

A Fully Automated and “Sailor Friendly” Plasma Arc Waste Destruction System

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ABSTRACT

The Plasma Arc Waste Destruction system (PAWDS) uses a plasma torch to rapidly and efficiently destroy combustible waste aboard ships. After eight years of development under the support of the US Navy and after two and a half years of operation aboard a commercial cruise ship, PAWDS has proven itself to be a viable alternative to traditional incinerators.

In the PAWDS, the waste is first shredded and then milled into a lint-like material. This milled waste is then rapidly gasified in a patented plasma fired eductor. The resulting synthesis gas is then mixed with air in the combustion chamber to produce a fully combusted off-gas. This off-gas is then rapidly cooled, preventing the reformation of dioxins and furans. The high energy density of the plasma flame and the use of a unique wall design for the thermal destruction section results in a system that can be rapidly started-up and shutdown within minutes and that is compact and lightweight, fitting into a single deck aboard a commercial cruise vessel or a Navy ship.

PyroGenesis with the support of the US Navy, continued to make improvements to the PAWDS over the last two years with the focus of making it a fully automated, operator-friendly system. This paper focuses on several improvements made to the automation and process control of the PAWDS during 2004 and 2005. These improvements include: implementing single button automatic start-up and shutdown sequences, designing and implementing independent control loops for maintaining favorable combustion and waste feed rates, and simplifying the operator interface. Several descriptive pop-up screens have been added to the operator interface to help guide the operator to either rapidly troubleshoot the system or to provide a reminder that maintenance is required on a specific item. Most importantly, the automation program has been designed so that these multiple regulatory control loops work together to intelligently control the system operation in order to compensate for variations in the waste composition. In the event of an abnormal system operation, the control system guides the operator to the action(s) required to bring the system back into normal operating conditions. If no response from the operator is detected when an operator intervention is required, the control system is also designed to take action to safely initiate an automatic shutdown sequence. The system is also designed to allow for remote access over the internet.

INTRODUCTION

Over the last eight years and under contract with the US Navy, PyroGenesis has been developing the Plasma Arc Waste Destruction System (PAWDS) designed for the treatment of solid aboard future Navy ships. In 1999, as part of an Advanced Technology Demonstration (ATD) program funded by the Office of Naval Research (ONR), PyroGenesis designed, fabricated and successfully demonstrated, in its Montreal facility, a first prototype PAWDS, for the treatment of waste generated aboard aircraft carriers. The PAWDS ATD prototype was tested over a period of three years and logged over 1,500 hours of operation. The Naval Surface Warfare Center Carderock Division (NSWCCD) and PyroGenesis Inc. (PGI) entered into a Cooperative Research and Development Agreement (CRADA) allowing the two parties to collaborate in the modification, testing and demonstration of PAWDS for installation aboard a non-Navy vessel. PGI benefited from commercializing this technology while the US Navy benefited from the development and early demonstration of a shipboard system. 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 since reliably demonstrated processing rates in excess of 400 lbs/hr^{3, 4, 5, 6, 7}.

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 2003² and has logged over 3500 hours of operation.

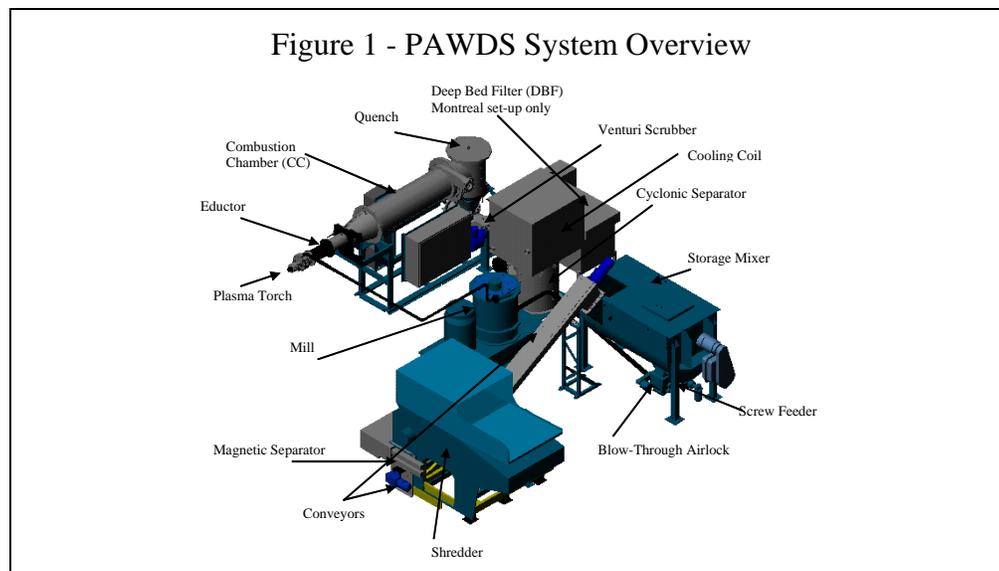
During the same period, the US Navy contracted PyroGenesis to build a new system at PyroGenesis' Montreal facility similar to the commercial or "industrial" design. This system, referred to as PAWDS - Engineering Development Model (PAWDS-EDM), is virtually identical to the system aboard Carnival's M/S Fantasy. It was built and installed at PyroGenesis where it has logged over 700 hours of operation since December 2003¹.

In 2004 and 2005 the US Navy contracted PyroGenesis to further refine the automation of the PAWDS system to make it "sailor-friendly". Although PAWDS has been successfully operated by trained personnel aboard the Carnival M/S Fantasy for the past 2.5 years, the US Navy PAWDS will be operated by trained sailors whose duties will invariably not be solely dedicated to operating and maintaining the PAWDS system. More specifically, the US Navy Sailors will experience a higher degree of rotation (possibly every few weeks) compared to the Carnival operators who typically are dedicated to operating the system for periods ranging from 4 to 9 months. This high degree of operator "turnover" necessitates that the training requirements be minimized. Currently the Carnival operators, with their experience are able to adjust the system's operating conditions depending on the composition of the waste stream. Given that the US Navy sailors will not have enough time to gain this "operator experience" the system must be able to automatically adjust its operating parameters to optimize its performance as a consequence of a varied waste stream mix. It was this need that resulted in the effort to make the PAWDS a "fully automated" system that could be easily operated by sailors.

SYSTEM DESCRIPTION

The key to the PAWDS is that combustible waste such as food, paper, textiles, wood, cardboard and plastics are transformed through a patented process into a highly efficient fuel⁸ prior to being gasified and combusted. The PAWDS is a continuous process in which the waste is first fed into a shredder where its size is reduced and then transported to a storage mixer using screw conveyors. A screw feeder is attached to the base of the storage mixer and is used to meter the waste into a blow-through airlock and then onwards to a mill. Air from a gasification blower is used to pneumatically convey the material to the mill. The mill pulverizes and dries the waste. The final product, leaving the mill, is a highly combustible and dry material that looks similar to lint from a household dryer. The milled waste “fuel” conveyed by air is then injected into a patented plasma-fired eductor⁹. In the eductor, this “fuel” is exposed to the high temperature of the plasma plume that results in rapid gasification of the solid waste into a synthesis gas. The resulting synthesis gas is then combusted with excess air in a patented¹⁰, lightweight combustion chamber, resulting in a fully oxidized off-gas, comprised of carbon dioxide and water. Any inorganic substances in the waste are transformed into an inert ash.

Upon exiting the combustion chamber, the gases enter a quench, where water is sprayed to reduce the temperature of the gas to 80 °C typically. Rapid cooling of the gas prevents any dioxin and furan formation, which typically occurs at temperatures between 200 and 500°C^{11, 12}. 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. A cyclonic separator separates the water/ash stream from the gas stream prior to its discharge into the ship’s stack. The ash/water stream inside the cyclonic separator is pumped through an in-line strainer or a deep bed filter to separate the inert ash fraction from the water. The strained water can be re-circulated to the quench spray nozzles to decrease the water consumption of the system aboard the ship. The main components of the PAWDS-EDM are shown in the Figure 1.



CONTROL SYSTEM DESCRIPTION

A Programmable Logic Controller (PLC) is used to operate the PAWDS. The operator interface combines the computer and the touch screen semi-mobile system. A picture of this unit is shown in Figure 2. It serves both as a touch screen and an internal computer station. This interface is connected to the PLC via an Ethernet network. This connection allows for remote monitoring and remote operation. If the Ethernet connection between the operator interface and the Programmable Logic Controller (PLC) is lost, the PLC will continue to control the system and will automatically initiate the normal automatic shutdown sequence. It is important to note that the operator always has the opportunity of pressing one of the many Emergency Stop (E-Stop) buttons, which would perform an immediate total shutdown, if something abnormal occurs.

All electric motors are connected to, and controlled by a Motor Control Center (MCC). All motors greater than 10 kW are equipped with a local ammeter for overload protection and for safety reasons. All starter units communicate with the PLC via a “DeviceNet” protocol, for all command and status information. The emergency stop circuit, however, is connected directly (hard-wired) to each motor starter.

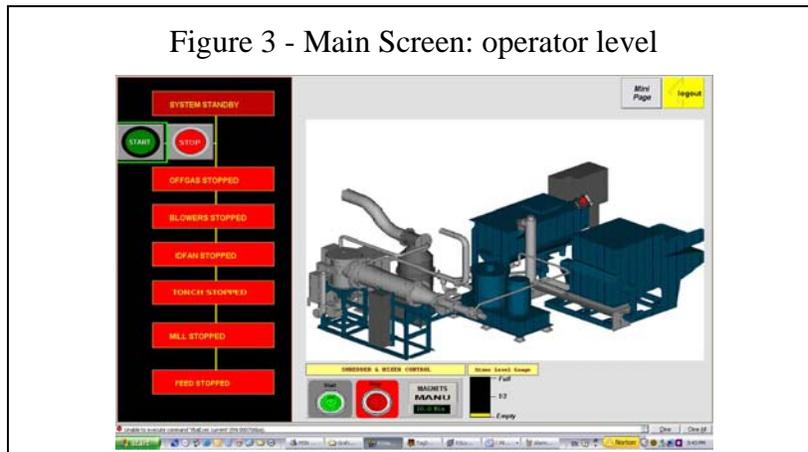


The control program is designed with two levels of accessibility: the operator level and the supervisor/maintainer level, which is password protected.

The operator level has the following functionality:

- Execution of automatic startup and shutdown sequences;
- Start/Stop of the Shredding sub-system;
- A mini page with essential system operation parameters;
- Data acquisition;
- Viewing, acknowledging and resetting of alarms;

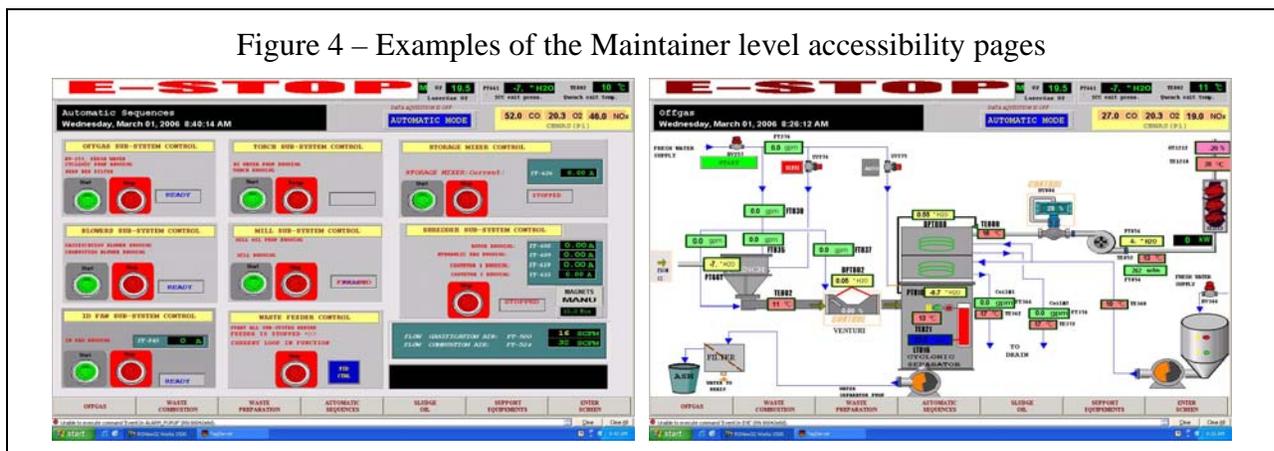
Figure 3 shows the main operator screen, ready to start the system.



The supervisor/maintainer level, in addition to the features of the operator level, has the following functionality:

- Manual start-up and shutdown of equipments for maintenance or troubleshooting purposes;
- Viewing of additional process parameters details;
- Changing of system operating parameters / set points;
- Viewing of specific sub-systems operation (all digital and analog outputs);
- Instrument Calibration;
- Data log Transfer;
- Viewing network status (Profibus, Devicenet, Controlnet);

Figure 4 shows examples of two pages of the maintainer level accessibility screens.



CONTROL NETWORK

A Profibus network is used to connect all pressure and flow instrumentation. The precision and speed of this network results in excellent system performance since it operates at 94 kb/sec and provides a much faster response than other alternative networks. This fast response is necessary to adjust critical control loops. In addition, this network architecture allows for instruments to be calibrated online without the need for individual local adjustments. A Devicenet network is used to communicate between the PLC and the Motor Control Center (MCC). This communication protocol significantly reduces the amount of wiring and, at the same time, increases the amount of information available from the motors such as overload trips, contactors, motor current, phase losses etc. A Controlnet network is used to connect to thermocouples and digital Inputs/Outputs (I/Os). This additional information facilitates troubleshooting of electrical problems in particular.

PROCESS OPERATION AND CONTROL

When the system is operating in automatic mode, the PLC monitors all on-line measurements and makes the necessary corrective actions to the system to ensure that it operates within its normal conditions. If an abnormal condition is detected, the system will typically give the operator a warning with some instruction on what to verify. If the problem cannot be corrected in a timely manner, or if the system has to be shutdown to correct the problem, the operator, will likely choose to initiate an automatic shutdown. In the event that the operator decides to wait until a critical alarm condition is reached, then the system will automatically shut itself down. Although the system is designed to be started, shut down and operated in automatic mode, it can also be operated in manual mode for maintenance and troubleshooting purposes through the supervisor/maintainer accessibility level. This mode of operation, however, still includes important safety interlocks so as to ensure that human error does not result in either equipment damage or compromise the safety of the workers.

Another important automatic safety feature of the system design is the Emergency stop feature (E-stop). This feature provides a hard-wired signal that will immediately stop all of the equipment simultaneously. This is not an ideal method to shutdown the system, since it results in the projection of poorly treated waste throughout the process which will necessitate cleaning prior to restarting the system. This feature is only used when there is an emergency situation.

AUTOMATIC START-UP AND SHUTDOWN SEQUENCES

Automatic Start-up

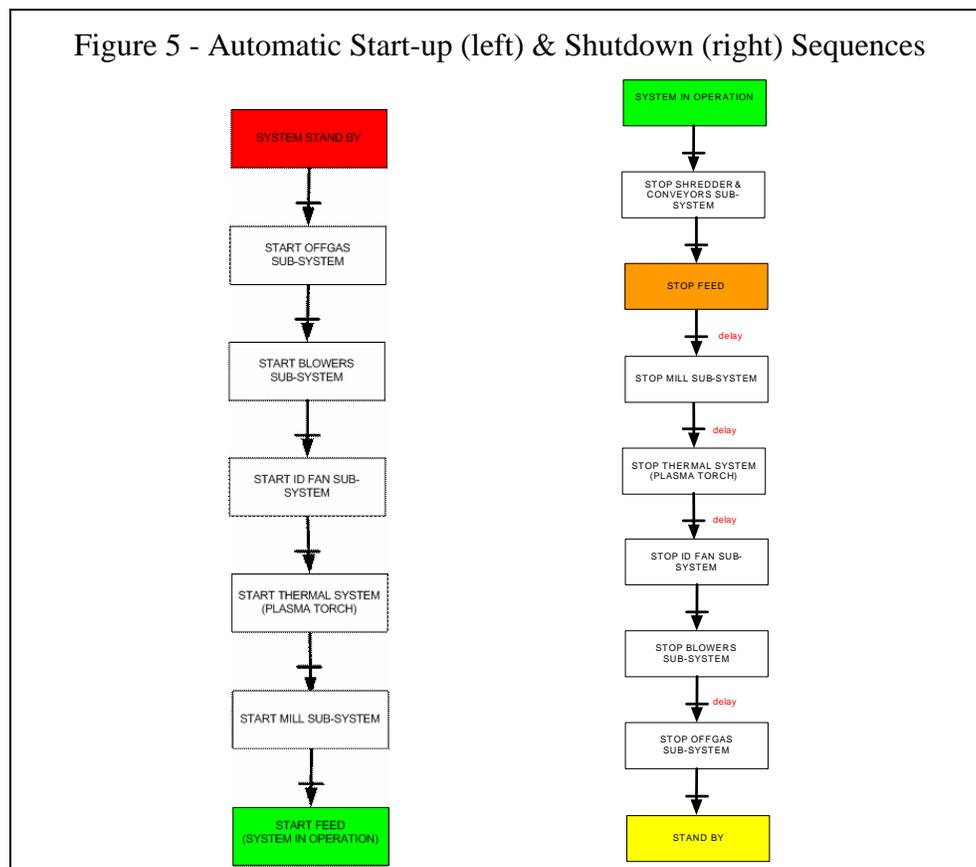
The automatic start-up sequence ensures that all required sub-systems are operating normally prior to allowing for the start-up of the subsequent sub-system. All utilities, such as compressed air and the cooling water circuits must be functioning normally prior to the startup of the off-gas sub-system. Similarly, the thermal section cannot be started if the gases have no place to be safely vented, for example if the Induced Draft (ID) fan is not operating. Once the thermal section is operating normally (i.e. the torch is running and all cooling water and air flows have been verified) then the mill sub-system start up sequence will be initiated automatically,

followed by the waste feed sub-system. The full automatic start-up sequence takes usually under 10 minutes to complete.

Automatic Shut-down

The automatic shutdown sequence is not quite a reversal of the start-up sequence. The shutdown sequence begins with the shredder and conveyors sub-system, if in operation, followed by the storage mixer sub-system. After a time delay, the screw feeder is stopped. Once the screw feeder is stopped, then the mill will stop after an additional time delay. This delay was integrated in the shutdown sequence to clear the waste feed line from any residual waste. Following the mill shutdown, a delay of couple of minutes will ensure that the mill has completely stopped and most of the material has been purged from the system prior to shutting down the plasma torch system. An additional delay is included before shutting down the ID Fan and blowers sub-systems to ensure that all combustion gases are evacuated from the system. Finally the off-gas sub-system is shutdown. The automatic shutdown sequence ensures that all equipment is protected, that the combustion gases are evacuated and that the feed lines are cleared to prevent any blockages once the system is restarted. It taken approximately 20 minutes to complete an automatic shut-down sequence.

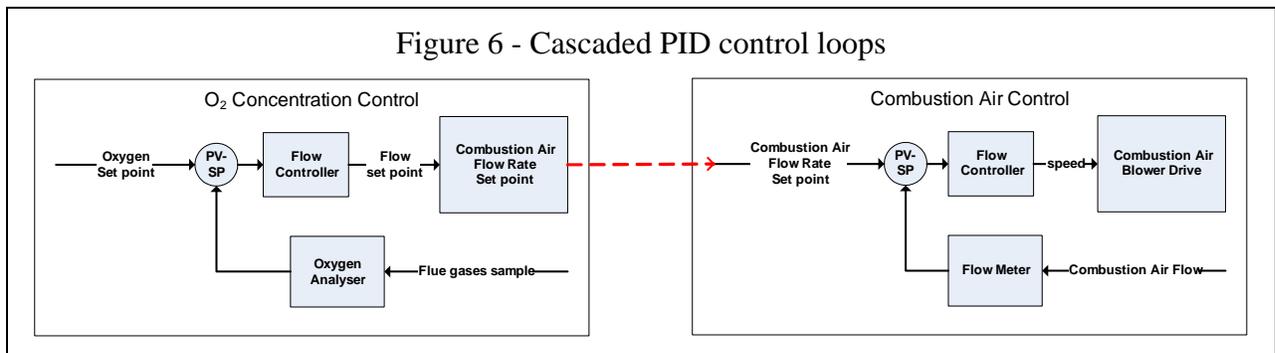
Figure 5 provides a graphical overview of the start-up and shutdown sequences



CONTROL LOOPS

To control the operational parameters, the control system uses regulatory feedback control loops with Proportional, Integral, and sometimes Derivative (PID) control actions. These control loops act on motor speed, valve opening and damper position to maintain targeted set points. There are nine main feedback control loops that work simultaneously to maintain the PAWDS within its normal operating conditions.

The targeted set points used by the control program in the different control loops can either be preset values (simple control loops) or obtained by the interaction between the various PID control loops (cascaded control loops). For example, the targeted combustion air blower speed set point is indirectly determined by the O₂ concentration in the flue gases control loop. Figure 6 shows an example of the cascaded control loop used to maintain a constant oxygen concentration in the flue gases.



The key to stabilizing the system is to ensure that one control loop does not destabilize another causing cycling between the key control parameters. In the example cited above, the addition of variable amount of combustion air in the combustion chamber will invariably impact the control of the vacuum inside the chamber. To ensure that the vacuum is maintained at is desired conditions this loop is programmed to react an order of magnitude more quickly as compared to the oxygen control loop. Similar interactions between the feed rate control and the amount of combustion air for example have inherent interactions with other control loops which need to be accounted for.

FULLY AUTOMATED CONTROL LOGIC

Another important disturbance to the system is the variation in waste stream composition. When the waste stream composition changes and becomes more or less humid or has more or less organic material (eg. plastics vs. food waste) the set point for feed rates needs to be adjusted to optimize the system capacity while maintaining good gasification and combustion processes. With the newly automated PAWDS this waste feed rate set point is adjusted automatically by the system.

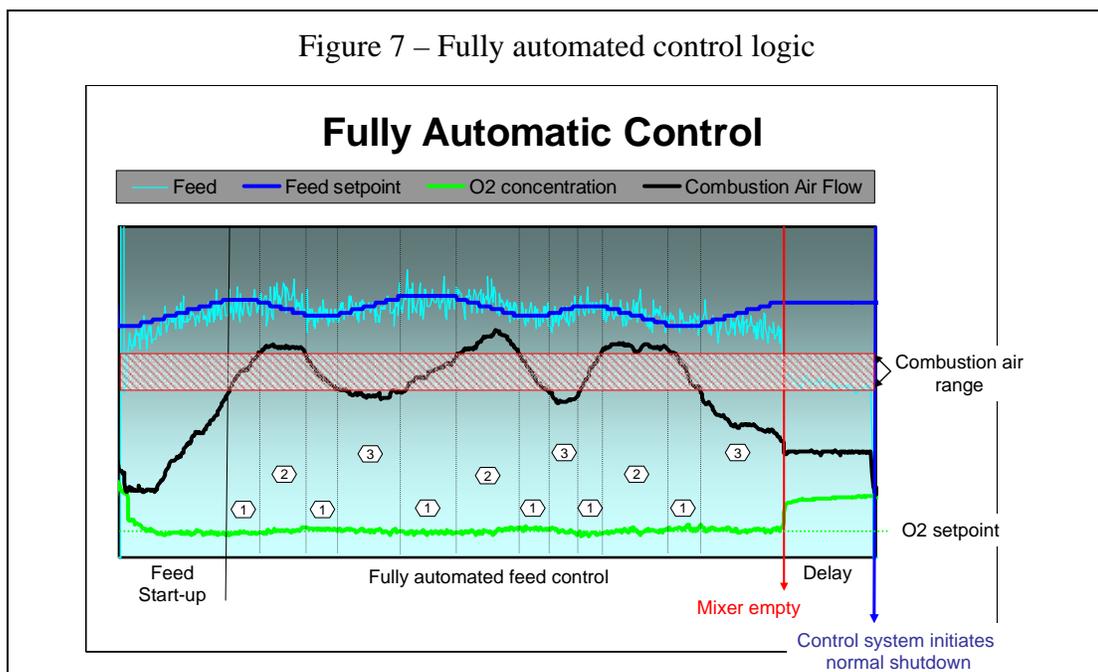
To ensure good gasification and combustion processes on one side while maximizing the system capacity for that specific waste composition on the other side, the key parameter is to maintain the combustion air flow rate in a specific range while ensuring a constant oxygen concentration in the flue gases. To accomplish this objective, the control system automatically increases or decreases the feed set point until the combustion air flow rate is within the preset range.

An example of this “fully automated feed control” is shown in the Figure 7 for the various stages of operation of the PAWDS. From this figure we can see that in the “feed start-up” stage, the feed set point is gradually increased by the control program until the combustion air flow rate reaches the lower limit of the preset combustion air flow rate range.

In this “fully automated feed control” logic, there are three kinds of responses provided by the automatic control system. These responses are summarized below:

1. If the combustion air flow rate is within the preset combustion air range, the control system will maintain a constant feed set point (Figure 7 - ①);
2. If the combustion air flow rate is higher than the higher limit of the preset combustion air range, the control system will gradually decrease the feed set point (Figure 7 - ②);
3. If the combustion air flow rate is lower than the lower limit of the preset combustion air range, the control system will gradually increase the feed set point (Figure 7 - ③).

The control system is also designed to automatically detect when there is no more waste feed to process in the system (i.e. when the mixer is empty) and will initiate the normal system shut down sequence. Prior to shutting down, however, a time delay is given to the operators in order to give them the possibility to fill-up the mixer with more waste, if required.



CONTROL SYSTEM INTERLOCKS

To ensure a safe operation of the system, many system interlocks have been integrated into the control program. These interlocks will trigger actions if an abnormal system operation is detected. Three kinds of actions can be triggered by the control system following the detection of an abnormal system condition:

1. Emergency stop: if the abnormal system condition detected is deemed unsafe for the workers or can damage the equipment, all equipment will be instantly shutdown;
2. Normal shutdown sequence: if the abnormal condition is not deemed unsafe for the workers or the equipment but cannot be fixed while the system is running, the control program will initiate a normal shutdown sequence of the system;
3. Stop feed: if the abnormal system condition is not deemed unsafe for the workers or the equipment and can be related to a temporary problem or a problem that could be fixed while the system is running (for example changing the nitrogen bottle), the control system will stop the waste feed to the system. After a specific time delay, if the system operation is back to normal, the control system will re-start the feed. If the problem is not fixed after the time delay or if the problem reoccurs several times during the day, the control system will initiate a normal shutdown sequence and will advise the operator.

Since the control system interlocks rely on the instrumentation and the network communication, the control program is also designed to take action in the case of an instrument failure or a loss of network communication. The PAWDS instrumentation has been divided into four categories, depending on the role they play in the control of the system. For each category, a different reaction is programmed in case of an instrument failure or loss of communication.

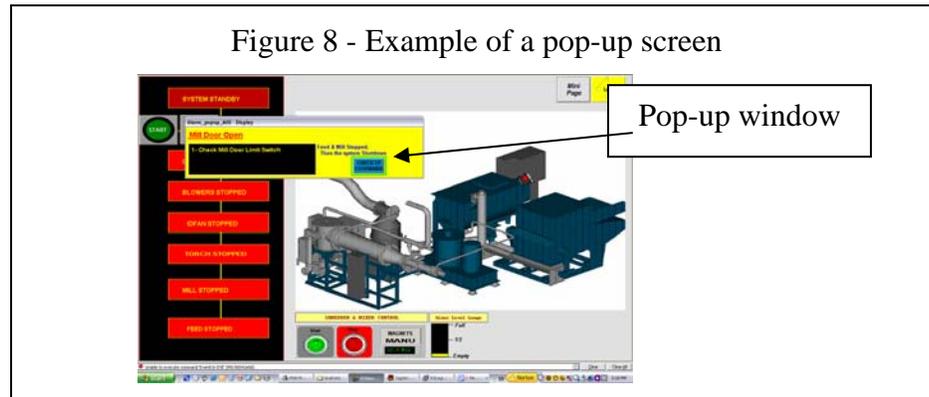
The four anticipated system responses are:

1. Critical instrument (for example all control cabinets): the control system will immediately initiate an emergency stop;
2. Important instrument (instrument needed for the control program or required by the regulation such as the thermocouple at the exit of the combustion chamber): the control system will initiate a normal shutdown sequence;
3. Useful instrument (for example the pressure transducer on the compressed air supply line): the control system will allow the system to operate normally but the system will not be permitted to re-start if the communication problem or the failure is not fixed after the system shutdown;
4. Monitoring instrument (such as thermocouple on the gasification air line): no action will be triggered by the control system; the problem will only be flagged to the operator.

POP-UP SCREENS

Pop-up screens have been added in the control program, in order to provide guidelines for troubleshooting the system and for maintenance purposes. In the case of abnormal events and at the end of each daily run, a clearly visible window appears on the operator interface. In this

window, the operator will find guidelines to investigate and fix the problem in the case of an abnormal event. In addition, at the end of each daily run the operator will find a description of the regular maintenance required prior to re-starting the system. To close the pop-up window, the operator has to acknowledge the message and confirm that he fixed the problem or completed the required maintenance. Figure 8 shows one example of a pop-up screen.



CONCLUSION

The PAWDS is a compact, reliable, safe and efficient alternative to methods currently being used to treat shipboard waste. Over the last two years, several modifications to the PAWDS system have been made to make the system a fully automated, operator-friendly system. Following these improvements, the system now operates with a single button automatic start-up and shutdown sequences. It also includes independent control loops for maintaining favorable combustion and waste feed rate conditions. Several descriptive pop-up screens have been added to the operator interface to help guide the operator to either rapidly troubleshoot the system or to provide a reminder that maintenance is required on a specific item. Most importantly, the automation program has been designed so that these multiple regulatory control loops work together to intelligently control the system operation with little to no operators' intervention. Finally, in the event of an abnormal system operating condition, the control system guides the operator to the action(s) required to bring the system back into a normal operating regime.

With these improvements in the automation of the system, the US Navy Sailors can now add waste as received, minimizing the requirement of blending waste to achieve a specific composition. Furthermore, the amount of training required for new sailors is significantly reduced given that there is never a requirement to change operation set points and if an abnormal condition is detected the system will guide the sailor to the area which needs to be verified (via user-friendly pop-up screens) so that he / she can quickly correct the problem. If any unusual operating condition is detected, the system will automatically shut itself down so that it is always safe and easy to use.

Future work will involve sailors operating the system at the PyroGenesis facility to observe "first-hand" their ability to operate the system and to gain their feed-back on its ease of use.

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