# The Plasma Arc Waste Destruction System – One Year of Maritime Experience

Christos Chronopoulos, Philippe Chevalier, Isabelle Picard, Aïda Kaldas, Pierre Carabin, and Gillian Holcroft
PyroGenesis Inc.
2000 William Street
Montreal, Quebec, H3J 1R8
and
Brian Swensen
Carnival Cruise Lines
Carnival Place, 3655 NW 87 Avenue
Miami, Florida 33178-2428

## ABSTRACT

The Plasma Arc Waste Destruction System (PAWDS) uses plasma energy, with temperatures between 5000 $^{o}$C to 10000 $^{o}$C to rapidly and efficiently destroy combustible waste aboard ships. With over six years of development under the support of the US Navy and after 18 months of operation aboard a commercial cruise ship, PAWDS has proven itself to be a viable alternative to traditional incinerators.

In September 2003, Carnival Cruise Lines were the first to install the PAWDS aboard their 2056 passenger (plus crew) capacity M/S Fantasy cruise ship. This system is able to treat ship waste such as paper, cardboard, plastics, textiles, wood, and food. Since its commissioning in October 2003, the capability and maintainability of the system has been evaluated in this real shipboard operating environment. As of the end of July 2004, it is being operated and maintained solely by Carnival Cruise Line personnel.

The Plasma system aboard the Fantasy typically operates at a rate of 400 to 450 lbs/hr, 7 days a week. Based on the shipboard operating experience, several process improvements in the areas of material handling, maintenance, automation, instrumentation and training have been made. These modifications have resulted in improved system stability and reduced down-time. Source emission testing by an independent laboratory has demonstrated that the PAWDS easily meets IMO MARPOL requirements for the destruction of solid waste.

## INTRODUCTION

For the last 6 years, under contract with the US Navy, PyroGenesis has been developing the Plasma Arc Waste Destruction System (PAWDS) for the treatment of solid waste to be installed aboard future Navy ships. In 1999, as part of an Advanced Technology Demonstration (ATD) program, PyroGenesis designed, fabricated and demonstrated, in its Montreal facility, a first prototype PAWDS system, for the treatment of waste generated aboard aircraft carriers. The PAWDS ATD was tested over a period of five years and logged over 1500 hours of operation. Developed under a Cooperative Research and Development Agreement (CRADA) with the US Navy, the technology won the 2002 Federal Laboratory Consortium (FLC) Award for Excellence in Technology Transfer. Originally designed for processing rates of 360 lbs/hr, PAWDS has demonstrated processing rates in excess of 425 lbs/hr (1, 2, 3, 4, 5).

PAWDS is a compact, reliable, safe and efficient alternative to methods currently being used to treat shipboard waste. The high energy density of the plasma flame and the use of a unique wall design for the thermal destruction section result in a system that is both compact (1/4 the size of a comparable incinerator) and lightweight (1/2 the weight of a comparable incinerator). An important feature for ship design is that this compact system is designed to occupy only one-deck. The system is highly automated, with single-buttons start-up and shutdown sequences and is designed so that operators with minimal skill-levels find it easy to operate.

In 2003, Carnival Cruise Lines, recognizing the benefits of PAWDS, selected the technology for implementation on one of their cruise ships, the M/S Fantasy. The system was installed in September 2003 and has been in operation since October 2003. It has logged to-date over 2000 hrs of operation.

During the same period, the US Navy contracted PyroGenesis to build a new set-up at PyroGenesis' Montreal facility similar to the commercial or "industrial" design. This system, referred to as PAWDS - Engineering Development Model (PAWDS-EDM), is in many aspects identical to the system aboard Carnival's M/S Fantasy. It was built and installed at PyroGenesis where it has logged about 700 hours of operation since December 2003.

This paper begins by providing a brief technical description of the PAWDS followed by a review of the operating experience aboard the Carnival Fantasy ship. Specifically the paper presents some of the operating and air emissions data from the PAWDS operation. It also describes several process control improvements and unit operation modifications that resulted from the experience gained from this shipboard operation.

## SYSTEM DESCRIPTION

The key to PAWDS patented process is that it first shreds and then mills waste into a lint-like material so that it is transformed into a highly efficient fuel (6). This milled waste is then rapidly gasified in a patented Plasma fired Eductor (7). The resulting synthesis gas is then mixed with air in the patented (8), lightweight Combustion Chamber, resulting in a fully oxidized off-gas, comprised of carbon dioxide and water. This off-gas is then shock-cooled from above 1,100°C to approximately 80°C, using a Water-Quench, preventing the reformation of dioxins and furans. Finally, the gas goes through a Venturi Scrubber, used to remove particulates from the gas, before being exhausted to the ship's stack.

The system consists of three basic sub-systems (Fig. 1): waste preparation, thermal destruction and off-gas treatment.

In the process, combustible waste such as food, paper, textiles, wood, cardboard and plastics are pre-treated through a series of size reducing equipment and converted to "lint". The waste pre-processing subsystem is composed of a Shredder, Shredded Waste Conveyors, a Storage Mixer, and a Mill. Waste is fed into the Shredder where its size is reduced. The waste is then transported to the Storage Mixer using Shredded Waste Conveyors. The purpose of the Storage Mixer is twofold as it mixes and homogenizes the waste and at the same time provides waste storage capacity of one to two hours. A Screw Feeder is attached to the base of the Storage Mixer and is used to meter the waste into the Blow-through Airlock and then onwards to the Mill. The Blow-through Airlock provides a seal between the atmospheric feed section of the system and the Gasification Air Blower. The air from this blower is used to pneumatically convey the material to the Mill. The Mill performs the final waste feed preparation step. The

Mill consists of blades that rotate at high speed thereby pulverizing the waste into fine fibres that resemble lint. This type of pre-treatment dramatically increases the surface to mass ratio of the waste particles, thus, allowing them to gasify rapidly when exposed to extreme heat. The final product, leaving the Mill, is a highly combustible and dry material that looks similar to lint from a household dryer. Effectively, the waste preparation sub-system converts a waste stream into a finely divided solid fuel stream.

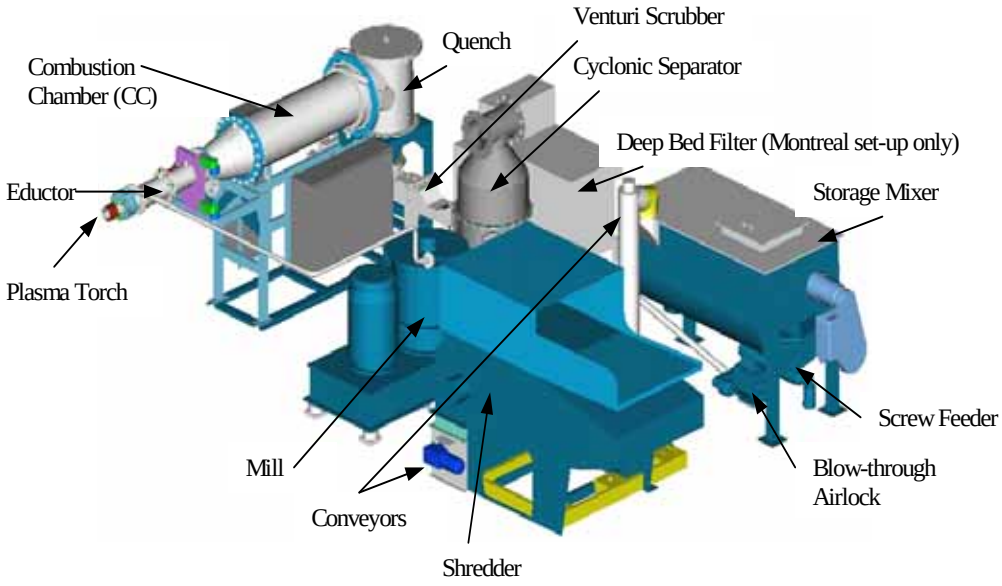


**Fig. 1. PAWDS System Overview**

The waste lint, which becomes the "fuel" to the system, is conveyed by air and injected into the Plasma-fired Eductor (Fig. 2). In the Eductor, the waste fuel or "lint" is exposed to a high temperature of approximately 1,000°C that results in rapid gasification of the solid waste into a synthesis gas composed primarily of carbon monoxide (CO) and hydrogen ($H_2$). This gas then flows into the Combustion Chamber, where additional air is used to complete the combustion and convert the synthesis gas into carbon dioxide ($CO_2$) and water vapour ($H_2O$). The gas temperature in the Combustion Chamber is typically about 1,100°C. Any traces of inorganic substances are transformed into an inert ash. A feature of the PAWDS technology is its use of air and/or water-cooled walls instead of heavy refractory for the Eductor and Combustion Chamber. Internal to the water-cooled jacket for the Combustion Chamber is an air-cooled liner made of superalloy.

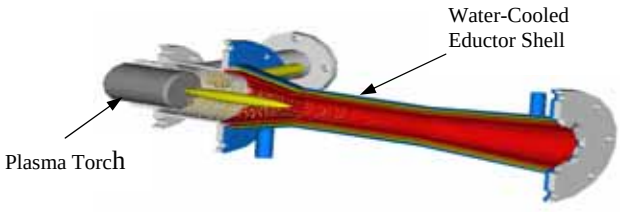


**Fig. 2. Schematic of the Plasma-Fired Eductor**

Upon exiting the Combustion Chamber, the gases enter the Quench, where water is sprayed to reduce the temperature of the gas to below 100 °C. Rapid cooling of the gas prevents any dioxin and furan formation, which typically occurs at temperatures between 200 and 500°C (9, 10). The cooled gases then enter a Venturi Scrubber where particulates are removed from the gas stream by trapping and collecting them in the water stream. In the Cyclonic Separator, the water/ash stream is separated from the gas stream prior to its discharge into the ships' stack. The ash / water stream inside the cyclonic separator is pumped through an inline strainer (a deep bed filter is used in the Montreal set-up) to separate the inert ash fraction from the water. The strained water is recirculated to the Quench spray nozzles to decrease the water consumption of the system aboard the ship.

## BUILDING THE SYSTEM

The detailed design of the PAWDS was initiated in January 2003, following the receipt of the contract from Carnival in December 2002. The goal was to ensure that the PAWDS was designed, built (Fig. 3), factory tested and ready for shipment by the end of August so that it would be ready for installation during the Carnival Fantasy pre-scheduled dry-dock in September 2003. This tight schedule necessitated that all detailed designs be completed within 2.5 months, to allow for 3.5 months of procurement, fabrication and assembly followed by 1.5 months of commissioning and testing and 0.5 months for disassembly, packaging and shipping. The entire system was shipped using two 40 foot container trucks which were then loaded onto a container ship to the Carnival dry-dock in Freeport, Bahamas.

**Fig. 3. Assembly at PyroGenesis Facility (Summer 2003)**

## INSTALLATION ABOARD M/S FANTASY

The PAWDS system was installed on the Carnival Cruise Lines MS Fantasy ship during its three-week dry-dock in September 2003. To expedite installation, a hole was made in the side of

the ship, at the location of the garbage room, to transfer the PAWDS equipment into the room. Although it is common practice during dry-docks to cut a hole in the side of the ship, future installations could be carried out during a regular cruise as all equipment, even the larger items such as the Shredder and the Thermal Treatment skid, can enter the ship through the marshalling (baggage) area. This modular design feature of PAWDS along with the fact that each piece or skid is relatively small is an important advantage in comparison to conventional shipboard incinerators. In addition, because the PAWDS occupies only a single deck and is relatively light weight, there was no need to cut through the decks. The only areas which required some structural reinforcement was well as vibration shock mounts was under the Mill and Shredder. The entire installation was carried out in four weeks using two persons from PyroGenesis (electrical and mechanical) plus a crew of electricians, pipe fitters and millwrights from Carnival's dry-dock team.

The system layout was designed to accommodate the existing garbage room space. In this design the system occupies a footprint of 8 m by 12 m or 1000 square feet and fits into a room space which has a ceiling or deck height of only 7ft 4in (Fig. 4). It should be noted that the layout of the system is very flexible and can be set-up in different configuration as required.

**Fig. 4. PAWDS Installation aboard Fantasy**

## TRAINING OF THE CREW

A formal training session was given to the Fantasy environmental crew and officers in October 2003 by Pyrogenesis (Fig. 5). PyroGenesis provided detailed operating and maintenance manuals for the system as well as quick reference guides. Two persons from PyroGenesis technical staff provided round the clock on-board technical support and hands-on operational training until March 2004. This technical team rotated every 3 to 4 weeks while the ship's crew rotated every 6 to 9 months. In April, the PyroGenesis support was reduced to only one person and in July 2004 PyroGenesis left the ship. Since this time PyroGenesis has been providing remote support from its Montreal office as well as occasional on-board electrical and operational training for approximately one week each time there is a change in operating personnel.

The PAWDS aboard M/S FANTASY is currently operated by the same environmental crew that handles all aspects of the waste management aboard the ship. No special skills are required to operate the system. One operator takes care of the system control, which is accomplished

through a centralized operator console while the other operator takes care of feeding the garbage into the shredder. The rest of the environmental team is responsible for collecting the garbage from the marshalling area and bringing it to the garbage room for processing.

**Fig. 5. Training of Fantasy Personnel**

## OPERATING EXPERIENCE

The PAWDS has been processing waste aboard the Carnival M/S Fantasy for over 18 months since it was installed and commissioned in October 2003. The system currently processes a combination of food, cardboard and cabin waste. Cabin waste is the waste generated in the passenger's cabins and is composed mainly of paper and plastics. The processed waste contains approximately 65% cardboard, 5% food and 30% cabin waste.

The system is designed to process waste at a rate of approximately 450 lbs/hr for up to 18 hours per day. As seen in Fig. 6, from October 2003 to February 2004 the system's operating hours were slowly ramped up to about 40 hours per week or 160 hours per month. At the beginning and due to the ship's itinerary, a maximum of only 70 hours were available each week to process the waste since the ship had not yet obtained permission to operate in the ports of the Bahamas. In the months of March to May 2004 several operating problems were encountered which resulted in a drop in operating hours. More specifically, some milling high amperage and overheating problems occurred as a result of inadequate mill blade replacement procedures as well as insufficient spare parts on the ship. PyroGenesis refined these maintenance procedures and then transferred this information to the ships crew. In addition, the ship has purchased much of the recommended spare parts, which helped to reduce lengthy downtimes.

Two environmental crew rotations have occurred to-date: the first in May 2004 and the second in October 2004. As seen in Fig. 6, this rotation caused a drop in operating hours for that month until the new operators got used to the system.

The system was delivered with two plasma torches, one in operation and one as a spare. The plasma torch is normally shipped back to Montreal to replace the consumable electrodes. In August 2004 and due to a problem with contamination of oil and dirt in the compressed air supply, premature failures of the air plasma torch occurred and resulted in periods of downtime since the ship was operating with only one torch. The problem of variable/poor compressed air quality was rectified by installing an air filter, a dryer and an oil trap. In addition, an additional spare torch was purchased. In the future, the Carnival operators will be trained to replace the plasma torch electrodes in situ.

In June 2004, the ship obtained permission from the Bahamian Port Authorities to operate in the ports of Nassau and Freeport after providing these local authorities with information regarding the emissions from the system. The system emissions are discussed in more details in the following section. At this point, the available operating hours increased from 70 hours per week to about 118 hours per week (18 hours per day for 6 days plus 10 hours when the ship was in the port of Florida. In July 2004, the weekly operating hours increased to about 50 hours per week. The gap between the available weekly operating time and the actual operating hours was due to the system being waste limited. In other words, PAWDS would process waste until there was no more waste aboard the ship. This lack of available waste was a result of two issues. The first issue was the result of internal shipboard procedures whereby the waste was still being off-loaded instead of being transferred to the PAWDS and the second problem was the inability of PAWDS to effectively process hard plastic waste. This shortfall in the capability of processing hard plastics by the PAWDS was the focus of further process improvements as will be discussed in the next section. This process improvement was implemented on the Carnival Fantasy in January 2005 and, as seen in Fig. 6, the processing rates have begun to increase since that time. Specifically, at the end of February 2005 the weekly rate increased to 53 hours or 212 total hours for that month. In addition, for both February and March 2005, the PAWDS was operated for 15 hours in a single day which is approaching its design capacity of 18 hours per day. To date, the system has logged nearly 2,100 hours of operation and processed approximately 900,000 lbs of waste.

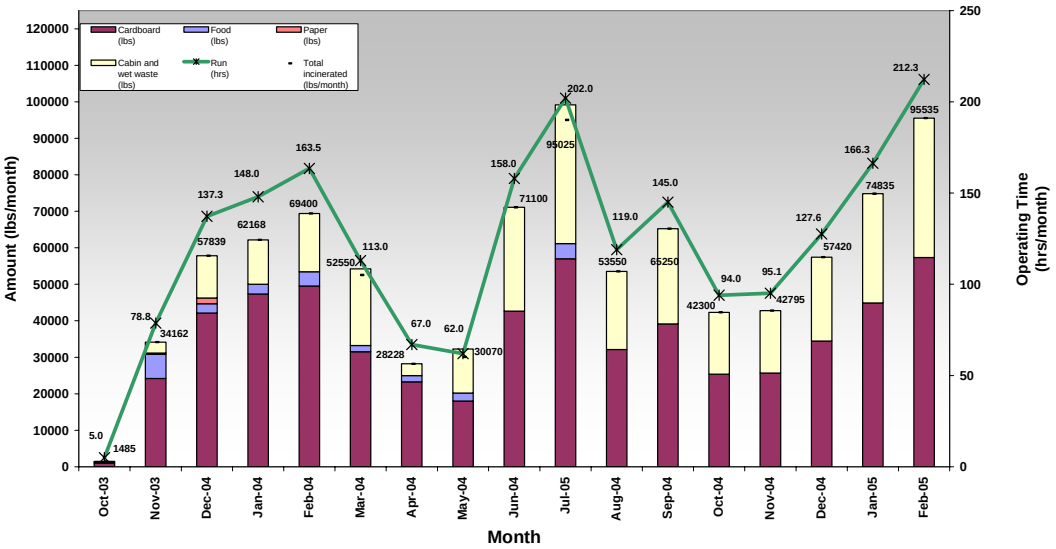


**Fig. 6. PAWDS Operating Hours and Processing Rates on M/S FANTASY**

## EMISSION RESULTS

On September 23rd, 2004 a certified external laboratory (Bodycote Material Testing of Sainte-Foy, Quebec) was used to sample and then analyze the off-gas emissions and ash generated from the PAWDS EDM system in Montreal. Since this PAWDS EDM is essentially identical to the system aboard the MS Fantasy, the results obtained can be used to certify both plasma systems.

The IMO/MARPOL regulations require that a 6 hour test be carried out using a waste feed mixture comprised of 50% food waste and 50% rubbish. Details of the mixture are summarized in Table I. The average feed rate during this test period was 425 lbs/hr.

**Table I – IMO/MARPOL TYPE II Solid Waste Composition**

| |
|---|
| 50% Food Waste |
| 50% Rubbish containing roughly: |
| - 30% paper |
| - 40% cardboard |
| - 10% rags |
| - 20% plastics |

A series of three 2 hours runs were sampled and tested. All the results obtained were clearly below IMO/MARPOL requirements as shown in Table II. On the basis of these test results PyroGenesis plans to request from Lloyds Register the formal IMO MED certificate.

**Table II – Air Emission Testing Results by Independent Company**

| **SAMPLING SCHEDULE** | | | | | |
|---|---|---|---|---|---|
| RUN NUMBER | 1 | 2 | 3 | Average | MARPOL Limit |
| DATE | 23/09/04 | 23/09/04 | 23/09/04 | | |
| STARTING TIME | 9h14 | 13h22 | 16h22 | | |
| ENDING TIME | 12h40 | 15h54 | 18h23 | | |
| **GASEOUS COMPONENTS (ppm & %)** | | | | | |
| $O_2$ (%) | 10.3 | 9.3 | 10.2 | 9.9 | 6-12 |
| $CO_2$ (%) | 10.1 | 10.9 | 10.2 | 10.4 | N/A |
| CO (ppm) | 145 | 106 | 72 | 108 | N/A |
| **GASEOUS COMPONENTS (mg/Rm$^3$)** | | | | | |
| CO (mg/Rm$^3$) | 165 | 122 | 82 | 123 | N/A |
| **CARBON MONOXIDE (mg/MJ corrected at 11% $O_2$)** | | | | | |
| CO (mg/MJ corrected at 11% $O_2$) | 81.7 | 55.8 | 40.7 | 59.4 | 200 |
| **OTHER MEASUREMENTS** | | | | | |
| OPACITY * | < 20% | < 20% | < 20% | < 20% | < 20% |
| UNBURNED COMPONENTS in the Ash (%) | < 1% | | | | < 10% |

* MICRO-RINGELMAN SCALE

## PROCESS IMPROVEMENTS

Since the system was installed on M/S Fantasy several process improvements were realized through the continued development work carried out in Montreal on the PAWDS EDM and sponsored by the US Navy. Some of these process and automation improvements that were implemented between February 2004 and January 2005 on the Carnival Fantasy are as follows:

1. Operational and mechanical modifications to the Mill to allow for the successful processing of hard plastics.
2. Maintaining constant Mill amperage by automatically controlling the Screw Feeder speed. This change resulted in a more stable waste feed rate to the Thermal Section. The Screw Feeder gear ratio was also modified to allow for better control.
3. Maintaining constant Mill temperature by automatically controlling the amount of fresh water injection to the mill.
4. The addition of several user friendly pop-up screens to improve the operators' ability to rapidly troubleshoot the system.

### Hard Plastics Processing

The waste mixture aboard a cruise ship typically contains around 10 % plastics in which roughly half of these plastics are "hard" (e.g. utensils, HDPE & PET). The original PAWDS Mill was unable to properly process these hard plastics (Fig. 7) and as a result these plastic fragments were frequently recovered in the ash discharged from the system. This situation not only caused upsets in CO emissions but also resulted in higher than acceptable organics contents in the ash.

**Fig. 7. Poorly Milled Plastics**

Improvements to the milling process were achieved during a development program undertaken in 2004 and sponsored by the US Navy. These improvements have resulted in a much reduced milled plastics particle size (Fig. 8).

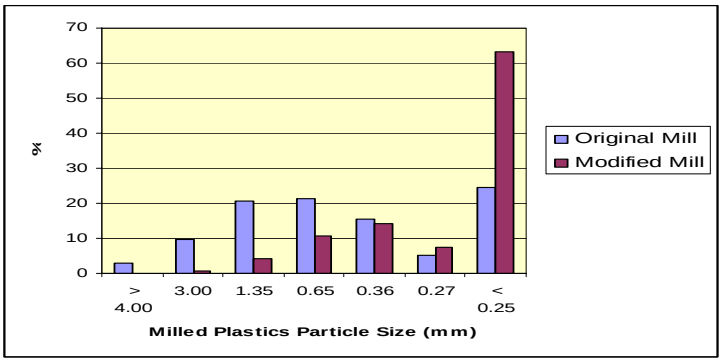


**Fig. 8. Improvement Achieved in Milled Particle Size**

The Mill modification resulted in a more finely produced particle size (over 60% finer than 250 microns) which was then successfully processed on the PAWDS with emission results much below MARPOL requirements. Fig. 9 provide examples of CO and NO emissions before and after these Mill modifications. It is apparent from these graphs that the off-gas emissions are both lower and much more stable. These Mill improvements were subsequently implemented on the M/S Fantasy in January 2005.

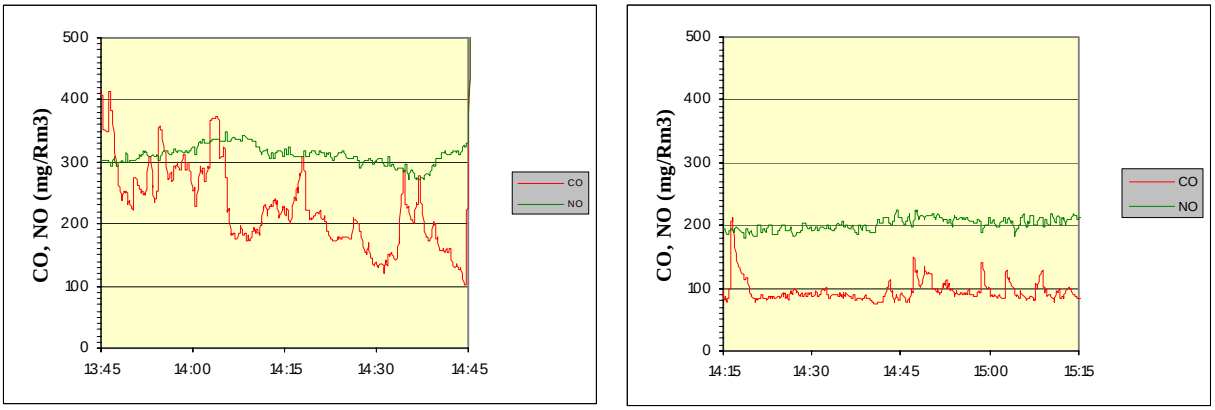


**Fig. 9. Example System Emissions before and after Mill Improvements**

## Process Control Improvements

The first process control issue that was addressed relates to the operation of the Screw Feeder which meters the waste into the Mill. The original Screw Feeder had a gear ratio that did not allow for turning down the feed rate when very dense wet waste was being processed and resulted in frequent jamming and consequently feed interruptions to the Thermal Section. In May 2004, a larger gear ratio and a new motor were installed which provided a higher torque at lower speeds to prevent jamming. The Screw Feeder speed was then automatically adjusted to control the Mill amperage to obtain a more stable waste feed rate to the Thermal Section.

Since the Mill uses a lot of mechanical energy to pulverize the waste, it generates a lot of heat. Although the custom designed Mill has a water jacket to remove some of this energy, there is still occasional overheating inside the Mill which causes materials such as low density polyethylene to melt. To remedy this problem, in August 2004 an automatic control of the Mill exit temperature was accomplished by modulating the amount of fresh water injection into the Mill. The careful control of the Mill exit temperature is key to ensuring that the waste entering the Thermal Section is neither too cold, which reduces the efficiency inside the Thermal Section, or too hot which causes material melting.

Several descriptive pop-up screens have been added to the operator interface in an effort to help guide the operator to either rapidly troubleshoot the system or as a reminder that maintenance is required on a specific item. Feedback from the Fantasy operators is that these screens have helped to reduce system downtime.

## CONCLUSION

A commercial PAWDS system has been installed on a cruise ship and has been running since October 2003. The system has logged nearly 2,100 hours of operation and processed roughly 900,000 lbs of waste since February 2005. External laboratory testing has shown that the system meets IMO/MARPOL emissions for operation at sea. In addition, the system is authorized to operate in the ports and waters of the Bahamas.

Several process improvements have been implemented on the commercial system with the goal of improving the system reliability. These improvements focused on increasing the ability of PAWDS to process all types of plastics as well as to refine the process control system to ensure a more stable waste feed rate and temperature to the Thermal Section. Automatic "pop-up" screens were added to the operator interface as a means of assisting the operator in rapid troubleshooting and as a reminder for maintenance.

Continued developments are underway with the aim of reducing the system's operating costs, as well as increasing PAWDS capability by being able to treat wastes such as sludge oil, as well as to consider the incorporation of energy recovery into the system. PyroGenesis's recent partnership in June 2004 with Deerberg-Systems, a leading supplier of shipboard waste management systems, will help make PAWDS a standard component of an integrated ship waste management solution.

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