ESTCP
Cost and Performance Report

(WP-201219)

In-Situ Shipboard Heat Exchanger Cleaning and Maintenance Using Innovative I_2 Bubble Infusion Technology

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ESTCP

ENVIRONMENTAL SECURITY
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COST & PERFORMANCE REPORT
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ACRONYMS AND ABBREVIATIONS

DO	dissolved oxygen
DoD	U.S. Department of Defense
ESTCP	Environmental Security Technology Certification Program
EF	degrees Fahrenheit
HX	heat exchanger
I_2	elemental iodine
I_2CP	I_2 Cleaning Protocol
I_2MP	I_2 Maintenance Protocol
LPAC	low pressure air compressor
mm	millimeter
µg/L	micrograms per liter
mg/L	milligrams per liter
NAVFAC EXWC	Naval Facilities Engineering and Expeditionary Warfare Center
NELHA	National Energy Laboratory of Hawaii Authority
NESDI	Navy Environmental Sustainability Development to Integration Program
NOM	natural organic matter
ppb	parts per billion
ppm	parts per million
psi	pounds per square inch
PVC	polyvinyl chloride
RCRA	Resource Conservation and Recovery Act
R&D	research and development
SDTS	Self Defense Test Ship
TDS	total dissolved solids
TSS	total suspended solids

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I_2 Air Fluid Innovation, Inc. was assisted in laboratory analysis by personnel from:

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Cornell University Ithaca, New York	Provided invaluable microbiological information
DCPAH of Michigan State University Lansing, Michigan	Provided iodine analysis
Heat Research Transfer Institute College Station, Texas	Provided invaluable heat exchange functionality information
Lit Labs West Babylon, New York	Provided metallurgical Scanning Electron Microscopy and spectrographic evaluation
Long Island Analytical Labs Holbrook, New York	Provided water sample testing
Dr. Mohammad Reza Malayeri Institute of Thermodynamics and Thermal Engineering Stuttgart, Germany	Head of fouling and cleaning in process industries

Finally, we would like to thank the Environmental Security Technology Certification Program Office (ESTCP) for providing funding for this demonstration.

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EXECUTIVE SUMMARY

The Department of Defense (DoD) operates vessels that use heat exchangers (HX) to cool ship's operating fluids and gases (i.e., water, compressed air, lubricants, etc.). Many of these HXs use the ocean water as the cooling medium where heat transfer occurs from the service fluid to the cooling water and the cooling water, now warmed, is returned into the ocean. Fouling of these systems reduces the efficiency of the HX, therefore increasing ship's fuel use and the generation of greenhouse gases. If the foul is microbiological in nature, increased corrosion can also lead to significant discharges of heavy metal ions.

Three approaches currently used to address bio-fouling are: no action, chemical/mechanical cleaning, or electro-chlorination. To restore a HX to full performance, it must be cleaned through either mechanical or chemical cleaning or a combination of both. Expensive and time consuming, this process produces a liquid containing high levels of dissolved metals and is normally a hazardous waste regulated by the Resource Conservation and Recovery Act (RCRA). After cleaning, either no action is taken or the system may be maintained through electro-chlorination. In either case, once water enters the HX, the system begins to foul immediately with fouling primarily indicated by both an increase in the temperature drop across the HX as well as an increase in HX inlet pressure.

Halogens (iodine, bromine, and chlorine) have long been used in water purification. Electro-chlorination, currently used by the Navy, is the electrolytic production of sodium hypochlorite from seawater. Unfortunately, recently enacted environmental regulations are challenging the use of chlorination. The elemental iodine (I_2) infusion protocols, demonstrated in this project, strips I_2 from iodinated resin beads using compressed air to form a perfusion of micro and macro bubbles within a fluid for remote disinfection. This patented technology was developed by I_2 Air Fluid Innovation, Inc. The iodinated bubbles interact with the cell walls of microorganisms (bacteria, larvae, etc.) within the fluid or on surfaces providing elemental iodine transfer. Iodine vapor offers a number of benefits including rapid disinfection and iodination of some foulants. The easily integrated infusion device is a safe, cost-effective system requiring little maintenance and energy.

The I_2 infusion process is at the core of two methodologies developed by I_2 Air Fluid Innovation used to retard bio-fouling: the I_2 Cleaning Protocol (I_2CP), and I_2 Maintenance Protocol (I_2MP). I_2CP uses bubbles in conjunction with mild acid or alkaline cleaners to remove existing foul within a HX. It mechanically disrupts foul, forces cleaner through bio-films and re-distributes cleaner to improve foul solubility. Where minerals are the foul and acid is the cleaner of choice, the solution retains low pH through vapor acidification. This allows for the use of milder acid cleaners, and due to bubble perfusion, the need for less volume of cleaner.

This project was completed in three phases: laboratory testing, field testing, and a shipboard demonstration. The overall goal of the project was the rehabilitation of an already fouled exchanger and a reduction in foul progression under normal operating conditions. In the first phase of the project in the laboratory, the team verified that the non-metallic and metallic materials commonly used within shipboard HXs were compatible with the chemicals used during

the I_2 protocols. The project team also verified that the iodinated bubbles did not increase the erosion rate on heat exchanger materials.

In the second phase, the team performed field testing at the National Energy Laboratory of Hawaii Authority's (NELHA) facility in Kona, Hawaii. At this facility, Makai Engineering, a subcontractor to I_2 Air Fluid Innovation, designed, installed, and monitored a device to determine foul retardation and metal erosion rates for five common HX metals using warm Pacific Ocean seawater. Testing was performed both in unlit conditions, emulating the HX interior, and sunlight conditions, fostering the growth of algae. Testing showed that the I_2 infusion process was not inhibitory to algae growth. Although initial qualitative indications showed a reduction in foul formation, numerous performance problems by Makai Engineering resulted in the project team not achieving the intended goals as specified in the Demonstration Plan.

In phase three, onboard the Self Defense Test Ship (SDTS), two identical Low Pressure Air Compressor (LPAC) HXs (Numbers 1 and 2), were used for the demonstration. Both received the I_2CP treatment to form a performance baseline. Both HXs were cleaned on the same day, requiring only 3 ½ hours each without the need for disassembly. Waste was collected and measured for volume and sampled for metal content. The time required and the effluent collected met the performance objectives for the I_2CP.

LPAC No. 1 was designated to receive the infusion protocol, I_2MP. The demonstration was performed over a period exceeding 9 months, with resin cartridges changed approximately monthly. No equipment maintenance was required during the demonstration period. Measurements of the inlet and outlet temperatures and inlet pressure readings were recorded on calibrated ship's gages. Water samples were periodically obtained to measure metallurgical elution and sublimation of iodine.

Although the project team had asked that each exchanger be used 50% of the time, in actuality, LPAC No. 1 was in use approximately 85% of the time. As expressed by the crew, typically this exchanger would have been cleaned every 3 to 6 months. At the end of the demonstration, the temperature and pressure parameters were still within the acceptable range. Water sampling indicated low metal and iodine levels within the effluent. LPAC No. 1 metal ion elution did not vary greatly whether the system was infusing or not.

At the end of the demonstration period, the LPAC units were disassembled and viewed for foul progression. The units were re-assembled and had an I_2CP performed using an acidic cleaner. The effluent from each was analyzed for Total Suspended Solids (TSS), Total Organic Carbon, and Total Dissolved Solids (TDS) as well has Ti, Cu, Ni, Zn, and Pb content before and after the cleaning. The inspection showed that the tubes were relatively clear of solidified foul. The cleaning solutions for both HXs indicated less metal elution than with normally used Navy cleaning procedures.

Unfortunately, this project did not result in a definitive clear indication of success. The fact that the LPAC No. 1 exchanger was used 85% of the time meant the control HX saw very little use. Ideally, the demonstration would have been continued until such time that the ship needed to perform a HX cleaning. Because the ship normally cleans the exchangers every 3 to 6 months,

the project team was able to show that use of the I_2 bubble infusion technology did achieve the most important goal of extending the period between cleanings by 50%.

Even with the limited indication of success, two follow-on Navy demonstrations of this technology have been initiated. The technology is undergoing study at the Undersea Naval Warfare Center in Newport, Rhode Island, as a hull foul retardant in conjunction with air bubble curtains. In addition, the protocol is under study at Pearl Harbor Naval Shipyard to prevent bio-fouling in a submarine salt water heat exchange support system that is used both pier side and in dry-dock. For this application, the I_2 technology would replace an existing electro-chlorination system. Although not approved at this time, the project team's technology integration plan includes working to get the technology demonstrated on a Navy combat ship with the demonstration period long enough to determine how long the I_2 technology can extend the period between HX cleanings.

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1.0 INTRODUCTION

1.1 BACKGROUND

The Department of Defense (DoD) operates vessels that use heat exchangers (HX) to cool ship's operating fluids and gases (i.e., water, compressed air, lubricants, etc.). These HXs primarily use ocean water as the cooling medium. This water is pumped through the exchanger where heat transfer occurs from the service fluid to the cooling water. The cooling water, now warmed, is returned into the ocean. As the cooling water moves through the exchanger's tubes or plates, microorganisms, organics, and minerals attach to the heat transfer surfaces and form fouling beds or bio-films. Water environmental conditions such as temperature or nutrients can accelerate fouling within the exchanger. Fouling not only reduces the efficiency of the unit, but also can cause complete failure.

Typically, fouling of HX devices onboard DoD vessels is addressed in one of three ways: (1) no action, (2) reactively through acid washing or mechanical cleaning, and (3) proactively through electro-chlorination. Each has impact concerning cost, mission readiness, energy use, and environmentally through greenhouse gas production, and the formation of hazardous byproducts. This project primarily addresses environmental problems associated with acid cleaning and foul prevention of shipboard HXs. During cleaning operations, in addition to removing the fouling materials, the acids also dissolved some of the HX metal. During a Navy evaluation (Ye et al., 2009), it was found that the liquid waste from acid cleaning had a concentration of 2000 parts per million (ppm) Cu, 800 ppm Ni, and 100 ppm Zn. This waste also had a pH of less than one. Depending on the size of the HX, these types of cleanings can result in the generation of thousands of gallons of hazardous liquid waste that is regulated by the Resource Conservation and Recovery Act (RCRA). This waste normally costs from $2 to $12 per gallon for disposal. Thus, the total cost for a HX cleaning can easily exceed $100,000.

On a few DoD vessels, to prevent fouling in HXs, over-chlorination is used, which results in free chlorine release into the ocean. Free chlorine may present a problem in that it can affect photosynthesis of marine organisms. At present, the Clean Water Act limits chlorine release within 200 nautical miles of shore to between 7.5 and 13 parts per billion (ppb). Proposed standards as part of the Uniform National Discharge Standards may further limit release within 12 nautical miles of the United States shoreline. The current standard chlorine dosing level for Navy ships is 200 ppb for 2 hours a day as a minimum to control bio-fouling (Fallis et al., 2002).

To improve the service life of DoD ship HXs, this project demonstrated the suitability of the innovative I_2 bubble infusion technology. This technology, a proprietary product of I_2 Air Fluid Innovation, Inc., is a safe, effective, easy to implement, and cost-effective method of reducing the fouling rate, as well a method to clean fouled HXs in a marine environment. The core technology is the patented iodine infusion method (U.S. Patent# 7,329,385) that reduces microbial counts within a fluid, an air stream, and vessel using elemental iodine (I_2) vapor infusion. It uses a low volume I_2 vapor eluted from iodine coated resin beads in an air stream to deliver the vapor via bubbles to remote sites for microbial interaction. This provides a targeted disinfection without the need for treating the entire water volume through repetitive bubbles/microbe or surface interaction. This demonstration showed that the I_2 bubble infusion technology can increase the period between cleanings while maintaining system efficiencies.

Additionally, the project showed that infused iodine bubbles as part of an in situ cleaning method, reduces cleaning time, the generation of acidic liquid waste, and HX maintenance costs.

This technology was successfully demonstrated to both clean and protect a shipboard HX on the Self Defense Test Ship (SDTS), for example the USS Paul F. Foster, home ported at Port Hueneme, California. Specifically, two of the ship's HXs were used for the demonstration. Prior to the actual demonstration, material compatibility testing was performed using materials normally found on DoD operated vessels. This testing was performed both in the laboratory and using ocean water at the National Energy Laboratory of Hawaii Authority (NELHA) facility located in Kona, Hawaii.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objective of this demonstration was to validate the safety, effectiveness, ease of implementation, and cost savings of the I_2 bubble infusion technology as a means to significantly reduce the fouling rate within a functioning HX in a marine environment. The project team also intended to show that I_2 bubble infusion technology when used onboard a ship as part of a cleaning protocol can significantly reduce the overall cleaning cost as well as the generation of hazardous wastes. These demonstrations were performed on a full scale HX onboard a retired Navy warship that is now operated as a Navy test ship. As part of the demonstrations, it was shown that the I_2 bubble infusion technology offers environmental, safety, and occupational health benefits as compared to the existing acid cleaning method.

1.3 REGULATORY DRIVERS

The primary environmental driver for implementing the I_2 bubble infusion technology is to reduce the generation of RCRA hazardous waste during HX acid cleaning operations. Depending on the operating tempo and location of the ship, HX cleaning operations can occur at frequencies of a few months or longer. In addition to this concern, another important issue is that a fouled HX reduces performance and thus increases energy consumption to operate the ship. This higher energy consumption results in more air pollution as well as greenhouse gas emissions (Casanueva-Robles and Bott, 2005). Currently, DoD vessels do not have air pollution emissions standards; however, the DoD has strict requirements to improve their energy efficiency.

2.0 DEMONSTRATION TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

This project demonstrated a patented iodine infusion technology (see Figures 1 and 2) that reduces the fouling rate and can be used to help clean ship's HXs. The I_2 bubble infusion technology reduces microbial counts within a fluid, an air stream, and vessel using I_2 vapor infusion. It uses a low volume I_2 vapor eluted from iodine coated resin beads in an air stream to deliver the vapor via bubbles to remote sites for microbial interaction. The technology provides a targeted disinfection without the need for treating the entire water volume through repetitive bubbles/microbe or surface interaction. The antimicrobial, mechanical, and thermodynamic properties of the iodinated bubble are the basis of two protocols using I_2 infusion: the I_2 Maintenance Protocol (I_2MP), and the I_2 Cleaning Protocol (I_2CP). The I_2MP prevents or reduces future fouling through the infusion of iodinated bubbles into the water stream supplying the heat exchanger during operation. The I_2CP is performed within an off-line HX without the need for disassembly with the I_2 infusion serving as a means help detach the foul.

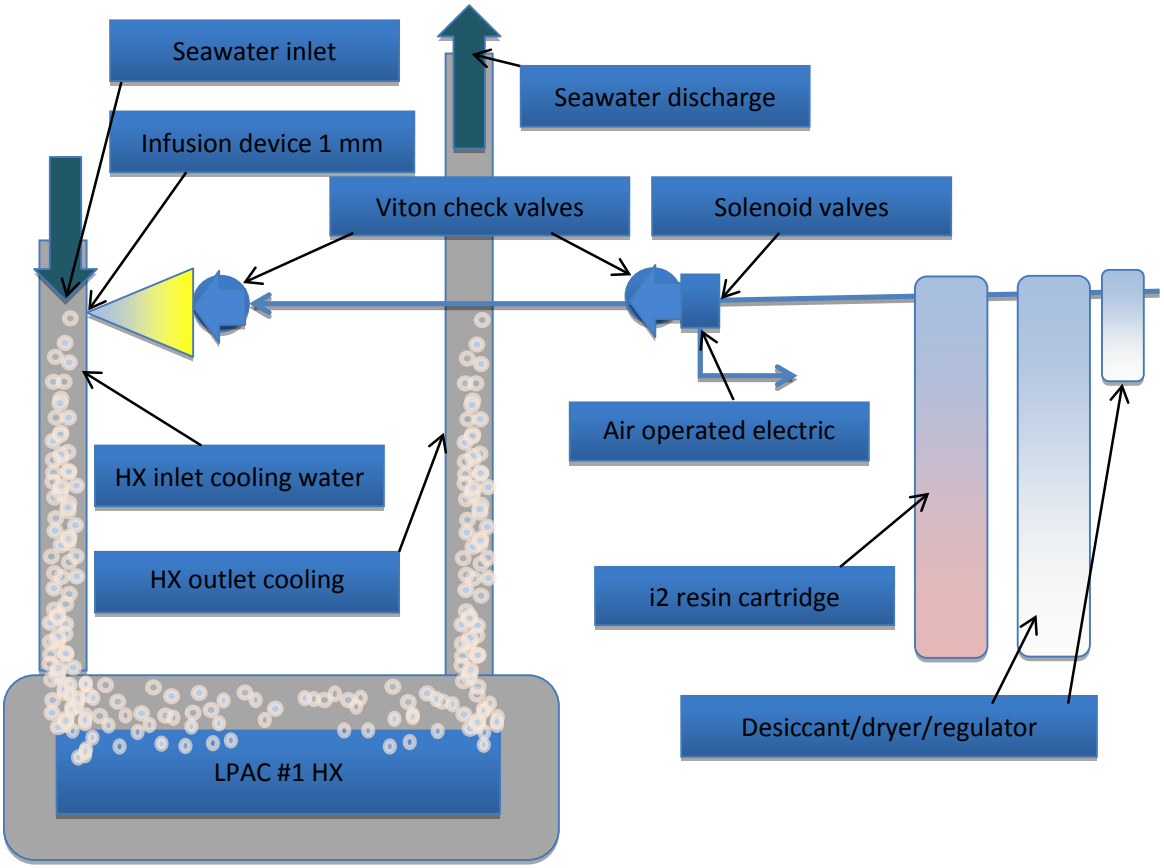

Figure 1. I_2 bubble infusion schematic.

Figure 2. I_2 bubble infusion device.

This device is used to directly transfer iodinated air into the HX at a predetermined duration and frequency. It receives compressed air from an air source and regulates it to correspond to 10 to 20 pounds per square inch (psi) over existing HX pressure conditions. This allows for air infusion into the water stream and prevents back flow from the exchanger. The infusion device removes moisture from the air that may hamper iodine resin elution. The air is then passed through the resin cartridge, which contains the iodinated resin. The cartridge system is designed to warm the air entering the resin bed to increase elution. These cartridges also contain Viton check valves. Once the air leaves the resin cartridge, it flows through a nozzle into the HX.

Elemental Iodine, which does not normally occur in nature, is a natural antimicrobial. Iodine does, however, naturally occur as the highly water-soluble iodide I^- ion. Iodine has long been used for water disinfection (Backer and Hollowell, 2008) and is a member of the halogen group, which includes bromine, fluorine, and chlorine, all known antimicrobials (Prescott et al., 2002). Iodide is primarily found in oceans, brine pools, plants, and the atmosphere just above the ocean surface. Iodine disinfection is a form of chemical sterilization in which oxidation of cell constituents and the halogenation of cell proteins occurs.

The innovative I_2 bubble process transfers I_2 vapor from resin surfaces via an air stream into a bubble perfusion to remote sites within a fluid for microbial inactivation. Iodine vapor remains trapped within the bubble and interacts with protein in the cell wall converting to iodide. The repetitive exposure of iodinated bubbles provides enhanced inactivation of the microbe. The pH, turbidity, and temperature of the water are less of a concern because the I_2 is contained within the bubble. As a result, there is little sublimation into the fluid itself, reducing biocide residue.

The I_2 infusion is used as part of both the I_2CP and I_2MP. The I_2CP cleaning method uses iodinated air and appropriate cleaner as part of an in situ method to eliminate the foul within HXs. The I_2CP method eliminates the need to break down the exchanger. Although cleaning in place methods have been available, they merely re-circulate the cleaner throughout the exchanger. The I_2CP method uses a cleaner suited for the foulant but imparts it in a way that reduces cleaning time and cleaner volume. After introduction of the cleaner into the exchanger, the timed bubble infusion occurs. The iodinated air agitates the cleaners as well as provides

reverse flow, pressurization, and disruption of fouling beds. Using iodinated bubbles to continually foam the cleaner has the added benefits of reducing the quantity of cleaner needed and reducing waste. The protocol can take between 3 to 8 hours with only limited staff intervention.

The I_2MP prevents or retards bio fouling on exchanger surfaces to increase the duration between cleanings as well as maintain system functionality. Bio-fouling occurs when water that contains salts, minerals, and bio-fouling species enters the exchanger and flows over a surface. The salts and minerals through sedimentary forces come out of solution and adhere to the warm surface. This can occur due to the slower, less turbulent water near the surface. Warmer surfaces can induce a condition known as inverse solubility whereby minerals precipitate out of solution in a warm environment. Once attached, the minerals form a rough surface that provides a platform onto which microbes can attach. Planktonic (free-floating) microbes and larvae can adhere to this mineral formation and begin attachment through the excretion of sticky substances. Once established, the microbes exude polysaccharides for protection. These immature bio-films act as a means to protect the young multiplying bacterial colonies. Once shielded from water buffeting, the microbes colonize rapidly and may form with other species to establish a robust bio-film, drawing nutrients and gases from the water while being protected from biocides. While the bio-film is forming (see Figure 3), the microbes use nutrients as food source and excrete organic enzymes that are corrosive to the plate surface on which they reside. This can cause pitting, roughness, or complete failure to the integrity of the plate. All the while, the bio-film is thickening and extending into the water path of the exchanger thereby reducing the flow space. This causes surface friction and diminishes the speed and volume of the water moving through the exchanger. Additionally, the polysaccharides and organic materials of the bio-film, including the microbes themselves, have a very low thermal conductivity factor effectively causing them to become insulation, thus inhibiting heat transfer.

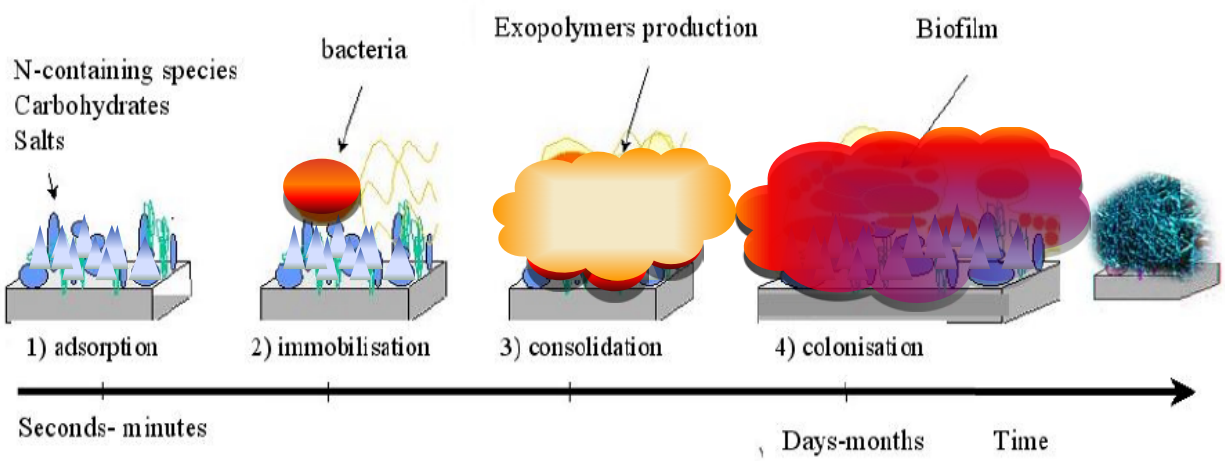

Figure 3. Foul formation.

The I_2MP method (see Figure 4) uses a timed infusion of iodinated air bubbles to prevent or reduce continued fouling. It does not require system disassembly; instead it treats HX systems chronically rather than acutely. The flow of iodinated bubbles introduced into the exchanger supply water disrupts immature fouling formations thus preventing hardened foul layers. At a predetermined time, a flurry of iodinated bubbles sweeps through the water pathways. It lifts and

dislodges newly attached microbes and larvae before they have a chance to attach securely. In addition, the repeated exposure to I_2 vapor inactivates those microbes securely attached. The infusion of bubbles mechanically lifts minerals not securely attached as well and disrupts any sedimentation. This occurs a number of times a day to prevent formation. Although it may not completely prevent foul formation, it will reduce its advance and reduce the bio-burden present, thereby increasing the time between cleanings. A timer infusion device controls the iodinated air flow. The cartridge containing the iodinated resin connects to the exchanger via the HX drain valve. The air used for infusion can come from any compressed source. The amount of iodine eluted is controlled by the cartridge size and air speed. The duration and pressure is controlled by the I_2 Infusion Device, which allows for I_2 vapor distribution at prescribed intervals and pressure. With I_2 infusion, it has been shown that only grams of iodine per month are needed for a typical HX.

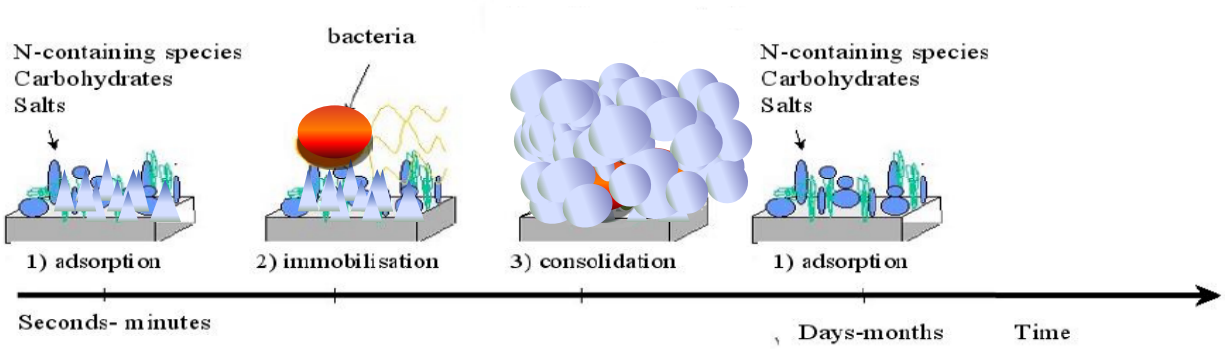

Figure 4. Foul disruptions with I_2 infusions.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Currently, the majority of DoD operated ships do not have a specific shipboard system to maintain HX performance. Some DoD ships do, however, have a shipboard electro-chlorination system to maintain performance. Regardless of the existence of shipboard systems, periodically the exchangers are taken out of service and cleaned by an expensive mechanical or chemical cleaning method. This work is almost always performed with the ship in port. The period between cleanings depends on the ship's operating tempo and area of operation. Those ships operating in warm water require more frequent cleaning. For DoD ships without chlorination systems, the primary advantage of using the I_2MP is that it can extend the period between HX cleanings.

The electro-chlorination process is similar to the I_2MP, but has significant cost, logistics, and environmental issues that make it less than an ideal solution. In this process, sodium hypochlorite is generated by the conversion of salt-water through direct current exposure and then the sodium hypochlorite is transferred into the salt-water stream upstream from the HX. Typical chlorine dosing is 200 ppb for 2 hours each day. Unfortunately, this dosing can result in chlorine discharges well above the seawater discharge limit set by the Clean Water Act. The I_2MP, on the other hand, discharges iodide and iodates; chemical compounds without discharge limits that are commonly found in seawater and kelp.

Both chlorine and iodine will react with natural organic matter (NOM) in seawater. These side reactions consume the active biocide available to kill bacteria. The reaction between NOM and chlorine also form disinfection by-products such as trichlorohalides, a significant environmental issue. Because chlorine reacts with NOM three times faster than iodine, its biocidal activity is quickly reduced in turbid waters.

Another fundamental difference between chlorine and iodine is their ability to promote corrosion of the applicable piping systems. Chlorine has an oxidation potential of -1.36, whereas iodine has an oxidation potential of -0.5. Therefore, chlorine has an increased corrosion effect over iodine.

As for equipment maintenance, the I_2MP equipment offers clear advantages. Electro-chlorination systems require cleaning of the electrolysis cells by acid washing. Typically, this washing is required once every 2-4 weeks for a period of approximately 2-4 hours. The I_2MP equipment, on the other hand, requires no maintenance other than a periodic cartridge change. All functions occur automatically; no cleaning or maintenance is required. Electro-chlorination does, however, have significant maintenance requirements including replacing anodes and gas filtration devices.

The physical size and electrical requirements are also significant problems for the electro-chlorination technology. This technology has a large footprint and depending on its capacity, may require over 100 square feet of floor space. The I_2MP equipment, however, only requires a 3 by 4 foot space on the wall or floor and a single unit can satisfy up to three exchangers. Electro-chlorination requires a fair amount of energy for sodium hypochlorite production and distribution. The I_2MP requires only a 115-volt, 15 amp connection for 120 minutes a day and compressed air supplied at 10 psi over HX system operating pressure at 1-3 cubic foot per minute, depending on the HX cooling water volume.

Regardless of the type of maintenance or lack thereof, all shipboard HXs will require periodic cleaning. Larger and inaccessible HXs are mostly cleaned using highly acidic cleaning solutions. Besides removing the marine fouling, these solutions can strip heavy metals from piping surfaces creating thousands of gallons of RCRA hazardous waste. This cleaning process can also require a significant number of technicians (3+) and man-hours (2 days) to perform.

The I_2CP offers a better alternative because it requires less labor and chemicals. In addition, it uses weaker acids that are safer for the workers. Through vaporous iodine infusion, the pH of the I_2CP cleaner is maintained, thus allowing for the use of weaker acid as well as reduced volume of acid. This reduction results in a significantly smaller and less hazardous waste stream, potentially saving thousands of dollars per cleaning. The I_2CP is also expected to be completed in a shorter time than the current cleaning procedures.

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3.0 PERFORMANCE OBJECTIVES

Table 1. Performance objectives.

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Iodine concentration in HX discharge water	Laboratory chemical analysis report	Total iodine concentration no greater than 200 ppb above seawater baseline*	Total iodine concentration was 30 ppb above seawater baseline during infusion.
Improve performance of HXs as a result of implementing the I_2CP	• Change in HX seawater inlet pressure as a result of the cleaning process • Change in temperature gain across the HX as a result of the cleaning process	• Reduce operational pressure • Reduce operational temperature gain	No changes in operational pressure or temperature gain were observed with the test and control HXs. Therefore, the results are inconclusive. Because the HXs were relatively clean at the time of the cleaning, this is not unexpected.
Improve performance of HXs as a result of implementing the I_2MP	• Maintain HX seawater inlet pressure compared to the control HX • Change in temperature gain across the HX as a result of the cleaning process	• Maintaining or decreased rise in operational pressure compared to rise in the control HX • Maintaining or decreased heat transfer compared to the control HX	The test and control HXs had similar temperature and pressure results even though the test HX was operated about six times as long. Previous practice suggests that this would result in at least a 50% increase in time between cleanings.
Qualitative Performance Objectives			
I_2MP Ease of use	Feedback from ship's system operators	Minimal operator input required	Ship's crew indicated no malfunction of the system due to I_2 infusion and no maintenance required by the crew.

* 200 ppb is the standard dosing rate for Navy chlorination systems

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4.0 SITE/PLATFORM DESCRIPTION

4.1 TEST PLATFORMS/FACILITIES

Prior to initiating the shipboard demonstration, pre-demonstration testing was completed at the NELHA located in Kona, Hawaii. NELHA is home of the National Defense Center of Excellence for Research in Ocean Sciences, a State of Hawaii agency administratively attached to the Department of Business, Economic Development and Tourism. Its purpose is to support DoD technology requirements; encourage leading edge Research & Development (R&D) in ocean sciences and technology in Hawaii; foster use of ocean R&D facilities in Hawaii; provide an interface between specialized small businesses with expertise in ocean related R&D, and DoD users of advanced technology; and develop avenues to ocean science expertise and facilities at the University of Hawaii. This facility was chosen for the testing because of the availability of warm ocean water and because it is a fully equipped and staffed research facility. This project used the staff from Makai Engineering, Inc., an ocean engineering and naval architecture company that was responsible for test sampling and cartridge changes. The project team was only required to start-up the test apparatus. They were not required to be on site during the whole testing period.

At the NELHA facility, the team tested the I_2MP using tubes made of clear plastic containing commonly found HX materials to simulate those found onboard DoD operated vessels. This assembly was situated in a dark room to help foster the growth of bio-slime. Warm Pacific ocean water was used for all the testing. Generally, the HX fouling rate is a function of water temperature, nutrient content, surface roughness due to mineral formation and flow rate; thus, the warmer the water, the higher the fouling rate. This facility provided warm, nutrient water at a relatively low flow rate. At NELHA, the team measured the fouling rate with the technology operating at the proposed shipboard Iodine infusion rate of 5 minutes every hour. The project team also performed a control test without infusion. The goal was to determine the fouling rate both with and without infusion on both the clear plastic surface and the varied materials found in HXs. Other pre-demonstration tests included compatibility testing of the I_2 bubble infusion technology with metallic materials commonly found in DoD shipboard HXs, confirmation of the presence of bio-fouling microbes as well as measurements of Iodine, pH, and dissolved oxygen discharges into the ocean water. To determine if iodine infusion had a detrimental effect on algae growth, a key constituent in the ocean's food chain, an identical assembly was operated in sunlight.

The shipboard demonstration consisted of two parts, a dockside cleaning and an operational demonstration. Testing was performed on two low pressure air compressors (LPAC) HX on the SDTS, Spruance Class destroyer ex-PAUL F. FOSTER. This ship is home ported at Naval Base Ventura County located in Port Hueneme, CA. It was selected for the demonstration because of its local homeport, the existence of typical DoD ship HXs, and the ship's status as a research vessel thus simplifying the approval process. For the cleaning demonstration, two identical LPAC salt-water HXs that are typical of those found on numerous DoD ships were cleaned using the I_2CP.

For the I_2MP demonstration, LPAC No. 1 was used, with LPAC No. 2 used as a comparison baseline. The equipment was installed onboard the SDTS and left in place for over 9 months.

During this test period, the ship operated in its normal pattern, coming and going from its Port Hueneme homeport. Because of factors out of the control of the project team, unfortunately, LPAC No. 1 was in service much more than LPAC No. 2 during the demonstration period.

4.2 PRESENT OPERATIONS

The DoD operates numerous ships that employ salt-water HXs. Currently, there are approximately 280 Navy combat ships, plus a number of Army and Coast Guard ships, with a number of exchangers per ship. Onboard ship, the size and purpose of the varied HXs are many. Typically, shell and tube designs are used, but plate and frame may be used as well. To maintain the HX, common practice is to take the exchangers off line with the ship dockside. Seawater HXs onboard ships and submarines develop layers of foul, which makes them less effective during normal ship operations. Removing foul using traditional methods is labor intensive and exposes the workers to hazardous materials. The acid flushing process can generate thousands of gallons of hazardous waste from each cleaning, places the workers at risk from handling acids, requires considerable personal protective equipment, and generates significant waste disposal costs.

HXs may also be cleaned through disassembly and mechanical cleaning. This method requires considerable labor and time. Once opened, the technicians use mechanical scrapping and/or an acidic cleaner solution to remove foul from the tube surfaces. This exposes the technician to not only the caustic cleaners but also the bio-foul and sharp edges of the exchanger. Additionally, mechanical scrapping erodes exchanger surfaces and disassembly may damage gaskets and exchanger components.

The salt-water environment primarily drives the frequency of cleaning. Generally, ships stationed in warmer waters (i.e., Persian Gulf, Pearl Harbor, etc.) require more frequent HX cleanings. Regardless of the cleaning method, fouling remediation is a costly operating problem that accounts for a significant portion of the ship’s maintenance budget in costs for man-hours, cleaners, and waste handling.

4.3 SITE-RELATED PERMITS AND REGULATIONS

For the pre-demonstration testing, the project operated under all host site permits and regulations at the NELHA. The project team was not responsible to obtain any additional permits. For the shipboard demonstration, no change to the existing water discharge permit was required. The federal Clean Water Act does not cover a discharge of Iodine into the ocean. The team did show, however, that during the testing on board the SDTS, all iodine discharges were below the Navy chlorine dosage limit set at 200 ppb. In the future, no environmental permits are expected to be required to implement this technology on DoD operated combat vessels. Disposal of the collected liquid acid cleaning solution waste is, however, regulated as a RCRA hazardous waste.

5.0 TEST DESIGN

The technical aspects of this project were completed in the three steps described below.

The first phase of testing ascertained the compatibility of the protocols on typical DoD shipboard HX materials. At the I_2 Air Fluid Innovations, Inc. facility located in Huntington Station, New York, materials commonly found in DoD marine HXs, both metallic and gasket materials were subjected to I_2CP and I_2MP. The purpose of this effort was to determine if the processes had any detrimental effect on these materials. Coupons of the metallic materials shown in Table 2 were subjected to a 4% by weight concentration of the acidic cleaner specified for the I_2CP.

Table 2. Tested DoD HX materials.

Metals Alloys	Non-Metal Materials
Hastalloy 276	Blue Guard
Copper Nickel 90/10	EPDM
Brass	N Butyl
Stainless Steel 316	Viton
Titanium Grade 2	

The coupons of the metallic materials were suspended in the acidic cleaner and infused with iodinated vapor mimicking the intermittent infusion agitation that occurs during the I_2CP protocol. A composite test using all the metals in one bath was performed to emulate conditions within a HX piping system where multiple metals in an acidic solution may react differently from a single metal sample exposure (i.e., galvanic reaction). The ratio of metals to cleaner was set to approximate what would be expected to be found within a HX. The cleaning solution was tested both before and after infusion exposure for Cu, NI, Zn, Pb, and Ti heavy metals.

Coupons of commonly found non-metallic materials, also shown in Table 2, were subjected to an 8% by weight concentration of the acidic cleaner, which is twice the concentration specified by the I_2CP. This produced a cleaning solution pH value similar to the current DoD cleaning procedures. This higher concentration was used for this testing because previous testing with gasket materials at normal concentration of 4% showed minimal gasket material changes. For this testing, the test procedure was the same as for the metallic coupon testing except for the acid concentration. The cleaning solutions used with the non-metallic components were tested both before and after infusion exposure for TDS.

The coupons of these non-metallic materials were also exposed to a 24 hour continuous infusion of iodinated bubbles while immersed in 76 degrees Fahrenheit (EF) seawater with 40 grams per liter of salt concentration. For this test, the iodine vapor elution was set approximately 50% greater by warming the resin to 97EF. The coupons were also exposed to bubbled ambient air for the same period and under the same water conditions. The fluid volume for each was checked for total dissolved solids (TDS) and total suspended solids (TSS).

Also at the I_2 Air Fluid Innovation facility, coupons of the metal materials noted in Table 2 were subjected to direct bubbling under pressure. The purpose of this testing was to simulate the I_2MP to verify that the bubbling action did not lead to erosion of the metallic HX materials. For this

testing, a coupon of each metal was held within a warmed 75°F saltwater bath. Iodinated air was directed at a single point on the coupon surface through a 1 millimeter (mm) nozzle held 1.5 inches from the surface. The coupon was angled to provide a sliding bubble contact after impact, as the bubbles would rise. One-half of the contact point was masked in plastic to provide a comparison between exposed and unexposed surfaces. A warmed I_2 cartridge was used to provide excessive iodine vapor within the bubble.

Each coupon was exposed to 6 hours of continuous airflow. At the completion of the testing, each coupon was tested by Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy. A cross sectional metallurgical evaluation at the contact point junction between the exposed and unexposed areas was also performed.

In the second phase of testing, warm seawater at the NELHA, Kona, Hawaii facility was used to determine whether I_2 infusion has a retardation effect on foul formation. Additionally, HX material compatibility to I_2 infusion was tested under conditions that more closely matched shipboard conditions as well as iodine output in effluent water during infusion. For this test, warm, nutrient rich, surface water was used for its ability to rapidly cause bio-fouling. Makai Engineering designed, assembled, installed, and monitored the study assembly as well as collected samples. Two assemblies were installed at the site. One was outdoors in full sunlight to help support growth of algae within the tubes while the other was indoors in darkness to help promote bacterial bio-film growth. The outdoor assembly was used solely to determine if iodine infusion had a detrimental effect on algae growth. The indoor assembly most emulates the conditions found within a heat exchanger. Although prevention of bio-films is important to the success of this technology, it is also important to ascertain that the protocol does not hamper growth of algae, an important component in the ocean's food chain.

The test assemblies consisted of one of six different metallic samples contained within a clear polyvinyl chloride (PVC) pipe with pump-fed water entering from the bottom and flowing out the top. The flow rate was slow (12 gallons per minute) to stimulate foul formation. Each tube was 1 inch in diameter and clear for observation. The indoor test assembly had five of the six tubes infused using the I_2MP. The infused and non-infused tubes were compared for foul rate, and tested for iodine discharge content, metal ion elution, pH, and dissolved oxygen (DO) content. The sample coupons within the infused tubes are the metallic materials identified in Table 2. The non-infused tube contained a Titanium Grade II sample. The tube assembly was designed to provide maximum elution of metals within the center of the tube and foul formation on the inner walls of the tubes. Because all surfaces within a HX that may be subject to bubble infusion are not linear, coiled CuNi 90/10 tubing was used to determine if angled bubble impact has a greater metal elution potential.

The third phase was under a field trial condition onboard a functioning ship, the SDTS home ported in Port Hueneme, California. The I_2CP was demonstrated to determine its efficacy. The I_2 infusion device was integrated into the system to determine ease of use. Hazardous waste generation from the I_2CP was determined under real life conditions. The I_2MP was demonstrated onboard to determine efficacy of the protocol to reduce the fouling rate. Inlet pressure and temperature drop comparisons to an unprotected HX were used to determine economic benefit. Lack of maintenance and minimal staff intervention were used to determine ease of use.

For the shipboard demonstration, the HXs supporting LPAC HX No. 1 and No. 2 were selected (see Figure 5). Both HXs were cleaned using I_2CP while only the No. 1 HX was maintained using I_2MP. The LPAC No. 2 HX served as a control. All significant events, including the cleaning operations and the installation of the I_2MP equipment, were timed in order to determine ease of implementing this technology.

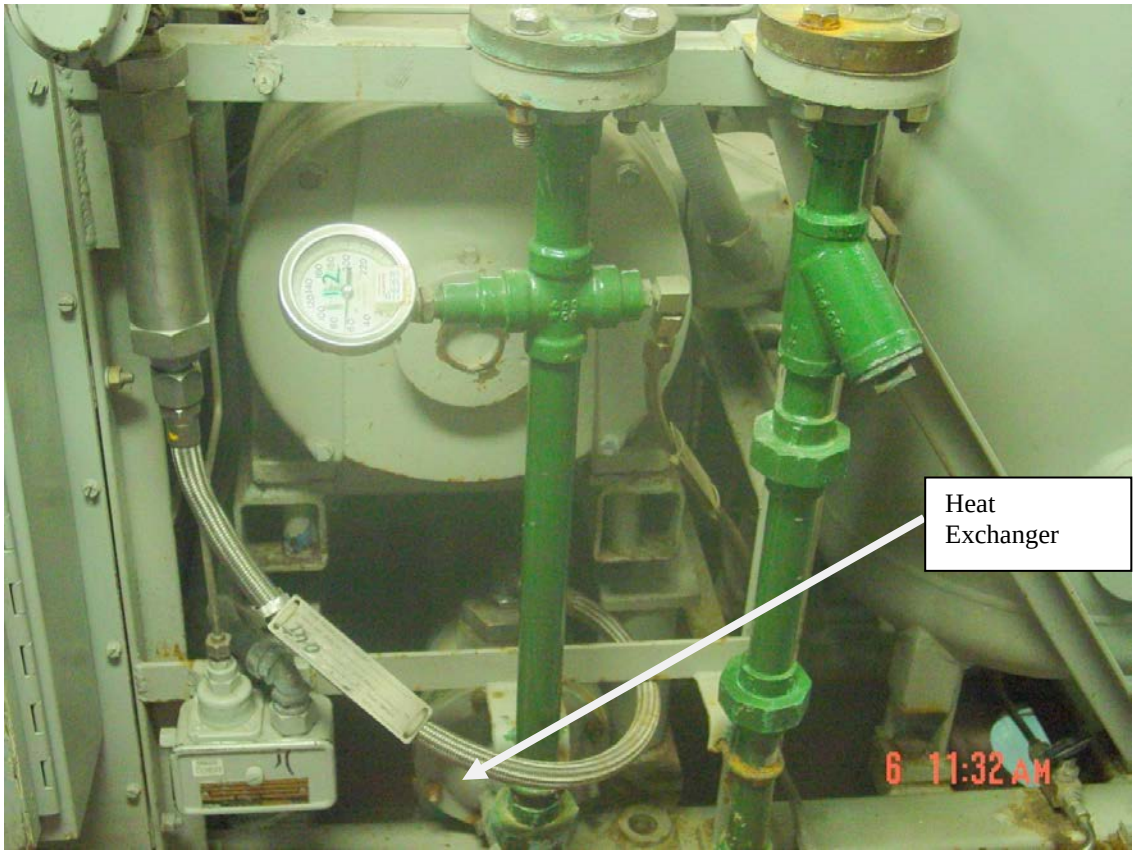

Figure 5. LPAC No. 1 HX.

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6.0 PERFORMANCE ASSESSMENT

In this section, the results are broken down into three parts. In the first part, laboratory results are discussed. This testing was primarily conducted to verify that the I_2 bubble infusion technology had no detrimental effects on materials commonly found in Navy shipboard HXs. The second part provides results from the NELHA testing. This work had four functions: 1) to qualitatively demonstrate the difference in the warm seawater fouling rate between an infused and non-infusion tube; 2) to qualitatively verify that I_2 infusion does not harm seawater algae; 3) to verify that infusion does not result in an increase in the metal erosion rate; and finally, to verify that the I_2 kills bacteria that can cause foul formation. The final part discusses the results from the shipboard demonstration. In this part, the project team repeat the metal erosion and bacteria kill testing. The project team also provide the results using ship's temperature and pressure gage measurements to indirectly show the difference in fouling between the infused HX and an identical control shipboard HX.

In Table 3, the results from the laboratory cleaning fluid testing as described in Section 5 are presented along with results from samples taken using an existing Navy acid cleaning procedure for fouled HXs. From the table, it is clear that the use of the low strength acid specified by the I_2CP has resulted in significantly lower concentrations of Cu and Ni than those commonly found using the existing procedure. The Zn concentration is greater; however, Zn normally has a much higher discharge limit so it is not normally the controlling factor for discharge. It is also clear that use of the I_2CP chemicals did not result in the degradation of non-metal materials commonly used in shipboard seawater systems as indicated by a minimal change in the TDS and no change in TSS concentration in the cleaning fluid. Together, these results confirm that the I_2CP is compatible with existing shipboard systems and its use will result in a less hazardous waste as compared to current acid cleaning procedures.

Table 3. Cleaning fluid comparisons.

Measured Items	Concentration in Fluid Before Cleaning	Concentration in Fluid After Cleaning Using I_2 Chemicals	Concentration in Fluid After Cleaning Using Existing Navy Cleaning Procedure*
Copper	130 µg/L	650 µg/L	2,000 µg/L
Lead	15 µg/L	68 µg/L	
Nickel	20 µg/L	130 µg/L	800 µg/L
Titanium	50 µg/L	50 µg/L	
Zinc	50 µg/L	250 µg/L	100 µg/L
pH@ 4% by weight	<2	<2	N/A
TDS	37,200 mg/L	37,000 mg/L	N/A
TSS	46.5 mg/L	46 mg/L	N/A
pH@ 8% by weight	0.86	0.85	N/A

*Values are from Reference 1
µg/L = micrograms per liter
mg/L – milligrams per liter

In regard to the iodine vapor perfusion metallic coupon bench testing described in Section 5, there was little to no erosion produced at the impact point where the iodinated bubbles interacted with the metal coupons. Comparison between exposed and unexposed sites indicated little to no surface changes. The non-metallic coupons similarly indicated little material disruption. Total dissolved and suspended solid testing indicated little change.

Unfortunately, the testing results from the NELHA facility were not as complete as the project team had originally outlined in the Demonstration Plan. The test program had to be restarted several times. All of the problems occurred because Makai Engineering did not adequately design nor monitor the testing.

After initiating the testing in September 2012 and running continually for only 2 months, the indoor test assembly water flow rate was found to be at an unacceptable low level, below what would be expected in a Navy shipboard HX. To correct this problem, flow to the outdoor assembly was discontinued, the indoor test assembly was completely cleaned, and the indoor testing restarted on November 25, 2012. During this test period, the team did confirm that the I_2 infusion did not appear to retard algae growth in the outdoor test assembly as shown in Figure 6. The project team also confirmed that even with an inadequate water flow rate, visual indications showed a reduction in bio-fouling (see Figure 7 and 8) in the infused tubes. Unfortunately, subsequent to November 2012, Makai was unable to maintain the system within the specified test parameters that matched the expected shipboard conditions.

Although the initial testing results, as indicated on Figures 6, 7 and 8, showed positive results for the infused tubes as to foul retardation and algae non-inhibition, problems first occurring in November 2012, made all subsequent data suspect.

Figure 6. Algae growth in outdoor infused tubes.

Figure 7. Bio-fouling in indoor un-infused tube.

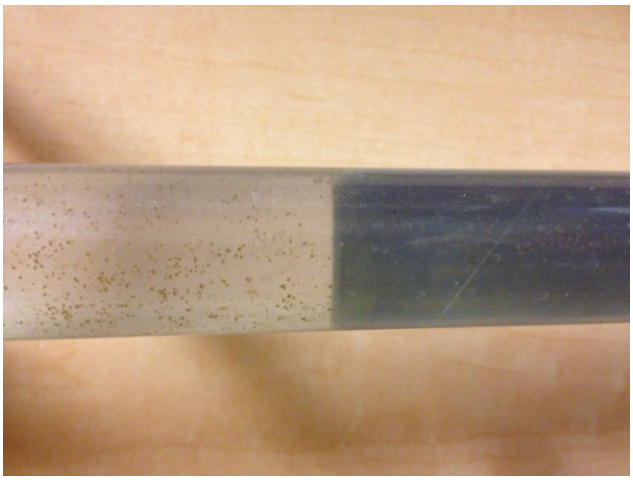

Figure 8. Bio-fouling in indoor infused tube.

The shipboard demonstration was initiated in March 2013, and continued through January 2014. Because the normal cleaning schedule for the LPAC HXs is 3 to 6 months, this demonstration period was selected to be long enough to verify whether or not the period between cleanings could be extended by at least 50%. Due to the LPAC HXs having just undergone a cleaning as part of a major maintenance period at a shipyard in Portland, Oregon, the exchangers were relatively clean at the start of the demonstration period. The project team thus observed no change in the HX inlet and outlet temperature or inlet pressure between the pre- and post-cleaning measurements taken during the initial cleaning at the start of the demonstration. Even though it was not identified in the Demonstration Plan, the project team decided to also clean the HXs at the end of the demonstration. Like the results from the initial cleaning, there were also no observed changes in inlet and outlet temperature or inlet pressure between the pre- and post-cleaning measurements taken during this final cleaning. This clearly indicated that little fouling occurred during the more than 9-month demonstration period in either of the HXs. Both of these cleanings were able to be successfully completed without any disassembly of the HXs and were performed within 3.5 hours creating less than 5 gallons of hazardous waste per exchanger.

An integral part of this shipboard demonstration was the safety of the I_2MP infusion protocol in regard to HX materials and iodine sublimation into seawater. In Table 4, results from a downstream water sample analysis for metals, I_2, DO, and pH are reported. These results are from sampling taken downstream from LPAC 1 during a period without infusion, LPAC 1 during an infusion event, and LPAC 2 without infusion. The water sample from the effluent of LPAC No. 1 exchanger shows that there is little elution of heavy metals. For LPAC No. 2 however, considerably higher heavy metal ion elution in the effluent was exhibited. This elevated metal elution may be due to a difference in the system design, microbiological induced corrosion, or existing corrosion. Also shown in the table was that the total iodine sublimation was less than the standard Navy dosing limit of 200 ppb. For LPAC No. 1, the total iodine was 30 ppb above background seawater iodine levels during an infusion event.

Table 4. Results of water sampling during shipboard demonstration.

	Cu (µg/L)	**Pb** (µg/L)	**Ni** (µg/L)	**Ti** (µg/L)	**Zn** (µg/L)	**I_2** (ppb)	**DO** (µg/L)	**pH**
LPAC 1 Non-infused	0.05	<0.05	<0.05	0.5	<0.05	60	7.22	7.88
LPAC 2 Non Infused	0.55	0.07	0.05	0.5	0.43	65	7.00	7.68
LPAC 1 Infused	0.04	<0.05	<0.05	0.5	<0.06	95	6.88 - 7.52	7.97

To indirectly indicate fouling of the LPAC HXs, inlet and outlet temperature and inlet pressure data was measured by the ship's crew from ship's calibrated gages for both LPAC No. 1 and LPAC No. 2 for the time period from just before the initial I_2CP procedure to just after the end of the demonstration. Generally, when the applicable HX was on-line, the ship's crew took measurements every 2 hours. In Figures 9 and 10, these pressure and temperature values over time are graphed. To smooth out the graph, the readings were averaged over a 4 day period with the average value plotted. Included on the charts, in block design, are the time periods that the individual exchangers were either in lead, lag, or secured for seawater system maintenance. Being in lead means that the compressor is operational and the HX experienced a load. Lag indicates that the compressor is off but ready to be used in case of a service issue with the lead compressor. The charts below show that LPAC No. 1 was in the lead approximately 85% of the time. The project team had originally requested that there would be a balanced use of the exchangers. Unfortunately, the ship was not able to meet this request.

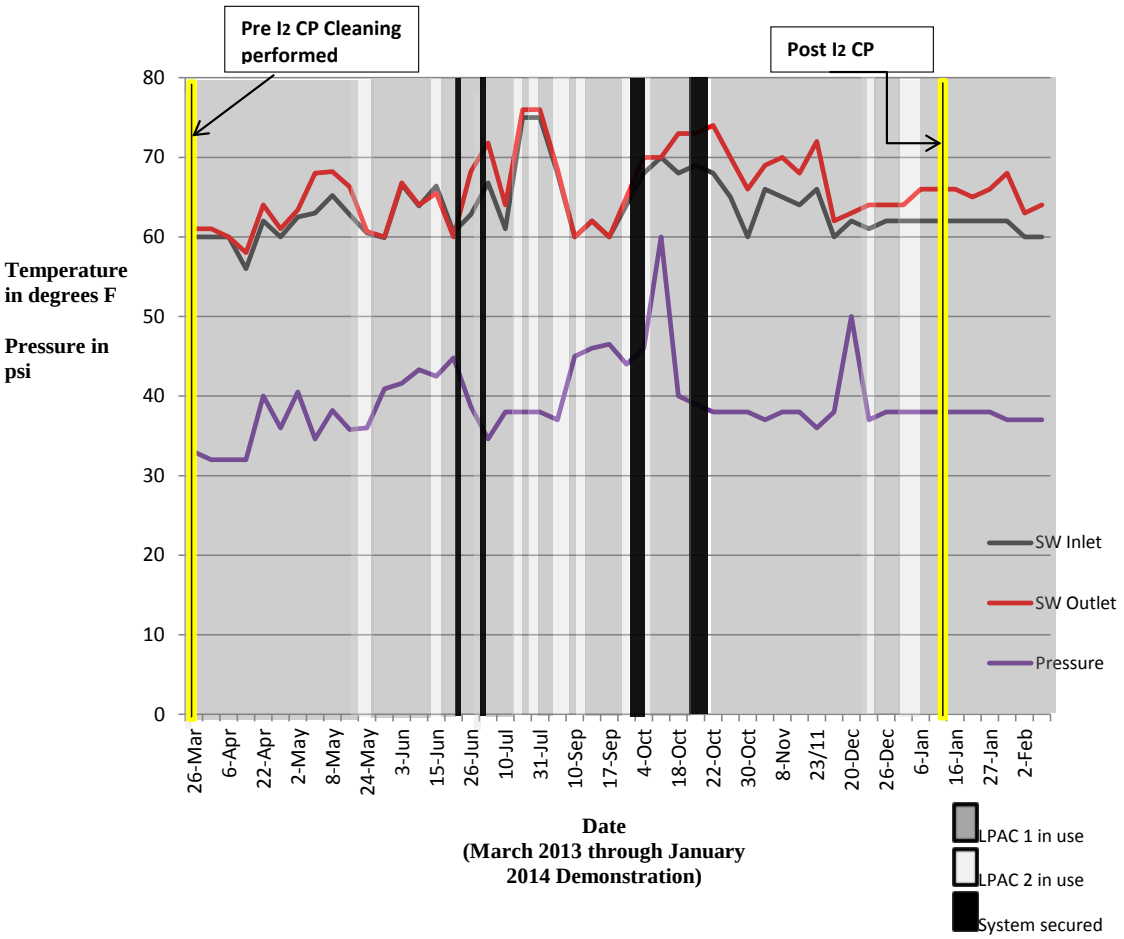

Figure 9. Inlet and outlet temperatures and inlet pressure for LPAC No.1.

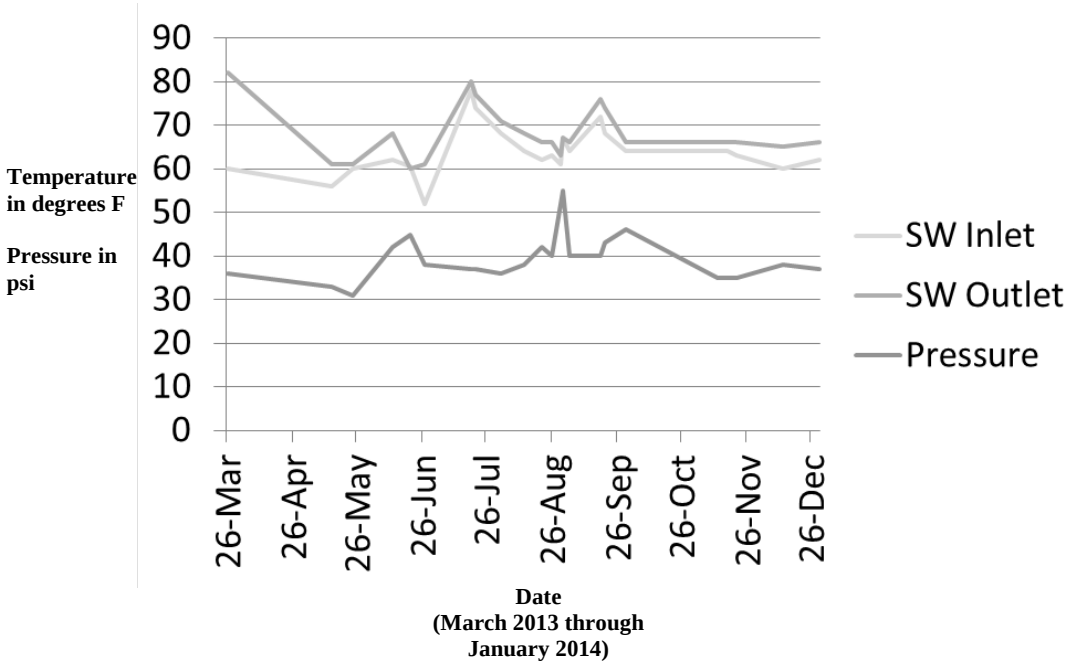

Figure 10. Inlet and outlet temperatures and inlet pressure for LPAC No. 2.

As indicated by the graphs, the inlet pressure of both the LPAC exchangers remained relatively constant over the demonstration period even though LPAC No. 1 experienced almost 6 times the load. The LPAC No. 1 data also shows two pressure spikes. These spikes were probably due to clogging of ship strainers. Unfortunately, the project team was not able to determine the cause for sure. The issues were resolved without maintenance of the exchanger itself. The fact that the pressure remained relatively constant indicated that neither exchanger fouled significantly during the demonstration period and that these exchangers are suitable for continued use before a cleaning would be necessary. Based on the usage history, in the absence of the infusion system, the ship's crew told the project team that they would have expected that the LPAC No. 1 HX would be significantly more fouled and would probably have required a cleaning during the demonstration period based on their normal experience of cleaning LPAC HXs every 3 to 6 months.

The absolute temperature values reported on the above graphs are solely a reflection of the seawater temperature. During the demonstration period, the ship was either moored in Port Hueneme or San Diego or in coastal waters off of southern California. Each of these locations represents a different temperature condition. In addition, given the length of the demonstration, the ship experienced seasonal effects as well. The temperature differential data indicated that there was adequate heat transfer throughout the demonstration period as indicated by a small but relatively constant temperature differential while a HX was under load.

At the end of the demonstration, but prior to the final cleaning, the ship's crew removed the exchangers head for observation by the demonstration team. Figure 11 shows significant sea grass and mud in LPAC No. 1, but little biological fouling. Similar results were found for LPAC No. 2. The HXs are designed to allow water flow from the top half of the tube bundle into a curved faceplate and then through the bottom. This is why the sea grass only presented in the top half. While both exchangers were disassembled, the project team inspected several of the HX tubes and found little solidified fouling.

Figure 11. LPAC No. 1 HX tubes prior to removing sea grass.

Unfortunately, this project did not result in a definitive clear indication of success. The fact that the LPAC No. 1 exchanger was used 85% of the time meant the control HX saw very little use. Ideally, the demonstration would have been continued until such time that the ship needed to perform a HX cleaning. However, because the ship normally cleans the exchangers every 3 to 6 months, the project was able to show that use of the I_2 bubble infusion technology did achieve the most important goal, namely extending the period between cleanings by 50%.

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7.0 COST ASSESSMENT

7.1 COST MODEL

Employing the I_2CP and I_2MP for cleaning and maintaining HXs onboard DoD operated ships should result in cost savings in two areas as compared to existing practices. Savings are expected by both lowering the cost of the cleanings and extending the period between cleanings. Currently, Navy shipboard HXs are often cleaned using strong acids in accordance with Uniform Industrial Process Instruction 5050-903C. This cleaning method generates significant quantities of very low pH wastewater that is highly contaminated with heavy metals, thus making this waste a RCRA hazardous waste. The primary difference between the current acid cleaning procedure and the I_2CP is that unlike the current process, the I_2CP uses weaker acids. In addition, by infusing iodine vapor during the cleaning, the cleaning solution acidity is maintained, thus resulting in less cleaning solution being used. It is expected that the I_2CP can be completed more quickly and with fewer workers. This will result in being able to return the ship to full operation more quickly.

The period between cleanings is determined primarily based on the ships operating history, with ships that have many operating hours and being home ported in warm water requiring the most frequent cleanings. As a general average, the team expects a typical DoD shipboard HX to be cleaned approximately once every 2 years. This is significantly longer than the reported 6 months for the LPAC HXs used in the demonstration. The more frequent LPAC cleanings are a result of the fact that these HXs are always exposed to seawater (except during maintenance periods), are used when the ship is both at sea and in port, and are relatively cheap to clean. Given this demonstration indicated that a 50% increase in the period between cleanings is reasonable, for this cost analysis the project team will assume an average of 3 years between cleanings when employing the I_2 bubble infusion technology.

For this cost analysis, the project team will make the cost comparison using the life cycle costs for employing the I_2CP and I_2MP technologies over the expected 15 year service life of the I_2 bubble infusion technology, and compare these costs to the costs of the current process of performing periodic HX chemical cleanings. Costs will be compared using a present value analysis methodology, assuming a 3% interest rate.

7.2 COST ANALYSIS AND COMPARISON

In Table 5, the cost difference between the two cleaning methods is summarized. These costs are based on cleaning the LPAC HXs. The equipment costs identified in the table include the expected costs for the government to buy the equipment. The project team will not attempt to identify those costs that are the same regardless of the cleaning method. For example, both cleaning procedures will require work instruction preparation and maintenance, labor costs for hazardous waste management, safety training, as well as the performance of compliance audits. The I_2CP costs identified in the table represent the actual costs during the shipboard demonstration. A hazardous waste disposal cost of $2.00 per gallon was used for the table. This estimate is representative of actual Navy costs. Cost for the current procedure to clean a similar HX has been provided by the Naval Surface Warfare Center Carderock Division - Ships Systems Engineering Station. When using this cost information, it is important to remember, however,

that the cost difference between the cleaning methods is not the whole picture. The potential ability of the I_2MP to extend the period between cleanings must also be considered.

Table 5. Cost comparison between I_2CP and current cleaning procedure.

I_2CP			
Direct Environmental Activity Process Costs			
Start-Up (One-time)		**Operation & Maintenance (Per cleaning event)**	
Activity	**$**	**Activity**	**$**
Equipment purchase	$1,200.00 For LPAC HX size	Labor to operate equipment	$300
Equipment installation	$100.00	Utilities (Electrical power and low pressure compressed air)	Nominal Cost
		Hazardous waste disposal costs (includes labor)	$300
		Cleaning chemicals	$100
		Consumables and supplies	$50
Existing Shipboard Chemical Cleaning Process			
Direct Environmental Activity Process Costs			
Start-Up (One-time)		**Operation & Maintenance (Per cleaning event)**	
Activity	**$**	**Activity**	**$**
Equipment purchase	Negligible For LPAC HX size	Labor to operate equipment	$3200
Equipment installation	$100	Utilities (Electrical)	Nominal Cost
		Hazardous waste disposal costs	$1200
		Cleaning chemicals	$1200
		Consumables and supplies	$200

Besides the cleaning costs discussed above, the team must also consider the costs of the I_2MP. Because most DoD operated ships have no system to maintain HX cleanliness (i.e., no chlorinization system), the costs for the I_2MP represents new additional costs. These costs are identified in Table 6. The I_2MP system can serve multiple HXs, however, the cost estimate below assumes one system per HX.

Table 6. Costs to install and operate a typical I_2MP system on a DoD vessel.

I_2MP			
Direct Environmental Activity Process Costs			
Start-Up (One-time)		**Operation & Maintenance (Annual)**	
Activity	**$**	**Activity**	**$**
Equipment purchase	$1200 (For installation on (1) LPAC exchanger)	Labor to operate equipment	Zero additional cost as it will be performed by ship personnel
Equipment installation	$600 inclusive of HX modification and mount	Ship's Utilities (Electrical power and low pressure compressed air)	$200
		Consumables and supplies (4 cartridge changes per year)	$800

For the life-cycle cost, the project team will compare costs using a present value analysis methodology that takes into account using the I_2MP throughout the equipment life cycle and the completion of numerous cleaning evolutions. For this analysis, the project team will assume that the I_2MP equipment has a 15-year service life and will not consider the possible use of a chlorination system. Thus, for both the existing cleaning and maintenance processes (i.e., no maintenance) and the I_2MP and I_2CP processes, the calculations will be run using a 15-year service life. The time between cleanings will be assumed to be 2 years for the existing cleaning process (seven cleanings during life-cycle) and 3 years for the new method (four cleanings during life-cycle). For the analysis, the project team will assume an interest rate of 3%. Because the cleaning equipment can be used hundreds of times, the cleaning equipment purchase cost will not be considered in this analysis. Purchase costs for the I_2MP equipment is estimated based on this equipment becoming a commercial item. Currently, each system is custom manufactured. Labor costs for the I_2CP is estimated based on actual times and representative fully burdened labor rates for the required trades at Naval Base Ventura County. Material and hazardous waste costs are based on actual invoice costs. Utility costs are based on estimated consumptions and actual cost per unit of consumption. Based on the above considerations, the single life-cycle present value cost for the existing process is approximately $32,800 and for the new process is approximately $16,500; saving approximately $16,300, or about 50% of the costs when both the I_2CP and I_2MP processes are employed over the service life of the I_2 bubble infusion equipment.

The above analysis is for one relatively small HX. A typical Navy ship has dozens of HXs, some of which are very large. Therefore, the potential savings for installing the I_2 bubble infusion technology on all the HXs on a Navy ship is significantly greater than reported above.

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8.0 IMPLEMENTATION ISSUES

The proprietary I_2 infusion technology is suitable for both new construction and retrofit applications; however, retrofits will always be more costly and will require a more involved integration effort. For Navy vessels, implementation will require the approval of the appropriate technical warrant holder(s). In general, this technology can be applicable for any shipboard HX where low pressure air is available. The decision to use this technology will be based on the justification of its cost in providing benefits to the system through extending the period between HX cleanings. Once the technology is approved, the implementation decision for the specific application will need to be made by the design agent for the applicable weapons platform. Each application will require some level of customization for system integration although the core technology remains the same.

The implementation of this technology should result in improved worker safety and a reduction in environmental risks. This occurs as a result of extending the periods between chemical cleanings using hazardous acidic cleaners. With less chemical cleanings, less hazardous waste disposal is required. From an environmental and safety standpoint, iodine use is much better than electro-chlorination. Unlike chlorine, iodine has no discharge limits into seawater. Implementations of this technology will not require the need for new environmental permitting.

Currently, the I_2 bubble infusion technology is custom manufactured for each application by a small business. If the DoD was to become a major user of this technology, it would appear that a new license manufacture would have to be established with the products established under the National Stock System. The technology is built using off-the-shelf components, except for the resin cartridges that are manufactured by a long established domestic manufacturer. Given the simplicity of manufacture, this product is amenable for rapid production expansion.

After completing the demonstration, the project team presented the demonstration results to the applicable Navy technical experts in Code 924 at the Naval Surface Warfare Center Carderock Division - Ships Systems Engineering Station in Philadelphia, Pennsylvania. Code 924 serves as the gatekeeper for the warrant holder(s) who have the ultimate implementation authority for Naval combat ships. With a Code 924 recommendation, the project team hopes to present the results to the warrant holder(s).

During the meeting with the Code 924 technical experts, they expressed the opinion that the I_2 bubble infusion technology may be of value to the Navy. Given the fact that the ESTCP demonstration did not continue until complete HX fouling, an additional demonstration, this time on a Naval combat ship, may be required before a final implementation decision can be made. The project team does not expect a final Navy decision on whether or not to proceed with the I_2 bubble infusion technology until such time that the Code 924 technical experts have had a chance to review the project's final report.

For implementing the technology on Army, Military Sealift Command, and Coast Guard ships, the project team will pursue a similar implementation path. Applicable technical experts have been identified and preliminary contacts made. Further implementation efforts with these groups will be delayed until the project's final report is issued.

In addition to the shipboard HX application, demonstrations for two other Navy applications of the I_2 bubble infusion technology are currently being initiated. The technology is undergoing study at the Undersea Naval Warfare Center in Newport, Rhode Island, as a hull foul retardant in conjunction with air bubble curtains. Air curtains have been shown to reduce the rate of fouling on hull surfaces but with limited success. The addition of a vapor antimicrobial will be studied to determine if it improves the efficacy of bubble curtains in retarding the formation of fouling beds. At Pearl Harbor Naval Shipyard, the technology is being demonstrated in a Navy Environmental Sustainability Development to Integration Program (NESDI) project to prevent bio-fouling within submarine conduits, both pier side and in dry-dock, as a replacement for electro-chlorination.

To identify potential additional customers and applications, the project team has engaged the Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) environmental technical implementation group. This group uses a variety of techniques to advertise to Navy professionals, technologies that may be applicable to address specific Navy environmental problems. They also have expertise assisting small businesses with the establishment of a business plan that will result in the capability to manufacture products sufficient to meet Navy needs. Finally, the project team will prepare an article for a future issue of the Navy's *Currents* magazine in order to advise a large number of Navy environmental professionals about the technology's availability and possible applications.

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APPENDIX A

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