# PLASMA ARC THERMAL DESTRUCTION TECHNOLOGY FOR SHIPBOARD SOLID WASTE

Eugene E. Nolting and Jon W. Cofield
Naval Surface Warfare Center, Carderock Division

Theodora Alexakis, Peter Tsantrizos and Platon Manoliadis
PyroGenesis, Inc.

## ABSTRACT

The Navy is supporting a research effort to develop a shipboard plasma arc waste destruction system. It is the goal of this program not only to process the tons of waste generated daily aboard large surface combatants such as aircraft carriers, but also to meet the unique operating requirements imposed on shipboard equipment. While the design was specifically developed for Navy warships, many of its features would also be advantageous for use with commercial vessels. These attributes include lower labor requirements, modular design for ease of installation in existing compartments, fast startup and shutdown, and a lightweight and compact thermal destruction unit. In this paper, we will discuss a new design concept for plasma-assisted thermal destruction equipment and the basic requirements for operating the thermal destruction equipment at sea, as well as describe the components of the full-scale demonstration that is currently underway.

## INTRODUCTION

When at sea, a Navy warship serves as both the home and workplace for the men and women of the crew. Almost every activity performed on a ship generates solid waste, which represents the most visible and largest volume of the shipboard waste streams. The solid waste generated is similar in composition to that created in cities, but unlike municipal rubbish, there is no space to bury the waste material and there is limited space for storing and processing it aboard ship. While small compared to municipal volumes, an aircraft carrier generates several tons of solid waste daily. Figure 1 shows a typical one-day production of non-food and non-plastic solid waste. Historically, much of the shipboard solid waste has been discharged overboard as the principal method of waste management. However, because of international interest in preserving the quality of the world's waters, the practice of at-sea discharge has become unacceptable. In order to meet the challenge of providing forward presence, Navy warships must be able to operate anywhere and anytime with unrestricted access to all operational areas, including littoral waters. Complete autonomy of operation requires the development of new technologies for the environmentally sound treatment of shipboard-generated solid waste.

Current practice has been to develop specialized equipment designed to treat the various components of the solid waste stream. Pulpers are used to grind up food, paper, and cardboard waste for diffuse discharge at sea. Plastic waste processors are employed to heat and compress plastic materials for shipboard storage, followed later by disposal ashore. Shredders are used to process glass and metal waste to assure negative buoyancy before at-sea disposal. Earlier Navy-sponsored studies have concluded that thermal destruction is the best technological approach for developing a single onboard system to process the wide variety of ship-generated solid waste (1). By building a centralized system to process the full spectrum of solid waste materials, manning requirements and operating costs are reduced. The primary interest in thermal destruction is that it converts combustible materials into gas. These burnable items constitute about 90% by volume of the solid waste stream. Of the many forms of thermal destruction technology, Navy sponsored studies have found that the use of ultrahigh temperature plasma has the best potential for treating the large variety of shipboard solid waste in a single, compact system (2, 3). However, several technology issues were identified as requiring resolution before a plasma-based waste destruction system can be deployed onboard a warship.

Plasma arcs have been used for a variety of industrial applications for well over 100 years (4). Plasma's high sensible energy content makes them particularly attractive for thermal destruction. Typically, plasmas are formed by the direct conversion of electrical energy to thermal energy, via an arc discharge in gas flowing between two electrodes by applying a sufficiently high voltage. Average gas discharge temperatures are characteristically in the neighborhood of 5,000 $^{o}$C. This is four to five times higher than found in conventional incinerators. These much higher temperatures cause faster chemical reactions with rates that can be several orders of magnitude greater than those of standard incineration. The extremely fast chemical kinetics can be used to implement an appreciably more compact design of the thermal destruction hardware. Ultrahigh operating temperatures also cause a more complete breakdown of complex organic molecules down to their atomic constituents, leading to cleaner destruction products. In addition, the plasma arc's higher temperatures create new chemical pathways not available to more conventional thermal destruction methods. As shown in Fig. 2, at temperatures above about 2,800 K, disassociation of molecu-

Fig. 1. Triwall boxes containing the average amount of solid waste generated daily by a Nimitz class aircraft carrier.

lar oxygen to atomic oxygen starts to occur and above approximately 5,500 K only atomic oxygen remains (5, 6). Atomic oxygen, which is highly chemically reactive, greatly enhances the thermal destruction process. Other very reactive radicals, such as OH, are produced as well. Finally, the use of plasma as the primary heat source makes the thermal destruction process less dependent on the waste's chemical energy for gasification. Effects due to variations in waste material heat content (for example, plastic versus moisture-laden paper) can be minimized because the plasma inputs an independent minimum energy into the thermal destruction process.

Although plasma technology has been successfully used for several commercial applications, it has never been deployed in the marine environment on a moving platform. The approach used to develop a Navy system has been to create a design that uses the inherent benefits of ultrahigh temperature waste destruction while being compatible with the ship's mission requirements. Plasma equipment design objectives include: reduction of system size and weight, lower total ownership costs, reduced manpower requirements both in number and skill level of operators, high reliability and availability, equipment operational safety, tolerance to mechanical shock and vibration, minimal electromagnetic interference (EMI), and rapid startup and shutdown of equipment. Addressing these issues has led to a new design for the plasma-arc equipment that greatly reduces its size and avoids the use of heavy refractory materials that are commonly found in commercial equipment. Refractory materials, such as alumina, are susceptible to thermal shock and require extensive heat-up and cool-down times to preserve their life. They are also vulnerable to damage during maintenance. Refractory liners on current Navy incinerators represent their largest maintenance cost. A plasma arc waste destruction system based on a novel design has been built for technical evaluation as part of the Navy's Advanced Technology Demonstration Program (7-12).

A Navy-patented design for the first stage of a two-stage burner for combustible waste is described in Reference 13. Figure 3 is an illustration of the plasma-fired eductor (PFE), which employs ultrahigh temperature plasma to gasify the organic-based waste as that waste passes through the eductor. Also shown in Fig. 3 is the prototype PFE used to quantitatively evaluate the concept. The objective of the eductor design is to force small combustible particles to interact with the ultrahigh temperature plasma plume so that they rapidly undergo destruction. The waste particles are sized to limit the thermal transfer time required to bring their entire mass up to gasification temperatures. Pyrolysis, the breakdown of combustible material's chemical bonds by thermal energy, occurs at temperatures above 350°C. This unit shown is on the order of one three-hundredth the volume compared to the size of conventional plasma systems of similar waste processing capacity.

In this paper, the PFE processing requirements and principles of PFE operation will be defined, the Advanced Technology Demonstration (ATD) plasma facility being used to demonstrate

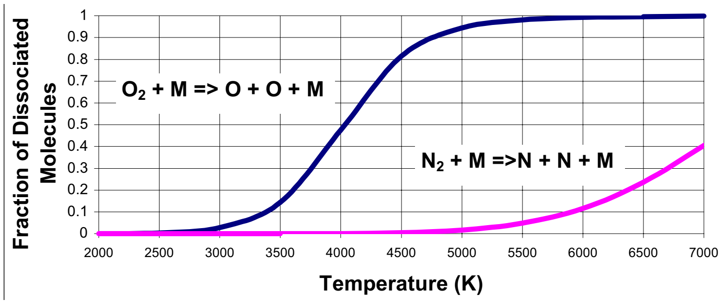

Fig. 2. This graph indicates the fraction of molecular dissociation as a function of air temperature at atmospheric pressure. Note in the primary operating range for the PFE, most of the oxygen will be dissociated, which enables thermal processes not possible in conventional incineration.

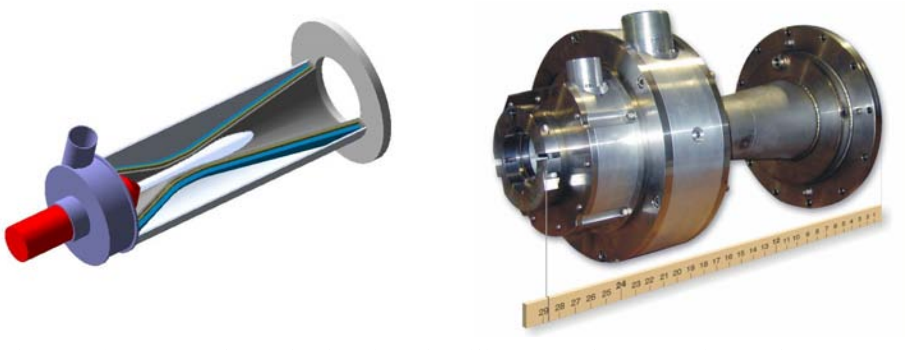

Fig. 3. (Left) A schematic drawing that illustrates the PFE's internal structure. (Right) The prototype plasma-fired eductor (PFE) in use at the demonstration facility. The PFE's nominal dimensions are 0.8 m long with a 0.2 m diameter. This represents a volume of approximately 1/300 that of conventional plasma systems with similar throughput.

the technology will be described, and some preliminary testing results will be presented.

## Waste Process Requirements

The design of any thermal destruction system is critically dependent on the quantity and characteristics of waste to be processed. Shipboard waste, like municipal garbage, comes in a variety of forms. For the purposes of classification of shipboard waste, there are two primary characteristics that are of interest: (1) its chemical energy or heating value and (2) its physical form. In terms of the chemical energy, waste material can be roughly placed into three categories: high heat value waste (e.g., plastics), intermediate heat value waste (e.g., paper, cardboard) and low heat value waste (e.g., high moisture content food). For reference, plastic has about three times the chemical energy per unit mass compared with dry paper. The physical form of the material is also critically important. While a pound of paper sheets and a pound of wood have approximately the same chemical energy, their substantially different forms impact the design of a system that must accommodate both.

Table I is a list of representative shipboard combustible waste. These items listed are based on Navy conducted shipboard solid waste survey data and characterize the amount and variety of waste materials that must be treated daily. The listed values are representative for the 95th percentile waste generation rate for a 5,500-person aircraft carrier crew at the 95th percent confidence level. Large day-to-day excursions are to be expected from these listed compositional values depending on the ships operating area and phase of deployment cycle. It is necessary to design the thermal destruction system to easily adjust to these variations. The process rate listed in the table assumes two thermal destruction units each with a 150-kg/hr throughput operated 18 hours per day. The choice of two units was made to improve system reliability and to increase equipment availability; it also allows better matching of the equipment capacity to the waste production rate. Designing the system to handle the high end of the waste production guarantees that very few days will exceed the capacity of the equipment. An average 75% duty cycle provides time for preventative maintenance and cleanup of the ship spaces. When necessary, it will be possible to operate the equipment for longer periods as well.

An additional complication is that the waste does not arrive at a constant rate throughout the day. Ship surveys show that no waste may be delivered for periods of several hours, followed by a sudden influx of material. Ship management practices could be used to modify the waste delivery rate, but to reduce shipboard impact, the plasma waste destruction system being developed has been designed with waste storage buffers.

## Principals of the Plasma-Fired Eductor (PFE) Operation

The details of the thermal destruction chemistry for solid waste are highly complex with literally hundreds of reactions and the production of many possible chemical species. Details of the reactions depend on parameters such as temperature, time, and local chemical composition. As a starting point, it is useful to look at the complete simplified combustion reaction under equilibrium conditions to estimate the amount of air required and quantities of products produced by the thermal destruction process. To first order, paper, cardboard and food, which comprise most of the combustible waste, can be represented as cellulose $(C_6H_{10}O_5)_n$. The chemical reaction for the combustion of one mole of cellulose can be written as:

$$C_6H_{10}O_5 + 6\,(O_2 + 3.76\,N_2) => 6\,CO_2 + 5\,H_2O + 22.6\,N_2. \quad (1)$$

This equation states that six moles of air, composed of 21% oxygen (by volume) and 79% nitrogen, are required to completely convert the cellulose into carbon dioxide and water vapor. This represents the minimum amount of air needed for complete combustion and is called the theoretical or stoichiometric air requirement. In practice, additional oxygen is required for two reasons: (1) The probabilistic nature of the combustion process results in some local conditions that are oxygen starved, and (2) at the stoichiometric composition, the equilibrium presence of CO is significant at the elevated temperatures of combustion. The additional air further shifts the reaction away from CO and towards $CO_2$ production.

Two-stage combustion is a common technique used to improve the efficiency of the combustion process, and it has been employed in the plasma system's design. In order to simplify shipboard logistics and operating costs, the PFE uses air both as the plasma torch gas and as the carrier gas that transports the waste into the PFE. During the PFE's operation, the amount of air, specifically the oxygen, is controlled to be on the order of 30% of the theoretical air indicated in Eq. 1. This produces a fuel rich environment. The thermal energy added by the plasma

**TABLE I**

Single Eductor Daily Process Rates

| Waste Component (As Received) | Process Rate (kg/day) | Weight % |
|---|---|---|
| **Food (Except for Non-Pulpable Items)** | 634 | 23.5% |
| **Paper (White Paper, Waxed Paper)** | 1012 | 37.6% |
| **Cardboard (Light, Heavy, Wax-Coated)** | 583 | 21.6% |
| **Plastics (Sheets, Bottles, Kimwipes)** | 237 | 8.8% |
| **Wood (Pallets, Dunnage)** | 84 | 3.1% |
| **Textiles (Rags, Clothing)** | 135 | 5.0% |
| **Miscellaneous (Floor Sweepings)** | 10 | 0.4% |
| **Total** | 2695 | 100.00% |

torch results in significant quantities of carbon monoxide, hydrogen, and char (carbon). These products are then converted in the second stage to carbon dioxide and water vapor by the addition of excess air. However, because the fuel gases and char are easy to oxidize, the amount of additional air required is reduced compared with typical single-stage combustion. This has important system implications, since the size of the system is a function of the gas volumes processed.

To quantitatively evaluate the operation of both the plasma-fired eductor and the secondary combustion chamber (SCC), it is necessary to include the reaction rates for the chemical pathways available. From chemical kinetics, it is well known that the rate equation for a single chemical reaction can be expressed in the form of a differential equation in terms of the reactants concentrations, $C_i$:

$$-dC_A/dt = k\, C_A^{\,a}\, C_B^{\,b}. \qquad (2)$$

In Eq. (2) time is represented by the variable, t, and the negative sign indicates that the loss rate of reactant A is proportional to the concentrations of each reactant raised to the power of the number of moles of that reactant for the specific chemical reaction. It can be shown that the rate constant, k, is a function of the absolute temperature, T, and has a general analytical form:

$$k = \mathcal{A}\, T^n \exp(-E_a/RT), \qquad (3)$$

where, $\mathcal{A}$ is the pre-exponential factor, $E_a$ is the activation energy for the reaction of interest, and R is the universal gas constant. The absolute temperature appears both in the exponential term and is also raised to the nth power (typically $-2 \leq n \leq .5$), and the value is dependent on the geometry of the molecule. For most cases, the value of k is dominated by the exponential term (14). Equation (3) indicates that the reaction constant rapidly changes with temperature (usually increasing). This phenomenon is related to the nonlinear characteristics of the Maxwellian distribution, which indicates a rapid growth in the number of particles exceeding the activation energy as the temperature increases (15).

As previously stated, the PFE operates at temperatures on the order of five times higher than conventional incinerators. Because of the exponential relationship of Eq. (3), the typical decomposition rate for cellulose into carbon monoxide, hydrogen, and methane is thousands of times greater at 5,000 °C. Since this is well beyond the temperature range typically used to analyze conventional combustion systems, new chemistry models had to be developed to predict destruction rates. These chemistry models have been installed in a computational fluid dynamics (CFD) software packages, so that the local reaction rates can be followed as the particles transit the PFE. Figure 4 is a result from the CFD model for a specific pre-prototypical PFE geometry. The model was used to compare the theoretical model with the experimental test results. General agreement of the theory with the measured data has been achieved.

In terms of safety of operation, the plasma torch offers two significant advantages. First, for the throughput rates required, less than 40 grams of waste material and gas products are in the PFE and secondary combustion chamber at any given time. Therefore, little chemical energy is available for uncontrolled release. Second, the system can be quickly started-up or shut-down, which is achievable by turning-on or shutting-off both the feed system and the torch power. Figure 5 shows the PFE during startup.

## THE ATD TEST FACILITY

A full-scale plasma arc solid waste destruction system has been built and is presently being tested in the pilot lab of PyroGenesis Inc., located in Montreal, Canada. In the waste destruction system, the bulk of the organic waste, including paper, cardboard, food, and plastics is first pretreated by size-

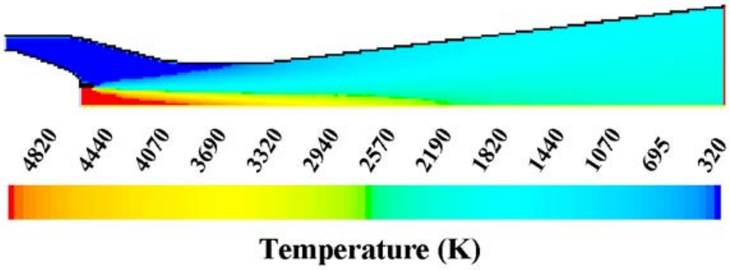

Fig. 4. Computational Fluid Dynamics (CFD) result indicating the temperature distribution for one of the pre-prototypical PFE geometries tested. Comparison of the theoretical analyses results compare well with the data collected.

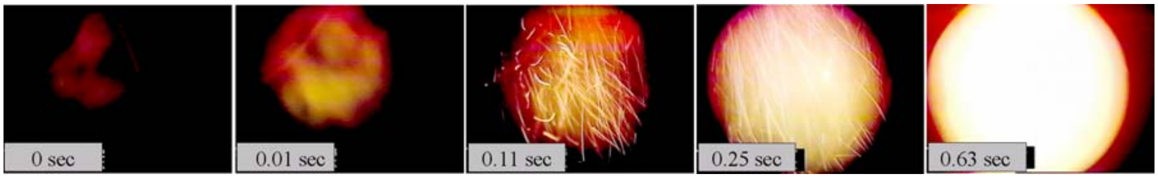

Fig. 5. A five-image sequence taken from a video of the PFE gasification during start up of the feed system. The view is of gases and particles burning at the output of the PFE the circular shape of the flame's image is caused by the aperture of the viewing port. Time evolves left to right and covers a total period of 0.630 seconds. In the first frame, only the torch is on, which is faintly visible. Fully operational conditions are shown in the third frame.

reducing equipment. The pretreatment dramatically increases the surface 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 solid fuel stream. The finely pulverized organic waste is then introduced into a plasma-fired eductor (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 into CO, $H_2$, $CO_2$, $H_2O$, ash, and other simple molecules. The resulting products leave the PFE and enter the SCC where the CO and $H_2$ react with additional air to form $CO_2$ and $H_2O$. A 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 used to meet local environmental regulations.

The overall system is divided into six sub-systems, namely:

- Feed Preparation System.
- Plasma-fired Eductor.
- Secondary Combustion Chamber.
- Off-Gas Treatment System.
- Support Equipment.
- Control and Instrumentation System.

Figures 6 and 7 present three-dimensional representations of the ATD test facility. Figure 6 shows the feed preparation system, and Fig. 7 shows the plasma-fired eductor, secondary combustion chamber, and off-gas treatment system.

The system was designed for the treatment of 150 kg/h of combustible waste having a composition similar to that presented in Table I. The whole system was specifically designed to be as compact as possible, so as to fit on one deck of a ship. However, other configurations, such as a two-deck system, are possible and may be desirable since gravity can be used to transport waste, eliminating the need for screw conveyors. The system was also designed for very low maintenance and to have minimal manpower requirements.

## Feed Preparation System

The feed preparation system, as seen in Fig. 6, was designed to process and reduce the size of waste, namely food, paper, cardboard, wood, textiles, and plastics into a suitable feed for the PFE.

The paper, cardboard, and food can be processed in a wet process which includes a pulper and water extractor. Alternatively, paper, cardboard, wood, textiles, and plastics, which may be food contaminated, can be processed separately in a dry process that includes a shredder and metal extractor. The two waste streams may be treated separately or mixed for subsequent drying, grinding, and feeding to the PFE. Food, paper, and cardboard are fed to the large U.S. Navy pulper (PS04) where the size of the waste particles is reduced to less than 0.006 m. Following the pulper, the slurry, consisting of approximately 1% solids, enters a water extractor (PS06) 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 (PS09) via the pressed pulp conveyor (PS08). Plastic, wood, and textile waste, which cannot be processed by the pulper, are fed into a dual-stage shredder (PS01), where their size is reduced to about 0.051 m by 0.016 m pieces. Paper and cardboard waste can be fed into the shredder as well. The shredded waste is then conveyed via the shredder conveyor (PS02) to the metal extractor (PS03), where any fugitive metallic items present in the shredded waste are removed. Leaving the metal extractor, the shredded waste is fed to the pressed pulp conveyer where it is mixed with the rest of the waste prior to further treatment. The pressed pulp conveyor is an auger with cut and folded flights, thus enabling the material to be mixed as it is conveyed to the hopper/mixer. The mixed waste is metered from the hopper/mixer via a rotary valve waste feeder (PS10), into the mill which sizes and dries (PS11). In the mill, the size of the waste is reduced to fine fibers, about 15 µm in diameter, and the moisture content is reduced from 50% to approximately 4% by weight. Drying of the pulped material is accomplished by the mechanical work performed by the mill in pulverizing the waste. Most of the air is separated from the solids in the cyclone (PS07). A controlled amount of air leaves the bottom of the cyclone with the dried, pulverized waste and is then fed pneumatically to the PFE.

## Plasma-Fired Eductor

The plasma-fired eductor consists of the eductor torch (PS12) and eductor (PS13), as seen in Fig. 7. The dry pulverized waste is gasified in the PFE and, thus, is converted to mostly CO and $H_2$ gases. The gas stream leaving the PFE consists primarily of $N_2$, CO, $H_2$, $CO_2$, and $H_2O$ and is at a temperature well in excess of 1,500 K. The inorganic portion of the waste becomes an ash product. The gas leaving the PFE then enters the SCC (PS21).

The eductor body is water-cooled and has thirteen ports to allow for thermocouples, to be used to monitor the liner and the cooling air temperatures.

An eductor liner is used to protect the eductor body and is in direct contact with the hot process. It also protects the high temperature reactions from being quenched by the cold eductor housing. The eductor liner is about 0.025 m smaller in diameter than the eductor body, which results in a 0.013 m gap between the liner and the body. Because there is a gap between the liner and the eductor body, the liner acts as a thermal radiation shield, keeping the eductor body cool. Also, cooling air is blown in the gap between the liner and the eductor body to provide additional cooling. Air-cooling has the advantage of being variable and, thus, allows the temperature of the liner to be controlled so that it, in turn, does not overheat. The heated eductor cooling air is then distributed to the SCC for use in the combustion process.

## Secondary Combustion Chamber

In the SCC, shown in Fig. 7, all of the combustible components in the synthesis gas from the PFE are fully combusted to produce $CO_2$ and $H_2O$. The average temperature at the SCC exit is controlled to approximately 1,200 K. To ensure complete combustion in the SCC, excess air is used to maintain a nominal oxygen concentration of 9% by volume in the off-gas.

Several criteria were considered important in designing the SCC. Some of these criteria include:

- Good mixing of the air with the synthesis gases from the PFE must be achieved.
- Adequate residence time of the gases must be allowed for complete combustion.

- The construction must be modular, so that changes in length and design may be incorporated during the demonstration phase.

The most innovative feature of the SCC is its wall construction that includes an air-cooled metal liner inside a water-cooled shell. This wall construction has some advantages, namely:

- High operating wall temperature to avoid the formation of dioxins and furans, and prevent condensation of condensable products of the wall surface.
- Easy maintenance due to its modularity.

## Off-Gas Treatment System

The combustion gas from the SCC enters the off-gas treatment system prior to discharge. The off-gas treatment system, as seen in Fig. 7, consists of a quench (PS23), where water is sprayed to reduce the temperature of the gas to less than 423 K (150 °C), and a venturi scrubber (PS24) for particulate removal. The 150 °C upper temperature limit is to ensure that the off-gas quenched to below the dioxin/furan formation temperature zone. A pump (not shown) is used to recirculate a portion of the effluent from the venturi scrubber back into the quench. An induced draft blower (not shown) is used to maintain a negative pressure in the PFE, SCC, and off-gas treatment system.

## Control and Instrumentation System

The control and instrumentation system has been designed to provide either automatic or manual control of all of the components of the waste destruction system. The automatic functions include startup, normal operation, normal shutdown and rapid shutdown.

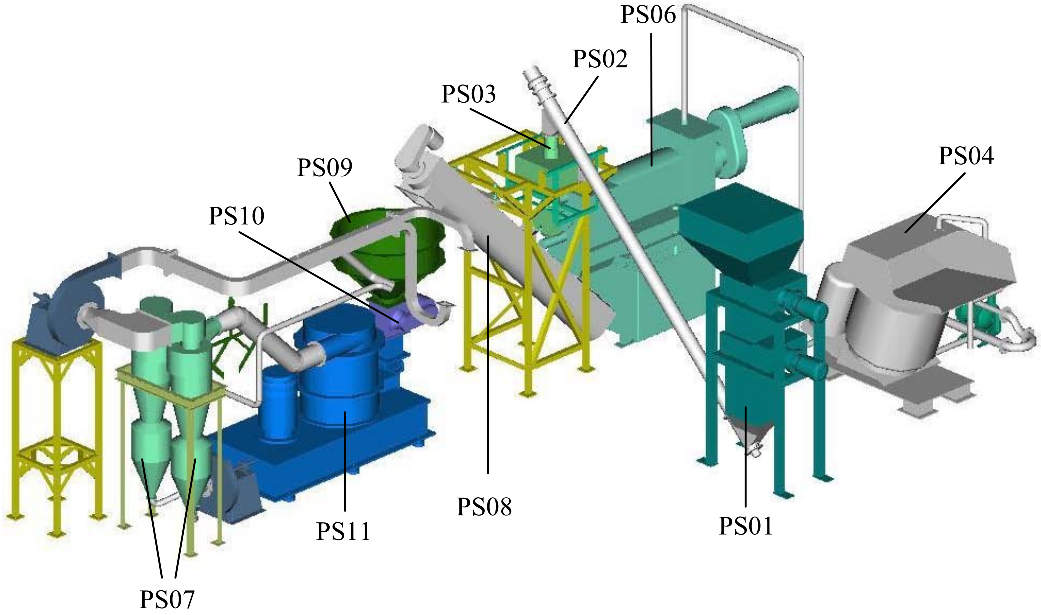

Fig. 6. Three-dimensional representation of feed preparation system.

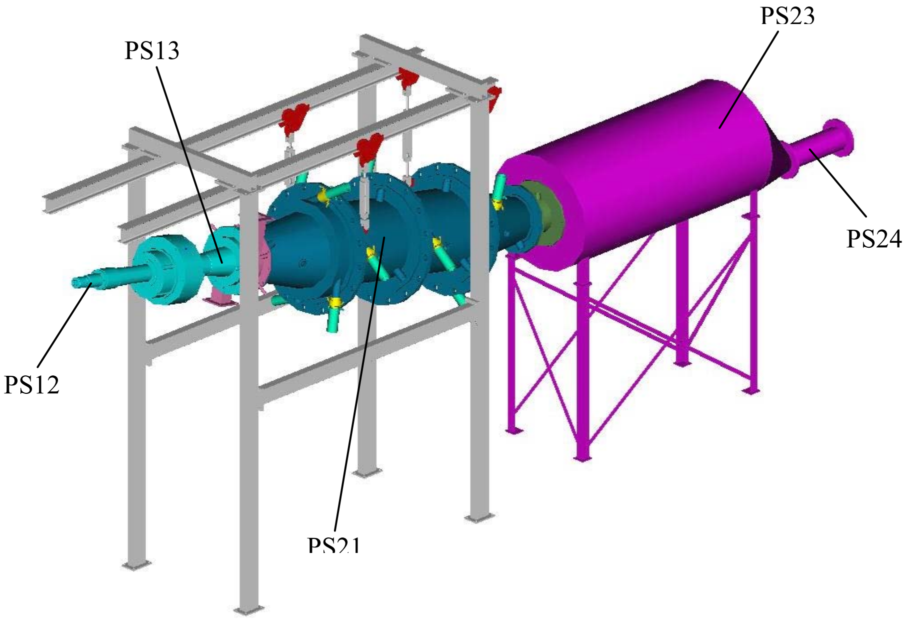

Fig. 7. Three-dimensional representation of the plasma-fired educator, SCC and off-gas treatment system.

The feed preparation system requires very little automation. Feed preparation equipment such as the shredder, pulper, water extractor, mill, and augers are operated at set speeds. The shredder and pulper are manually fed with waste by one or two operators. Even though the operation of the feed preparation system is manual, the main control system monitors the feed system's operating condition and can shutdown the feed preparation system in case of an emergency.

The operation of the plasma torch is fully automated. Startup, steady operation, normal shutdown, and emergency shutdown are handled by the control system. The various functions of the torch can also be manually turned on/off or adjusted (for testing and troubleshooting); however, the control system rejects operator inputs that can create dangerous conditions. The torch system, along with the entire ATD hardware, are electrically and, where needed, mechanically interlocked to prevent personnel injury or equipment damage.

The PFE and SCC are simple vessels but, because of the high process temperatures involved in gasifying and combusting organic waste, a large portion of the ATD sensor suite is allocated to monitoring and protecting these vessels and their operators from injury. The sensors on the three vessels provide measurements of gas, water, and liner temperatures to aid in a calorimetric analysis of the system. The vessels are also equipped with a number of ports available for gas sampling at different locations.

The off-gas system is fully automated and is able to self-adjust for variations in the flow of exhaust gas and acid levels in the gas. The status of the off-gas system is monitored, so that any failure of the off-gas system rapidly shuts down the operation of the rest of the PAWDS equipment.

## PRELIMINARY TEST RESULTS

### Feed Preparation System Tests

The purpose of the feed preparation system is to produce a solid waste fuel that is suitable for thermal destruction by the PFE. The feed preparation system must accomplish the following:

- Produce a solid fuel with a particle size less than 0.002m, having uniform particle size distribution, and a final moisture content less than 20%.
- Result in minimum solids carryover in the cyclone overflow.
- Deliver a controlled amount of carrier air going to the PFE along with the waste particles.

Two types of tests were performed on the feed preparation system: wet and dry. In the wet tests, the system was run using the pulper and shredder as was described earlier in the description of the ATD facility, with a waste composition specified in Table I. The dry tests, however, involved passing paper, cardboard, wood, textiles, and plastics through the shredder, thus eliminating the need for the pulper and water extractor.

The pulper (PS04) and water extractor (PS06) were tested as part of a series of wet tests. Since the pulper is oversized, in terms of its capacity, for this application, a maximum throughput of 408 kg/h was obtained. This is almost three times the required throughput of 150 kg/h. In addition, the pulper performed without any significant operational problems. The solids concentration of the slurry leaving the pulper ranged between 0.6% to 5%. The water extractor was found to perform very well, resulting in a dewatered product having moisture content between 45% to 55%. The operational lower limit of the water extractor was found to occur when the feed rate of solids in the slurry was less than 0.45 kg/min, approximately a factor of five below the design goal. Under this condition, the residence time of the solids in the water extractor was so long that the material is excessively dewatered, resulting in hardened material that obstructed the path for water flow.

The shredder (PS01) and auger-type conveyors (PS02 and PS08) were tested with various compositions, for both the wet and dry tests. The major challenges associated with these pieces of equipment were:

- Inadequate shredding of large polystyrene pieces, because of its unreliable gravity feeding into the shredder and
- Wrapping of polyethylene film and textiles around the shaft of the shredder and augers.

The shredder used for this study is a test shredder, and is smaller and less powerful than what would be required for shipboard use. Lessons learned during the demonstration test will be used to specify a suitable shredder for the shipboard system.

The mill, which sizes and dries, (PS11) was tested with waste obtained during the wet and dry feed preparation tests. The wet tests produced material in a form more suitable for treatment in the mill, due to its high moisture (50%) content and reduced size (mostly pulped waste with some shredded plastic). The moisture protects the waste from overheating as a result of the frictional milling process. As a result, the product exiting the mill was very uniform in size and finely pulverized (<0.0016 m in length and approximately 15 μm in diameter). A micrograph of the pulverized solid waste fuel is shown in Fig. 8. Shredded waste produced during the dry tests was more difficult to process due to its low moisture content (7%) and larger size (0.051 m by 0.013 m). The low moisture content resulted in excessive heating of the material in the mill, which potentially poses an ignition hazard. This problem was overcome by installing a water spray just before the inlet to the mill to moisten the shredded waste prior to processing. In addition, it was found that some of the shredded material, produced during the dry test, was not completely processed by the mill, resulting in some carryover of larger solid pieces. However, even the incompletely processed waste was still smaller than the specified size of 0.002 m, and thus is not expected to cause any operational problems for the PFE.

After optimizing the operation of the feed preparation system, a suitable solid waste fuel was obtained for processing in the gasifier. The size of the particles obtained was much less than 0.002 m long. In fact, fiber lengths of less than 0.0016 m

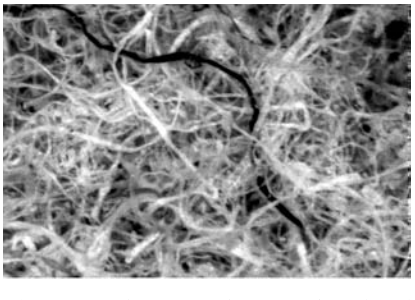

Fig. 8. Micrograph of pulverized solid waste after milling.

were obtained. The size distribution of the particles was fairly uniform and the moisture content was typically 2-4%. The cyclone was adequately controlled to minimize the solids carry over in the overflow and to fix the amount of carrier air leaving the underflow with the solid waste fuel particles.

### Thermal Destruction Tests

Once the feed preparation system was successfully tested to produce a suitable solid waste fuel for the gasifier, thermal destruction tests commenced; although, the results are too preliminary to include in this paper. Gasification testing will result in a good understanding of the gasification process in terms of gasification efficiency and synthesis gas composition, as well as determining the operational limits of the thermal destruction process. Gas sampling at the exit of the PFE and analysis by gas chromatograph (GC) will provide useful data in studying and optimizing the process. A continuous emissions monitor has been installed to analyze the composition of the gas leaving the SCC and the exhaust gas in the stack.

## CONCLUSIONS

While the thermal destruction of combustible waste is simple in concept, the development of a shipboard plasma arc waste destruction system has required the detailed understanding of the many aspects of basic combustion, chemistry, and the engineering sciences. The design of equipment to treat the wide varieties of forms and chemical compositions of solid waste found aboard ships requires a robust process. In this project we have brought together expertise from within the Navy, industry and academia to address technical issues that are unique to the ultra-high temperature combustion and marine environment.

A plasma arc waste destruction system based on the two-stage eductor combustion has been built as part of the Navy's ATD Program. The objective of the ATD is to demonstrate all the technologies necessary to deploy a plasma arc waste destruction system aboard a warship. In this paper we have described that demonstration facility and some of the results obtained to date.

## ACKNOWLEDGEMENTS

The authors want to express their appreciation for the support given by the Office of Naval Research Project Officer, Dr. Steven McElvany Code 331, and the Naval Sea Systems Command Program Manager, Mr. Carl Adema, SEA 05R24. This work is supported as part of the Advanced Technology Demonstration Program. The authors also wish to acknowledge the contributions by numerous scientists and engineers from several organizations; these include technical experts from NSWCCD, PyroGenesis Inc., the Naval Research Laboratory, Geo-Centers Inc., John J. McMullen and Associates Inc., and the University of Maryland.

## REFERENCES

1. Shipboard Pollution Control, U.S. Navy Compliance with MARPOL Annex V, Committee on Shipboard Pollution Control, Naval Studies Board, National Research Council, National Academy Press, Washington, DC, (1996).
2. Navy Report to Congress, U.S. Navy Ship Solid Waste Management Plan for MARPOL Annex V Special Areas, (November 1996).
3. CHOPRA, H., High Temperature Controlled Thermal Destruction of Surrogate Solid Waste, Master of Science Thesis, University of Maryland,(May 1993).
4. COUNTS, D. A., BRUCE D. SARTWELL, STEVEN H. PETERSON, ROBERT KIRKLAND, and NICHOLAS P. KOLAK, Thermal Plasma Waste Remediation Technology: Historical Perspective and Current Trends, Naval Research Laboratory Memorandum Report No. 6170-99-8335,(1999).
5. HANSEN, C. F., Approximations for the Thermodynamic and Transport Properties of High-Temperature Air, National Advisory Committee for Aeronautics, Technical Note 4150, Washington, DC, (March 1958).
6. NIESSEN, W. R., Combustion and Incineration Processes, Applications in Environmental Engineering, Marcel Dekker, Inc., New York, NY, (1994).
7. RICHARD, R. V., KEATING, E. L, DENTLER, J., COFIELD, J. W., NOLTING, E. E., PECHULIS, M. J., SHIFLER, D. A., VAUGHTERS, D. S., and WONG, C. R., "Navy Shipboard Plasma Arc Waste Destruction System (PAWDS) Baseline Conceptual Design", Proceedings of the 1997 International Conference on Incineration and Thermal Treatment Technologies, Oakland, CA, (May 1997).
8. NOLTING, E. E., VAUGHTERS, D. S., COFIELD, J. W., PECHULIS, M. J., and KELLY, C. M., "Navy Shipboard Plasma Arc System Development Program", Proceedings of the 1997 International Conference on Incineration and Thermal Treatment Technologies, Oakland, CA, (May 1997).
9. TALMY, I. G., ZAYKOWSKI, J. A., MARTIN, C. A., COFIELD, J. W., DALLECK, S., WONG, C. R., and NOLTING, E. E., "Occurrence and Suppression of Thermite Reaction in Slags from Destruction of Navy Shipboard Wastes", Proceedings of the 1997 International Conference on Incineration and Thermal Treatment Technologies, Oakland, CA, (May 1997).
10. UHM, H. S., COFIELD, J. W. NOLTING, E. E. and GUPTA, A. K. "Air Torch Modeling for Thermal Destruction", Proceedings of the 1997 International Conference on Incineration and Thermal Treatment Technologies, Oakland, CA, (May 1997).
11. PETERSON, S. H., COUNTS, D. A., HAN, Q., SARTWELL, B. D., TALMY, I.G., ZAYKOWSKI, J. A., and MARTIN, C. A., "Slag Formation from Navy Solid Waste with a Plasma Arc Torch Destruction System", Proceedings of the 1997 International Conference on Incineration and Thermal Treatment Technologies, Oakland, CA, (May 1997).
12. NOLTING, E. E. and COFIELD, J. W., "Development of a Shipboard Plasma Arc Waste Destruction System", Proceedings of the American Society of Naval Engineers Marine Environmental Symposium, (October 1999).
13. U.S. Patent Number 5,960,026, 28 September 1999, Naval Surface Warfare Center, Carderock Division.
14. METZ, C. R., Physical Chemistry, McGraw-Hill Book Company, New York, (1976), p 197.
15. MAHAN, B. H., University Chemistry, 2nd Edition, Addison-Wesley Publishing Company, Inc., Reading, MA, 1972, p 377.