COMPACT PLASMA WASTE ELIMINATION SYSTEM FOR SHIPS

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SUMMARY

A Compact Plasma Waste Elimination System has been developed by PyroGenesis Inc. as part of the U.S. Navy's Advanced Technology Demonstration program. The novel system combines a simple milling process for converting waste into a uniform and highly combustible fuel rapidly and cleanly.

In the process, combustion occurs in two stages, the first stage gasifies the milled waste using the patented plasma-fired eductor and the second stage fully combusts the synthesis gas produced by the eductor. The system is compact and lightweight, since it does not use refractory materials, requires no segregation of combustible waste, modular to ease shipboard installation and has quick startup and shutdown capabilities. As will be shown in this paper, the system has been demonstrated for the treatment of solid waste, including food, paper, cardboard, plastic, wood and textiles. Experimental combustion efficiencies were found to be greater than 99.8% and compliance to MARPOL Annex VI standards was demonstrated.

Based on the experienced gained during the demonstration period, a conceptual design of the commercial shipboard system has been developed, and will be presented in this paper.

AUTHOR'S BIOGRAPHY

Dr. Theodora Alexakis is presently the Program Leader of PyroGenesis Inc.'s Compact Plasma Gasifier Department. Dr. Alexakis has been employed by PyroGenesis Inc. for the past 10 years, during which time she worked in the areas of plasma production of fullerenes, gasification/vitrification of ash using graphite arc technology and compact plasma-arc thermal treatment systems for shipboard waste.

Dr. Peter Tsantrizos is the Chairman and Chief Technology Officer of PyroGenesis Inc. Prior to founding PyroGenesis Inc., Dr. Tsantrizos led the Advanced Materials Program at the Noranda Technology Center, Arthur D. Little and Nestle. Dr. Tsantrizos has worked on the development of plasma technologies for the past 20 years. His areas of expertise include plasma torch development, thermal spraying, plasma metal atomization, plasma fullerene production and plasma waste treatment.

Mrs. Aida Kaldas is presently leading the process development efforts for PyroGenesis Inc.'s Compact Plasma Gasifier Department. Prior to joining PyroGenesis Inc., Mrs. Kaldas has led several development programs working for Orica (formally ICI Explosives) for over 20 years. Her areas of expertise include process optimization and debottlenecking, process modeling and particles processing.

Mr. Sebastien Pelletier is presently the Process Engineer responsible for the overall operation of the Compact Plasma Waste Elimination System. Mr. Pelletier has been working for PyroGenesis Inc. for the past two years. He has made several contributions in the development of the current compact plasma system for waste elimination.

Mr. Platon Manoliadis is the Design Group Head at PyroGenesis Inc. Mr. Manoliadis has been employed by PyroGenesis Inc. for the past 10 years and has been responsible for the design of several plasma systems for thermal spray, metal powder production and waste treatment applications.

1. INTRODUCTION

PyroGenesis, as part of the U.S. Navy's Advanced Technology Demonstration program, has developed a Compact Plasma Waste Elimination System capable of treating all types of combustible solid waste generated onboard ships. The approach used to develop this innovative technology has been to create a design that captures the inherent benefits of ultrahigh temperature waste destruction, using plasma technology, while remaining compatible with the ship's mission requirements. Some of these mission constraints are: restrictions on system size and weight, reduced labor requirements, both in number and skill level of operators, high system reliability and availability, equipment operational safety, tolerance to mechanical shock and vibration, minimal electromagnetic interference (EMI), and rapid startup and shutdown of equipment.

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

The Compact Plasma Waste Elimination System developed jointly by PyroGenesis and the U.S. Navy for shipboard solid waste has many advantages over conventional incinerators. Using this technology, all waste, including food and plastics, can be treated without segregation. It is expected that the commercial system will require only two operators and will be extremely compact (240 ft^2), occupying only one deck of a ship and weighing less than ten tons. Also, because of the novel air-cooled construction of the wall of the combustion section, described later in this paper, startup and shutdown is achieved in less than five minutes. A size comparison of PyroGenesis' Compact Plasma Waste Elimination System with a conventional marine incinerator is shown in Figure 1.

2. BACKGROUND

Thermal destruction is recognized as the most effective method of reducing the volume of solid waste. When performed efficiently, combustible materials are transformed into benign gases (primarily CO_2 and H_2O) with a minimum amount of residue. There are many commercially available thermal destruction technologies on the market, but earlier U.S. Navy sponsored studies have found that the use of ultrahigh temperature gases, created with an electric arc discharge, or plasma, has several potential advantages over such thermal destruction processes [1].

Plasma is formed when enough energy is forced into a gas, causing the atoms of the gas to break into negatively charged electrons and positively charged ions. The formation of plasma, through a plasma-generating device such as a torch is relatively simple. An electric arc is formed in a gas flowing between two electrodes having a voltage difference to cause dielectric failure. The low mass gas in the arc is resistively heated to extremely high temperatures of 10,000 ^{o}C or higher. The flowing gas carries the thermal energy out of the torch in the form of a plume.

The concept of the technology developed by PyroGenesis and the U.S. Navy, and described in this paper combines a simple milling process for converting waste into a uniform and highly combustible fuel with a plasma-arc-assisted compact combustor that burns the

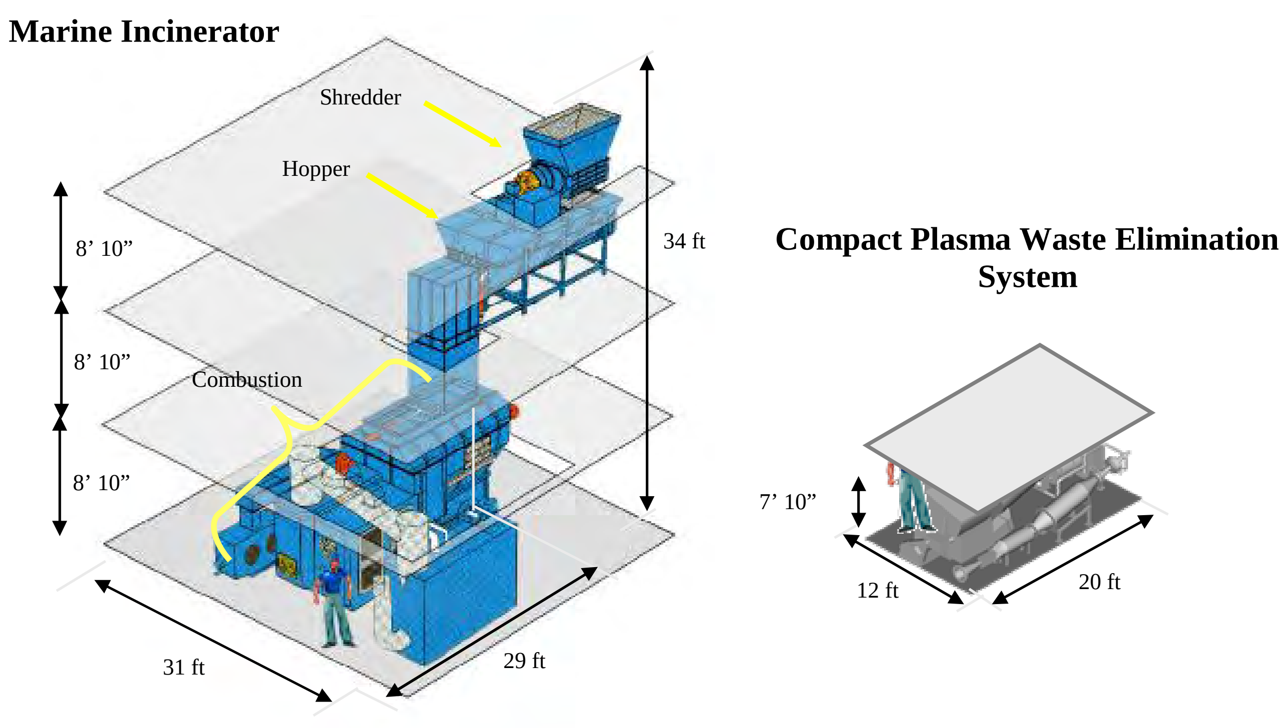

Figure 1: Comparison of Compact Plasma Waste Elimination System With Marine Incinerator

fuel rapidly and cleanly. By maximizing the surface area to mass ratio of waste through the milling process and feeding the milled particles into a high temperature plasma, chemical destruction occurs at rates that are orders of magnitude faster than in conventional incineration. This implies that a more compact system design can be developed. Secondly, the intimate mixing of the particles with the high temperature plasma results in the complete destruction of complex molecules down to the atomic level, thus leading to cleaner combustion by-products. Lastly, 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 food, can be minimized because the plasma supplies the energy for the thermal destruction process. This enables the thermal destruction of a broad spectrum of solid wastes.

The central element of this thermal destruction system's design is the plasma-fired eductor, shown in Figure 2. Internal to the water-cooled jacket shown in the photograph is an air-cooled metallic liner. The use of a metallic liner, instead of refractory, eliminates the need for slow heat-up and cool-down times to prevent thermal shock that leads to catastrophic failure of refractories. The air-cooled liners are relatively inexpensive, easy to install and are expected to have a lifetime in excess of six months during normal use. The eductor shape forces the mixing of the waste with the plasma.

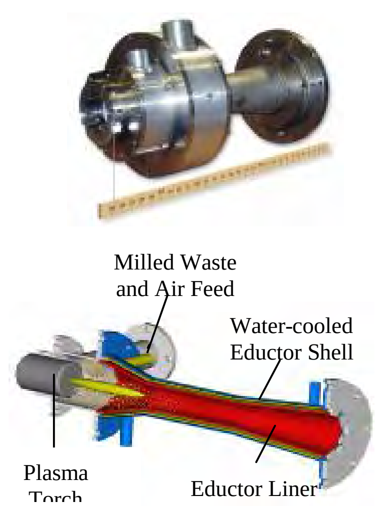

Figure 2: Photograph and Schematic of Plasma-fired Eductor

3. DESCRIPTION OF TECHNOLOGY

A full-scale prototype of the Compact Plasma Waste Elimination system for shipboard solid waste has been built and tested in the pilot lab of PyroGenesis Inc., located in Montreal, Canada [2,3]. A three dimensional representation of the prototype system may be seen in Figure 3.

In the system, mixed combustible waste is first pretreated through a series of size reducing equipment. The pretreatment dramatically increases the surface area to mass ratio of the waste particles, thus allowing them to gasify rapidly when exposed to extreme heat. Effectively, the pretreatment converts a solid waste stream into a fuel stream.

Waste is introduced into the process either by being fed into the pulper (1) or shredder (2). The pulper processes food, paper and cardboard, whereas the shredder may handle all types of waste. In the pulper, the size of the waste particles is reduced to less than ¼ inch, and the waste leaves the pulper as slurry, consisting of approximately 1% solids. The slurry enters a water extractor (3), where water is mechanically removed to yield an extracted product containing approximately 50% solids by weight. The extracted waste is then conveyed to the hopper/mixer (4). In the shredder, waste is reduced to pieces that are typically less than one inch in any dimension. The shredded waste is then conveyed to the metal extractor (7), where any fugitive metallic items present in the shredded waste are removed. Leaving the metal extractor, the shredded waste is conveyed to the hopper/mixer, where it is blended with the pulped waste. The mixed waste is metered from the hopper/mixer via a weigh-belt feeder (not shown) and a rotary valve into the mill (6). In the mill, the size of the waste is reduced to fine fibers approximately 15 µm in diameter, which resembles lint from a household dryer. In addition to pulverizing the waste, the mill also dries the waste, resulting in particles with a moisture content of approximately 4% by weight. Drying of the pulped material is accomplished by the mechanical work performed by the mill grinding the waste particles. A known quantity of air is fed into the mill to carry the fine particles to the eductor and to partially oxidize the waste in the plasma-fired eductor. The dried waste, along with the carrier air and generated water vapor, is then fed to the plasma-fired eductor for thermal treatment.

The plasma-fired eductor (7) serves as the first of a two-stage system for waste combustion. In the plasma-fired eductor, the amount of oxygen (air) is controlled to provide less than the theoretical amount necessary for full combustion; i.e. fuel rich. A small amount of air is also used as the plasma forming gas for the plasma torch. The thermal energy supplied by the plasma plume breaks apart the complex molecules resulting in the production of syngases, primarily CO and H_2. When the high temperature syngases (> 1100 °C) exit the plasma-fired eductor, they flow into the combustion chamber, where additional air is added for complete combustion. The gas temperature in the combustion chamber is typically about 1,000-1,100 °C. To ensure complete combustion in the combustion chamber, the quantity of process air is controlled to maintain an oxygen concentration of 6-12% by volume in the off-gas.

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

Upon exiting the combustion chamber, the gases are rapidly quenched with a water spray to prevent any trace formation of unwanted complex molecules (dioxins and furans). The Off-Gas Treatment System consists of a quench, where water is sprayed to reduce the temperature of the gas to less than 100 °C (373K), and a Venturi scrubber for particulate removal. An induced draft blower (not shown in Figure 3) is used to maintain a negative pressure in the system. The facility in Montreal is also equipped with acid gas scrubbers (not shown), which would not be required for shipboard use.

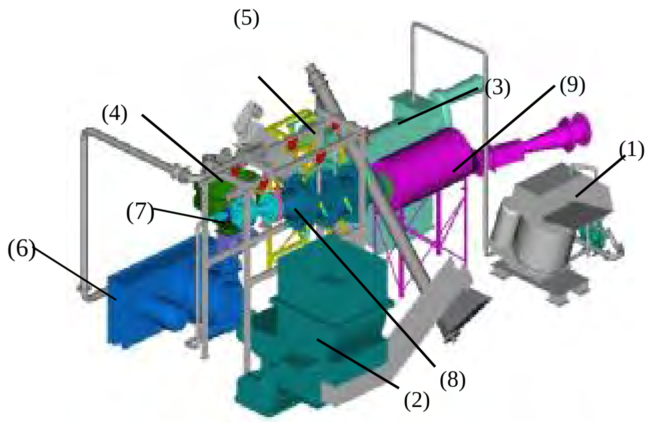

Figure 3: Overall Layout Drawing of Full-scale Prototype at PyroGenesis

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

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

4. RESULTS AND DISCUSSION

4.1 PROCESS PERFORMANCE

The process has been successfully demonstrated with a variety of waste types. The categories of waste included in this study and their processing rate are listed in Table 1. The amounts listed represent half of the 95th percentile U.S. aircraft carrier waste generation rates. The notional carrier system has a dual plasma-fired eductor process to allow continuous operation during maintenance periods.

Table 1. Categories and Processing Rate of Combustible Solid Waste

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

Using these waste streams, the process has been operated using the following modes of operation:

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

Under all three modes, the process was found to comply with MARPOL Annex VI standards. Table 2 shows a comparison of typical experimental results with the MARPOL limits.

Table 2. Comparison of Experimental Results to MARPOL Limits

Type of Emission	MARPOL Limit	Typical Experimental Results
$O_{2, \text{dry basis}}$	6-12%	9.0%
CO	200 mg/MJ[1]	40 mg/MJ
Soot Number	Bacharach 3 or Ringleman 1	Opacity < 5%
Flue gas temperature in combustion chamber	850-1200 ºC	950 – 1100 ºC
Unburned components in ash residues	<10%	<3%
Flue gas temperature	200 ºC max.	<100 ºC

[1] Conversion based on 0.23 m^3 of evolved combustion gas per MJ of energy.

The only element that has not been tested to date is the soot number. Nevertheless, the low measurement of the opacity in the stack gases and the high combustion efficiency of the process are clear indicators that the process is well within MARPOL requirements.

The nominal feed rate of the process during the study was 163.7 kg/h (6 lb/min), with the composition presented in Table 1. The process was found to be very flexible in terms of accepting a wide range of waste materials. In the pulper only mode of operation, pulp was fed to the mill at 50% moisture content. By comparison, in the shredder only mode, the waste material was significantly dryer (<15% moisture). Because the mill also dries the waste, in addition to pulverizing it, the plasma torch does not have to provide the energy required for vaporizing the water in the waste. As such, the combustion process is not affected by the moisture content of the waste, as is the case with conventional incinerators.

Although the operation of the system meets MARPOL requirements, it was deemed important to estimate the overall combustion efficiency of the process. The combustion efficiency was estimated in two ways. The first method was made based on the comparison of the volatile content of the ash collected after the Venturi scrubber with that of the milled waste fed to the plasma-fired eductor. Loss-on-ignition (LOI) tests at 550 °C were performed on samples of dry ash after the thermal processing process, as well as the milled waste collected after the mill. These results are shown in Table 3.

Table 3. Example of LOI Analysis on Milled Waste and Ash

Type of Material Tested	LOI at 550 ^{o}C
Milled waste	88%
Ash	<3%

The combustion efficiency, based on the reduction in the volatile component, may be calculated using Eq. 1:

$$\frac{LOI_{milled\,waste} - LOI_{ash}\left[\frac{100 - LOI_{milled\,waste}}{100 - LOI_{ash}}\right]}{LOI_{milled\,waste}} \quad \text{(Eq. 1)}$$

Based on this analysis, the combustion efficiency was determined to be greater than 99.6%

The second method used to determine combustion efficiency involved comparing the CO versus CO_2 concentrations (Eq. 2) as follows:

$$\frac{CO_2}{(CO_2 + CO)} \quad \text{(Eq. 2)}$$

The combustion efficiency using this calculation was found to be greater than 99.8%.

4.2 SYSTEM OPERABILITY AND RELIABILITY

To date, the system has operated for over 300 hours and has been shown to require only two operators for consistent operation, one feeding the waste, the other monitoring the control console. The mill, which is the workhorse of this thermal treatment system showed relatively high durability and reliability. The blades of the mill showed some wear during the course of testing and were replaced only once. The blades, presently made of carbon steel, can be made of a harder material to improve durability. The air-cooled liners used in the plasma-fired eductor and combustion chamber performed very well under normal operating conditions. In fact, the liners in the combustion chamber did not require replacement throughout the testing period. The eductor liner failed during non-standard operating conditions and was replaced on few occasions. However, replacement of the eductor liner is a 30-minute operation after which the system is up and running again. The torch electrodes were changed very infrequently and mostly as a precaution. Experience accumulated over the prototype-testing period at PyroGenesis has resulted in a desirable system reconfiguration to further improve the compactness, robustness and ease of maintenance of the proposed commercial system.

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

4.3 SYSTEM RECONFIGURATION FOR SHIPBOARD INSTALLATION

Based on the experience gained during the operation of the prototype Compact Plasma Waste Elimination system, a conceptual design for a commercial shipboard system was developed. The new design was aimed at improving reliability and robustness, increasing compactness and facilitating maintenance. The new design includes a Hopper/Mixer that provides a buffer for at least two hours of storage. The pulper is an optional piece of equipment that may be located remotely, in the galleys where food waste can be pulped and then transported by pipeline to the waste treatment site. The overall footprint, excluding the pulper, is 12 feet by 20 feet, with a height of approximately 8 feet. Because of its modularity and one-deck installation, the system is not only suitable for new ships, but may also be easily retrofitted on existing ships. A layout drawing of the commercial shipboard system may be seen in Figure 4.

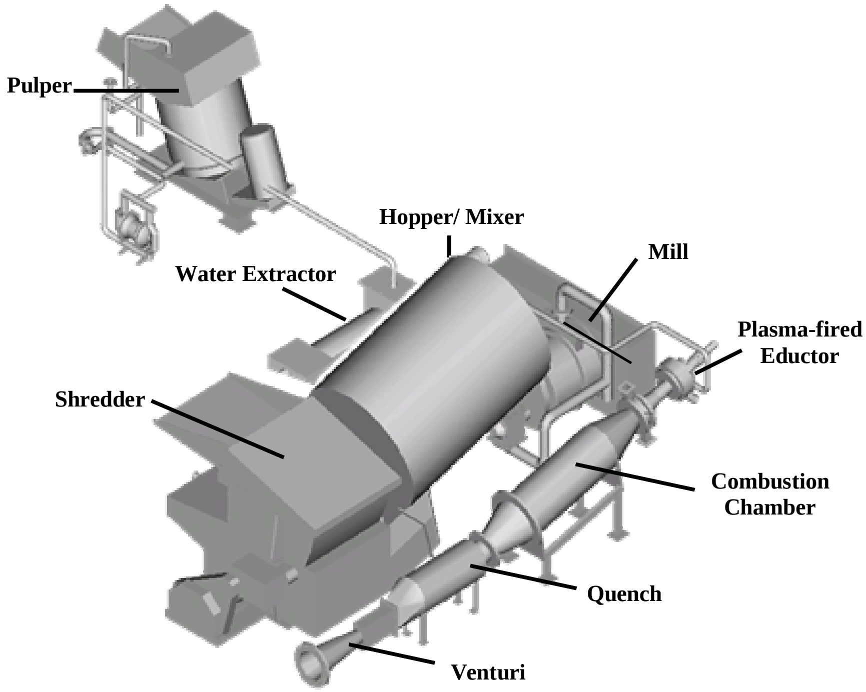

Figure 4: Layout Drawing of Conceptual Shipboard System

5. CONCLUSION AND FUTURE WORK

A Compact Plasma Waste Elimination System has successfully been demonstrated for the treatment of shipboard solid waste. Experimental combustion efficiencies were found to be greater than 99.8% and compliance to MARPOL standards was demonstrated. The system was run for over 300 hours requiring only two operators to feed the waste and run the equipment.

Based on the experienced gained during the demonstration period, a conceptual design of the commercial shipboard system has been developed. It is expected that such as system will be installed on board a ship within the next 18 months for sea trials to assess its operability, reliability and maintainability in a shipboard environment.

Further development is on-going at PyroGenesis to demonstrate the system for other types of waste such as waste oil, oily sludge and concentrated backwater and greywater sludges. The technology presented in this paper is ideally suited for treating combustible waste onboard large ships, such as aircraft carriers and cruise ships (2000-5000 people). Since smaller ships (200-500 people) have similar challenges as large ships with greater restrictions on space, a program to design and demonstrate an ultra-compact system for smaller ships will be initiated in the near future.

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