <sub>2</sub> O	9.6	9.5	4180	4231
N <sub>2</sub>	72.0	70.4	31351	31351

Because the airflows used in the model are the same as those used in the experimental run, the molar flow rate of N<sub>2</sub> in both cases should be the same. Knowing the molar feed rate of N<sub>2</sub>, the total molar feed rate can be calculated for the actual case, since N<sub>2</sub> is known to contribute 71.0% of the total. Based on this information, the molar flow rates of all of the components could be calculated. The combustion efficiency is then calculated by:

$$\text{Combustion efficiency} = \frac{[\text{mol} / \text{h}]_{\text{CO}_2(\text{actual})}}{[\text{mol} / \text{h}]_{\text{CO}_2(\text{ideal})}} \times 100 \quad (\text{Eq. 1})$$

Based on this analysis, the combustion efficiency was found to be 100%. This type of analysis is useful in providing some validation of the results. However, errors can be contributed to the fact that the waste composition and feed rate vary greatly during the course of operation.

To substantiate this result, calculations of combustion efficiency were made based on the volatile content of the ash collected after the Venturi scrubber. Loss-on-ignition (LOI) tests at 550 °C were performed on samples of dry ash, as well as the milled waste collected after the mill. These results are shown in Table V.

Table V. Results of LOI Analysis on Milled Waste and Ash

Test	LOI at 550 °C
Milled waste	88 %
Ash	<3%

The combustion efficiency, based on the reduction in the volatile component in solids, may be calculated by:

$$\frac{LOI_{\text{milledwaste}} - LOI_{\text{ash}} \left[ \frac{100 - LOI_{\text{milledwaste}}}{100 - LOI_{\text{ash}}} \right]}{LOI_{\text{milledwaste}}} \quad (\text{Eq. 2})$$

The estimated combustion efficiency, based on results of loss-on-ignition tests of the volatile content of ash, was found to be greater than 99.6%.

#### Energy Balance

Energy balance calculations were performed around the PFE and SCC combined. The inputs and outputs are shown in Figure 4. Estimated theoretical energy loss to the cooling water was found to be 88 kW. Actual cooling water losses ranged from 100 to 120 kW.

**System Operability and Reliability**

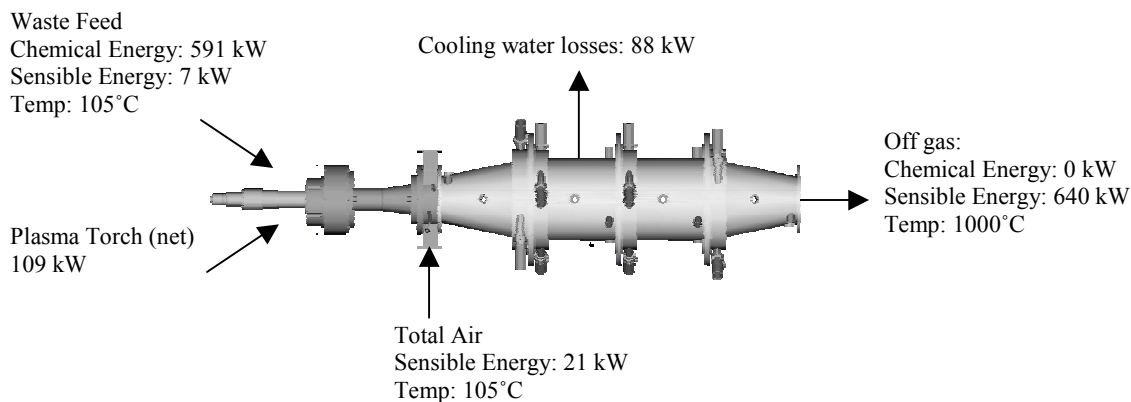


Fig. 4. Summary of Theoretical Energy Balance Calculations

To date, the system has operated for over 300 hours and has been shown to require only two operators for consistent operation, one feeding the waste, the other monitoring the control console. The mill, which is the workhorse of this thermal treatment system showed relatively high durability and reliability. The blades of the mill showed some wear during the course of testing and were replaced only once. The blades, presently made of carbon steel, can be made of a harder material to improve durability. The air-cooled liners used in the PFE and SCC performed very well under normal operating conditions. In fact, the SCC liners did not require replacement throughout the testing period. The PFE liner did fail during non-standard operating conditions and was replaced on few occasions, however, replacement of the liner is a 30-minute operation after which the system is up and running again. The only consumable items in the process were found to be the torch electrodes, which were changed very infrequently and mostly as a precaution. Incorporating the desired system modifications, especially to some of the commercial off-the-shelf equipment will lead to a robust and easy to maintain system.

The plasma-arc-assisted thermal treatment system was designed to shut down safely in case of any failure to any piece of equipment. A number of failure modes were tested to verify the efficacy of the control system in dealing with them. The failure modes tested include actuation of the “Emergency Stop” switch, loss of torch power, loss of torch cooling water flow, loss of cooling water to vessels, loss of cooling air to liners, general loss of power and loss of the induced draft fan operation. In all cases, the system was able to suspend operation briefly or safely shut down, as the case required. Startup and shutdown of the system was found to be less than 5 minutes in most situations.

**CONCLUSION AND FUTURE WORK**

The plasma arc assisted thermal treatment system has successfully been demonstrated for the treatment of shipboard solid waste. Experimental combustion efficiencies were found to be greater than 99.6% and compliance to MARPOL standards was demonstrated. The system was run for over 300 hours requiring only two operators to feed the waste and run the equipment. The system was found to be easy to maintain and the control system was found to respond successfully to the various failure modes that were tested.

Future work will involve further characterizing the system in terms of its operability, reliability and maintainability in a shipboard environment. In addition, the system will be tested with other types of waste such as used oil and concentrated sludges (blackwater and greywater).



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