



FINAL REPORT

TR-NAVFAC-EXWC-EV-1404

In-Situ Shipboard Heat Exchanger Cleaning and Maintenance Using Innovative I₂ Bubble Infusion Technology

ESTCP Project WP - 201219

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July 15, 2014

REPORT DOCUMENTATION PAGE				FORM APPROVED OMB NO. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be					
1. REPORT DATE (DD-MM-YYYY) 07-15-2014		2. REPORT TYPE Final Report		3. DATES COVERED (From – To) March, 2012 to January, 2014	
4. TITLE AND SUBTITLE In-Situ Shipboard Heat Exchanger Cleaning and Maintenance Using Innovative I ₂ Bubble Infusion Technology				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Holden, Bruce				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NAVFAC EXWC 1000 23rd Ave, Port Hueneme, CA 93043				8. PERFORMING ORGANIZATION REPORT NUMBER TR-NAVFAC-EXWC-EV-1404	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Environmental Security Technology Certification Program 4800 Mark Center Drive, Suite 17D08 Alexandria, VA 22350-3605				10. SPONSOR / MONITOR'S ACRONYM(S) ESTCP	
				11. SPONSOR / MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT This report summarizes the results of a two year project led by the Naval Facilities Engineering and Expeditionary Warfare Center to demonstrate the potential for the patented I ₂ infusion system to reduce the rate of foul within Department of Defense shipboard heat exchangers. Fouling of DoD shipboard heat exchangers is a chronic and costly operating problem that requires significant maintenance. The heat transfer performance and efficiency decreases due to the fouling of the heat exchanger plates and tubes resulting in additional fuel consumption and increased greenhouse gases. Costly and labor consuming, remedial chemical cleaning protocols currently used produce considerable hazardous waste. Through the infusion of air containing elemental iodine vapor into the heat exchanger, this demonstration has shown that the formation of biological foul has been reduced and the period between physical cleanings extended while maintaining acceptable system parameters.					
15. SUBJECT TERMS None					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Holden, Bruce
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code) 805-982-6050

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List of Acronyms

cfu	Colony Forming Unit
DO	Dissolved Oxygen
DoD	Department of Defense
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
HIO	Hypoiodous Acid
HXs	Heat Exchanger(s)
I ₂ CP	Cleaning Protocol
I ₂ MP	Maintenance Protocol
LPAC	Low Pressure Air Compressor
NAVFAC EXWC	Naval Facilities Engineering Command 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
RCRA	Resource Conservation and Recovery Act
R&D	Research and Development
SERDP	Strategic Environmental Research & Development Program
SDTS	Self Defense Test Ship
SMSC	Standard Microsystems
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
TSS	Total Suspended Solids
UV	Ultraviolet

Acknowledgments

The project team would like to acknowledge the significant efforts put forth by several participants. We would like to particularly thank the Naval Surface Warfare Center, Port Hueneme Division. They served as the host organization for the shipboard demonstration and provided logistical support.

Joseph Scharf, from the Naval Surface Warfare Command, assisted in the selection of the heat exchangers used in the demonstration and provided invaluable information regarding Navy heat exchanger system construction, performance and maintenance issues. The crew from the Self Defense Test Ship (ex USS Paul Foster) and the support staff from Advantage Technology, Inc. installed, maintained, and collected performance data during the demonstration. They also provided valuable guidance and interpretation of the demonstration results. Paul Stirling from Puget Sound Naval Shipyard provided invaluable expertise on ship board heat exchanger cleaning methods.

I₂ Air Fluid Innovation, Inc. was assisted in laboratory analysis by personnel from:

1. ALS Environmental Laboratories, Jacksonville, Florida that provided water sample testing
2. Cornell University, Ithaca, NY that provided invaluable microbiological information
3. DCPAH of Michigan State University, Lansing, Michigan that provided iodine analysis
4. Heat Research Transfer Institute, College Station, Texas, that provided invaluable heat exchange functionality information
5. Lit Labs, West Babylon, NY that provided metallurgical, Scanning Electron Microscopy and spectrographic evaluation
6. Long Island Analytical Labs, Holbrook, NY that provided water sample testing
7. Dr. Mohammad Reza Malayeri, Head of fouling and cleaning in process industries, Institute of Thermodynamics and Thermal Engineering, Stuttgart-Germany

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 (HXs) 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 thus 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 I₂ infusion protocols, demonstrated in this project, strips elemental iodine (I₂) 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 I₂ 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 I₂ infusion process is at the core of two methodologies developed by I₂ Air Fluid Innovation used to retard bio-fouling; the I₂ Cleaning Protocol (I₂CP) and I₂ Maintenance Protocol (I₂MP). I₂CP 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, we verified that the non-metallic and metallic materials commonly used within shipboard HX were compatible with the chemicals used during the I₂ protocols. Also verified was that the iodinated bubbles did not increase the erosion rate on heat exchanger materials.

In the second phase, we preformed field testing at the National Energy Laboratory of Hawaii Authority's (NELHA) facility in Kona, HI. At this facility, Makai Engineering, a subcontractor to I₂ 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 I₂ 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) heat exchangers (Numbers 1 and 2), were used for the demonstration. Both received the I₂CP 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 I₂CP.

LPAC No. 1 was designated to receive the infusion protocol, I₂MP. The demonstration was performed over a period exceeding nine 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 I₂CP performed using an acidic cleaner. The effluent from each was analyzed for Total Suspended Solids (TSS), Total Organic Carbon (TOC) and Total Dissolved Solids (TDS) as well as 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 heat exchanger saw very little use. Ideally, the demonstration would have been continued until such time that the ship needed to perform a HX cleaning. Since the ship normally cleans the exchangers every three to six months, we were, however, able to show use of the I₂ bubble infusion technology did achieve our 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, RI 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 utilized both pier side and in dry-dock. For this application, the I₂ 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 I₂ technology can extend the period between HX cleanings.

1.0 INTRODUCTION

1.1 BACKGROUND

The Department of Defense operates vessels that use heat exchangers 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 heat exchange 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 [Reference 1], it was found that the liquid waste from acid cleaning had a concentration of 2,000 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 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 heat exchangers, 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 [Reference 2].

To improve the service life of DoD ship HX, this project demonstrated the suitability of the innovative I₂ bubble infusion technology. This technology, a proprietary product of I₂ 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 heat exchangers in a marine environment. The core technology is the patented iodine infusion method (US Patent# 7,329,385) that reduces microbial counts within a fluid, an air stream, and vessel using elemental iodine (I₂) vapor infusion. It uses a low volume I₂ 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 I₂ 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, ex USS Paul F. Foster, home ported at Port Hueneme, California. Specifically, two of the ship's heat exchangers 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 NELHA facility located in Kona, Hawaii.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of this demonstration was to validate the safety, effectiveness, ease of implementation, and cost savings of the I₂ bubble infusion technology as a means to significantly reduce the fouling rate within a functioning heat exchanger in a marine environment. We also intended to show that I₂ 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 I₂ 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 I₂ 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 [Reference 3]. 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 2.1 and 2.2) 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 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 [Reference 4]. 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 MP and the I_2 CP. The I_2 MP prevents or reduces future fouling through the infusion of iodinated bubbles into the water stream supplying the heat exchanger during operation. The I_2 CP 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.

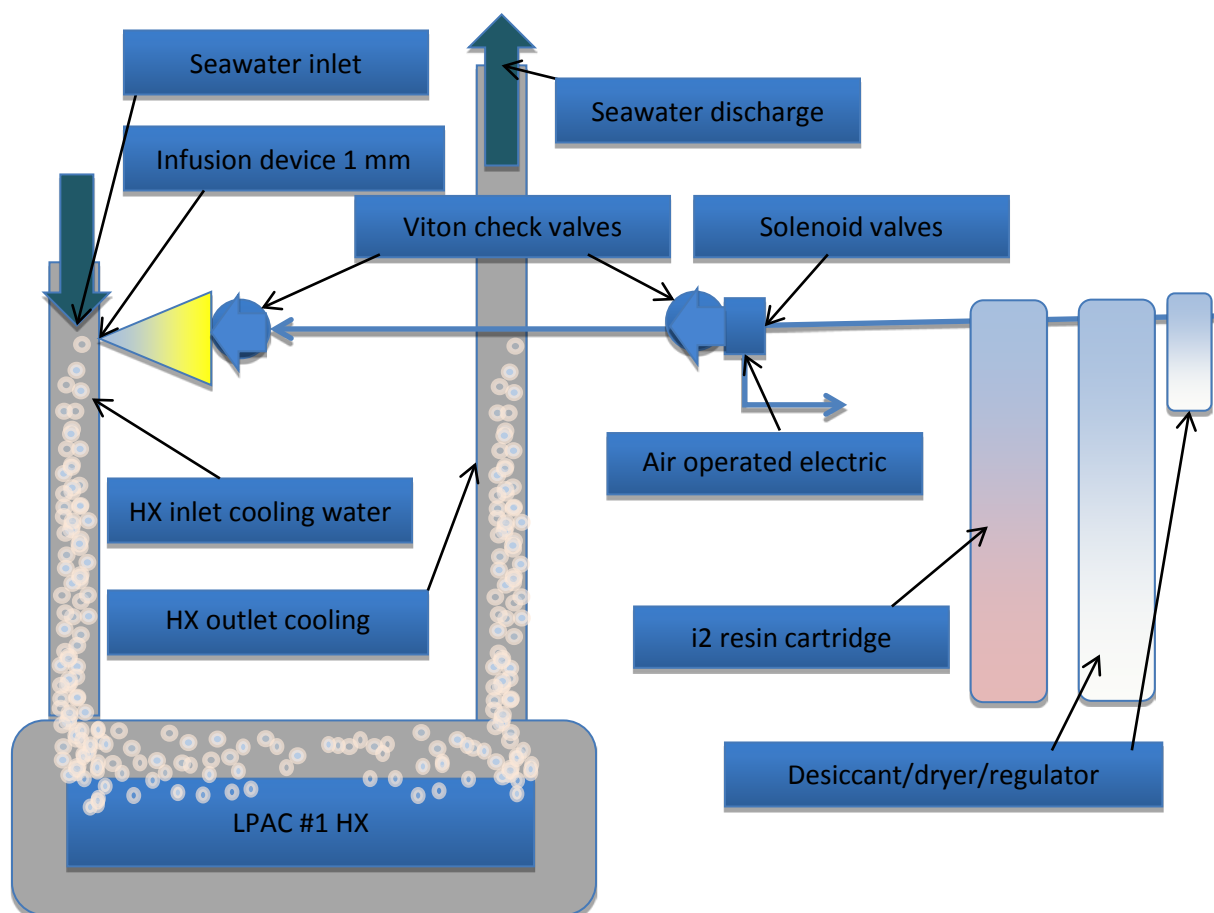


Figure 2.1
 I_2 Bubble Infusion Schematic



Figure 2.2
I₂ Bubble Infusion Device

This device is used to directly transfer iodinated air into the heat exchanger 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 heat exchanger.

The infusion device has a number of safety features, which prevents seawater from entering the compressed air source in the event of depressurization. Brass Viton check valves with Hastalloy springs prevent back flow to the compressed air source. An air operated electric switch prevents activation of the solenoids if compressed air is not present. The air is injected into the water stream using a 1 mm nozzle containing a particulate filter.

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 [Reference 5] and is a member of the halogen group, which includes bromine, fluorine, and chlorine, all known antimicrobials [Reference 6]. 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. Activated iodine reacts in electrophilic reactions with enzymes of the respiratory chain as well as with amino acids located in cell membrane and cell wall proteins [Reference 7]. The well-balanced tertiary structure necessary for maintaining the respiratory chain such as cell integrity is disrupted and the microorganism is irreversibly damaged [Reference 8]. The I₂ species is very effective in water over a wide pH range from 6 to 8 and does not lose effectiveness until the pH of water reaches 10. Among the various iodine species, both elemental iodine molecules and hypoiodous acid have disinfection capability

[Reference 9]. Molecular iodine is important in the inactivation of microorganisms due to its stability over a wide pH range when compared to hypiodous acid [Reference 10]. Iodine is superior to chlorine, commonly used for water disinfection, due to the greater chemical stability of the product and less reactivity with organic nitrogenous contaminants [Reference 11], that is important for use in the presence of organic turbidity. Chlorine may also have a deleterious effect on sea life through the inactivation or reduction of phytoplankton photosynthesis. Studies done at the San Onofre, California power plant on release of chlorine into coastal waters show an inhibitory effect of almost 50% after 24 hours at .01 ppm [Reference 12].

Iodine occurs in seawater at a concentration of 0.05 ppm and is concentrated in some algae and seaweeds [Reference 13]. It is present in seawater principally as two chemical species, iodate and iodide. Iodine in seawater is highly unstable and converts to these species rapidly after interaction with organics within the seawater [References 14 and 15]. Iodine as iodide is a vital nutrient found in many marine plant and animal biological samples [References 16 and 17]. Iodine is a poor algacide and therefore should not impede algae growth in seawater.

Iodine has the ability to bind to quaternary ammonium anion exchange resins as tri- or pent-iodide complexes [References 18, 19 and 20]. These complexes are a demand-type disinfectant, releasing iodine only when needed, thus allowing for a longer lifetime of product and minimizing casual exposure to iodine. This technology was chosen for use onboard NASA missions as an effective way to disinfect water. Additionally, iodine resin is used in biohazard filtration masks to prevent inhalation of microbes [Reference 21].

The innovative I₂ bubble infusion transfers elemental iodine 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 since the I₂ is contained within the bubble. Because of this, there is little sublimation into the fluid itself, reducing biocide residue.

The performance of pentaiodide resin was reported for microorganisms as a 4-log inactivation of bacteria and viruses [Reference 22 and 23]. Studies indicate that the presence of pentaiodide ions on the resin will lead not only to greater disinfection efficiency but also to an increased level of iodine vapor downstream for enhanced remote disinfection [Reference 24 and 25]. Iodine in vapor form has long been known to be highly antimicrobial [Reference 26] and has been shown to be highly effective in reducing both pseudomonas and e.coli in water from independent studies. Bubbles have shown promise in reducing bio-fouling on ship hull surfaces [Reference 27] and within clinical waterlines [Reference 28] as well as an increase in surface heat transfer within shell and tube exchangers [Reference 29]. Independent studies have recently shown a foul inhibiting effect of bubbles on minerals in plate heat exchangers [Reference 30]. The bubbles induce turbulence within a water stream and move fluids away from heat exchange surfaces.

The I₂ infusion is used as part of both the I₂ Cleaning Protocol and I₂ Maintenance Protocol. The I₂CP cleaning method uses iodinated air and appropriate cleaner as part of an in situ method to eliminate the foul within heat exchangers. The I₂CP 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 I₂CP 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 I₂MP 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 on to 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 2.3), the microbes utilize 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.

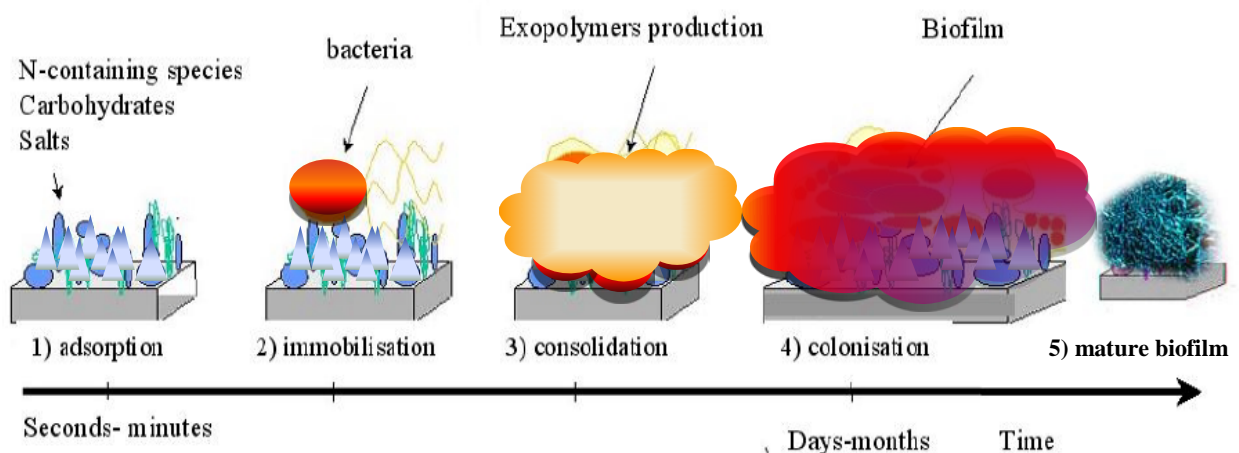


Figure 2.3
Foul Formation

The I₂MP method (see Figure 2.4) 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 I₂ 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 and thus increase 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 I₂ Infusion Device, which allows for I₂ vapor distribution at prescribed intervals and pressure. With I₂ infusion, it has been shown that only grams of iodine per month are needed for a typical heat exchanger.

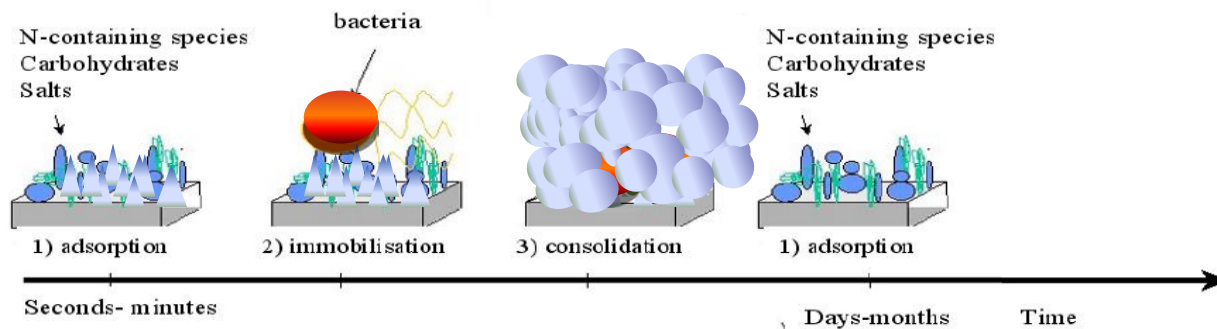


Figure 2.4
Foul Disruptions with I₂ infusions

2.2 TECHNOLOGY DEVELOPMENT

In 2004, the first independent study of the I₂ bubble infusion technology was completed. By 2007, the technology had been developed sufficiently that United States Patent# 7,329,385 was granted. Also in 2007, the I₂ bubble infusion technology had its first commercial implementation. It was used on a fouled industrial geothermal heat exchanger at Standard Microsystems (SMSC), an electronics technology manufacturing facility located in Hauppauge, New York. Between 2009 and 2010, several other commercial implementations were completed including the first salt water application for a site in Bermuda. In Bermuda, both the I₂CP and I₂MP methods were used. This ESTCP demonstration represents the first use of the technology on a ship and the first application on a shell and tube HX.

At the SMSC facility, rapid iron bacteria fouling was the problem. To address this issue, the I₂ Cleaning Protocol was implemented. Fouling of this geothermal system impeded system efficiency as indicated by high inlet and outlet pressures as well as a drop in heat transference.

Additionally, there was backpressure within the diffusion wells. The standard treatment protocol, including the hyper-chlorination of the supply and recipient wells and the supply pipe system as well as disassembly of the heat exchangers, had previously been tried unsuccessfully. The I₂CP treatment was successfully completed in approximately ninety minutes. Figures 2.5 and 2.6 show the cleaning results. No mechanical scrubbing was required and all cleaning was performed in situ.

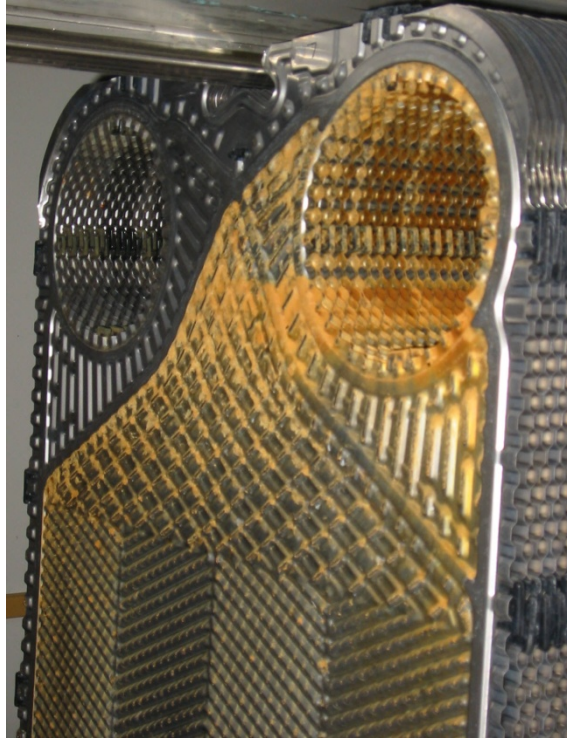


Figure 1.5
HX Plate Surface Prior to I₂ CP

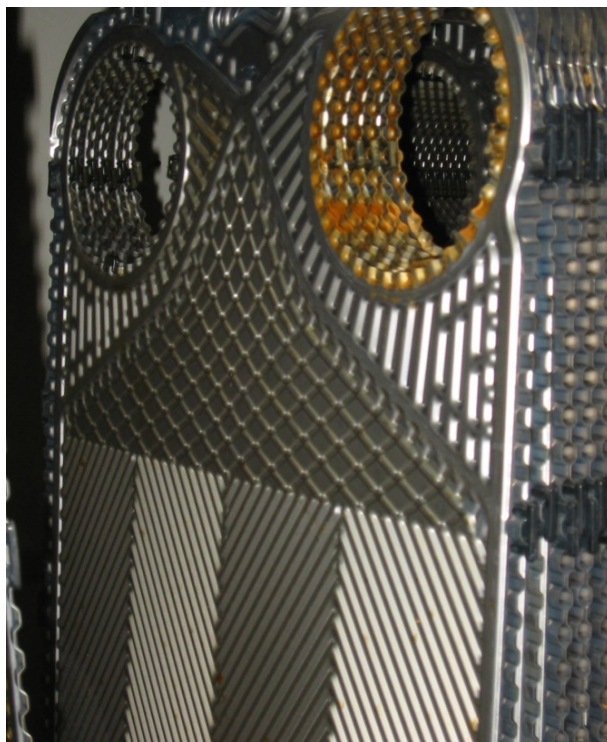


Figure 2.6
HX Plate Surface after I₂CP

In addition to several commercial implementations, the technology has also been independently bench tested at the CADENTRIX lab in Canada as well as at the Dental Consultants, Inc. lab located in Ann Arbor, Michigan. Results from these lab tests show that the I₂ bubble infusion technology reduces bacterial levels dramatically. In both tests, plastic reservoirs containing distilled water and samples of various test organisms (e.coli, staphylococcus A, and pseudomonas A) were bubbled for 1 and 5 minute intervals. Aliquots of each sampling were drawn and incubated. In both independent studies, I₂ infusion reduced the microbial counts of the sampled organisms in 1 to 5 minutes. The CADENTRIX testing showed 100% inhibition of both e.coli and pseudomonas after 5 minutes exposure time. The Dental Consultant testing showed 100% inhibition of e.coli, pseudomonas A., staphylococcus A, and mixed sample after a 5-minute exposure time. Unfortunately, both of these reports are copywrited so, therefore, they cannot be included as appendices to this report. Pseudomonas was recognized as a potent foul producer in heat exchangers in a previous Strategic Environmental Research & Development Program (SERDP) project report [Reference 31].

In 2009, the I₂ infusion method was tested to prevent fouling within an ultraviolet purification system at the Queens Botanical Gardens, Flushing, NY. This facility employed a geothermal system for heating and cooling. Iron reducing bacteria from the supply wells would cause extensive fouling within the heat pumps and recipient wells. An ultraviolet (UV) water purifier was put in place to reduce or eliminate viable bacteria from the supply water. Within days, the bacteria would foul the quartz sleeves within the system and UV transmission would approach zero. The I₂ infusion device was placed upstream to the UV purifier and tested for the inhibition

of fouling. It prevented or retarded fouling of the sleeves and maintained transmissibility for extended periods [Reference 32].

In 2013, the technology was presented at the International Ultraviolet Association meeting in Karlsruhe, Germany for UV quartz sleeve foul prevention and at the European Heat Transfer Symposium in Budapest, Hungary. An abstract describing its use in land based heat exchangers was chosen for publication [Reference 33]. Later that year the technology was integrated into the Bermuda Hospital geothermal system to help retard fouling of this system. The technology is also the subject of investigation through the Navy's Environmental Sustainability Development to Integration (NESDI) Program. NESDI funded a study of the retardation of fouling within a support system HX used to replace a ship's HX while the ship is undergoing maintenance in a dry dock. This study was started in late 2013 and will use infused iodinated bubbles via a venturi. Additionally, the protocol will be used as part of a study to prevent hull fouling on ships in port. This is being performed by the Naval Warfare Center, Newport, RI and will start scheduled for Spring, 2014.

Also in 2013, the protocol was tested for microbial reduction of both water and surface microbes as part of a United States Department of Agriculture study with Cornell University to determine if I₂ infusion would reduce the levels of bacteria associated with bovine mastitis, a contamination of cow teats. The test results showed a Log 4.5 to 6 reductions of both surface and waterborne microbes after a 90 second exposure. The total iodine residue was of less than 1/10th of that normally found with teat disinfectants. A copy of the report summary is included as Appendix C.

A new patent pending device was developed in 2013 by I₂ Air Fluid Innovation, Inc. that will allow for a cost effective and simple integration of I₂ infusion into HX systems. It allows for the timed infusion of iodinated bubbles into the inlet cooling water side using a novel venturi infusion device.

2.3 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 I₂MP is that it can extend the period between heat exchanger cleanings.

The electro chlorination process is similar to the I₂MP, 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 heat exchanger. 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 I₂MP, on the other hand, discharges iodide and iodates; chemical compounds without discharge limits that are commonly found in seawater and kelp. Utilizing chlorine necessitates the need to maintain a narrow pH range (6.5 to 7.5) to maximize effective biocidal action. The effect of even a minor increase or decrease in pH can negate disinfection. The chemical reaction of water with the chlorine solution raises the pH level thereby compounding the problem. In addition, chlorine tends to off-gas as it moves out of the pH range of 6.5 to 7.5, thus potentially causing a worker safety issue. The active iodine compounds, I₂ and Hypoiodous Acid (HIO), used in the I₂MP are, however, much less sensitive to variations in pH, maintaining their effectiveness over a broad range of pH as shown in Table 2.1.

Table 2.1
Effect of pH on Active Iodine and Chlorine Compounds*

pH	% of Active Iodine Species (I ₂ and HIO)	% of Active Chlorine Species (Hypochlorous Acid)
3	87.5 - 100	100
4.5	87.7 - 100	100
5	87.7 - 100	97.7
6	89.1 - 100	96.8
7	94.2 - 98.3	75.2
7.5	92.0 - 92.2	48.0
8	78.9 - 78.3	23.2
8.5	58.2 - 57.6	9.0
9	37.7 - 37.5	2.9

**Comparison is at a constant 25°C. (pH in Bold is that of seawater)*

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 I₂MP 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 I₂MP 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 I₂MP 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 I₂MP 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, dependent on the HX cooling water volume.

Regardless of the type of maintenance or lack thereof, all shipboard heat exchangers will require periodic cleaning. Larger and inaccessible heat exchangers 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 I₂CP offers a better alternative since 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 I₂CP 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 I₂CP is also expected to be completed in a shorter time than the current cleaning procedures.

Since the I₂MP and I₂CP processes are relatively new and have only completed limited demonstrations, exchanger size and type may present a challenge as the protocols have only been used on plate and frame exchangers of the 50 to 500 gallon capacity. Prior to this demonstration, the protocols have not been used on shell and tube exchangers nor on those of extremely large size, 500 gallons plus.

3.0 PERFORMANCE OBJECTIVES

Table 3.1
Performance Objectives

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Iodine concentration in HX discharge water	<ul style="list-style-type: none"> Laboratory chemical analysis report 	<ul style="list-style-type: none"> Total iodine concentration no greater than 200 ppb above seawater baseline* 	<ul style="list-style-type: none"> Total iodine concentration was 30 ppb above seawater baseline during infusion.
Improve performance of HXs as a result of implementing the I ₂ CP	<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> Reduce operational pressure Reduce operational temperature gain 	<ul style="list-style-type: none"> No changes in operational pressure or temperature gain were observed with the test and control HXs. Therefore the results are inconclusive. Since 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 ₂ MP	<ul style="list-style-type: none"> Maintain HX seawater inlet pressure compared to the control HX Change in temperature gain across the HX as a result of the cleaning process 	<ul style="list-style-type: none"> Maintaining or decreased rise in operational pressure compared to rise in the control HX Maintaining or decreased heat transfer compared to the control HX 	<ul style="list-style-type: none"> 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 ₂ MP Ease of use	<ul style="list-style-type: none"> Feedback from ship's system operators 	<ul style="list-style-type: none"> Minimal operator input required 	<ul style="list-style-type: none"> Ship's crew indicated no malfunction of the system due to I₂ infusion and no maintenance required by the crew.

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

4.0 SITE/PLATFORM DESCRIPTION

4.1 TEST PLATFORMS/FACILITIES

Prior to initiating the shipboard demonstration, pre-demonstration testing was completed at the Natural Energy Laboratory of Hawaii Authority located in Kona, HI (see Figure 4.1). 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 utilized the staff from Makai Engineering, Inc., an ocean engineering and naval architecture company that was responsible for test sampling and cartridge change. The project team was only required to start-up the test apparatus. We were not required to be on-site during the whole testing period.

At the NELHA facility, we tested the I₂MP 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, we measured the fouling rate with the technology operating at the proposed shipboard Iodine infusion rate of five minutes every hour. We also performed a control test without infusion. Our goal was to determine the fouling rate both with and without infusion on both the clear plastic surface and the varied materials found in heat exchangers. Other pre-demonstration tests included compatibility testing of the I₂ 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.



Figure 4.1
NELHA, Kona, Hawaii

The shipboard demonstration consisted of two parts, a dockside cleaning and an operational demonstration. Testing was performed on two LPAC heat exchangers on the Self Defense Test Ship, Spruance Class destroyer ex PAUL F. FOSTER (see Figure 4.2). 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 heat exchangers, and the ship's status as a research vessel thus simplifying the approval process. For the cleaning demonstration, two identical LPAC salt-water heat exchangers that are typical of those found on numerous DoD ships were cleaned using the I₂CP.

For the I₂MP 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.



Figure 4.2
Self Defense Test Ship, Spruance Class destroyer ex USS PAUL F. FOSTER

4.2 PRESENT OPERATIONS

The DoD operates numerous ships that employ salt-water heat exchangers. 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 heat exchangers are many. Typically, shell and tube designs are used, but plate and frame may be used as well. To maintain the heat exchanger, it is the common practice to take the exchangers off line with the ship dockside. Seawater heat exchangers 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.

Heat exchangers 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 heat exchanger 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, our 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. We 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. This testing was performed at bench scale at the I₂ Air Fluid Innovation, Inc. facility in Huntington Station, NY with analysis of the test components and results confirmed by an independent laboratory. The purpose of these tests was to determine if either the I₂MP or the I₂CP protocol had a deleterious effect on HX materials commonly found within a DoD marine heat exchanger. The acid/water effluent was tested for hazardous materials including heavy metal ions and change in pH.

In the second phase of testing, warm seawater at the NELHA, Kona, Hawaii facility was used to determine whether I₂ infusion has a retardation effect on foul formation. Additionally, HX material compatibility to I₂ infusion was tested under conditions that more closely matched shipboard conditions as well as iodine output in effluent water during infusion.

The third phase was under a field trial condition onboard a functioning ship, the SDTS. The I₂CP was demonstrated to determine its efficacy. The I₂ infusion device was integrated into the system to determine ease of use. Hazardous waste generation from the I₂ CP was determined under real life conditions. The I₂MP 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.

5.1 PRE-DEMONSTRATION TESTING AND ANALYSIS

At the I₂ Air Fluid Innovations, Inc. facility located in Huntington Station, NY, materials commonly found in DoD marine heat exchangers, both metallic and gasket materials were subjected to I₂CP and I₂MP. 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 5.1 were subjected to a 4% by weight concentration of the acidic cleaner specified for the I₂CP. This 4% concentration is commonly specified by heat exchanger manufacturers. Since the I₂CP uses a weaker acid, the resulting cleaning solution pH was greater than the less than 1 pH that commonly results from using the current DoD acid cleaning procedure. For this testing, the chemical exposure was continued for ten hours, which is approximately 3 times the normal cleaning duration. During the testing, the iodine vapor was continuously infused at a pressure of 30 psi and a flow of ½ cubic feet per minute with the solution continually re-circulated. The I₂CP cleaner is a blend of citric and sulfamic acid with added corrosion inhibitors. Both of these acids have pH values higher than the acids commonly used for heat exchanger cleaning such as hydrochloric and phosphoric acids.

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 I₂CP protocol. A composite test using all the metals in one bath was performed to emulate conditions

within a heat exchanger 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 using the Environmental Protection Agency (EPA) approved test procedure EPA 200.7 Rev 4.4 (Inductively Coupled Plasma-Atomic Emission Spectrometry test procedure). Initial and final pH was measured using EPA test procedure SM 18-21 4500-HB (00). For the metals testing, the project team considered acceptable results as being below levels obtained using the current cleaning procedure.

Coupons of commonly found non-metallic materials, also shown in Table 5.1, were subjected to an 8% by weight concentration of the acidic cleaner, which is twice the concentration specified by the I₂CP. This produced a cleaning solution pH value similar to the current DoD cleaning procedures. This higher concentration was used for this testing since 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 using the EPA 160.1 glass fiber filtration test procedure, Total Suspended Solids (TSS) using the EPA 160.2 glass fiber filtration test procedure, and for pH. For the TDS and TSS tests, the project team considered a change between the before and after results of 2% or less to be a good indication that the cleaning solution caused only insignificant material changes.

The coupons of these non-metallic materials were also exposed to a 24 hour continuous infusion of iodinated bubbles while immersed in 76 degree 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 97° F. At a typical room temperature of 72° F, the iodine resin elution results in a vapor containing approximately 150 ppm of I₂ within 10 seconds at the discharge nozzle. At 97° F, the equivalent I₂ concentration is approximately 250 ppm. 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 TDS and TSS.

Table 5.1
Tested DoD Heat Exchanger 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	

Also at the I₂ Air Fluid Innovation facility, coupons of the metal materials noted in Table 5.1 were subjected to direct bubbling under pressure. The purpose of this testing was to simulate the I₂MP to verify that the bubbling action did not lead to erosion of the metallic heat exchanger 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 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. Figure 5.1 is a picture of the actual test apparatus. 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. The air emanating from the nozzle was shown to contain at least 12 ppm using iodine test strips.

Each coupon was exposed to 6 hours of continuous airflow. At the completion of the testing, each coupon was rinsed in distilled water and delivered to Lit Labs, an aerospace materials testing lab in Wyandanch, NY, for 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.

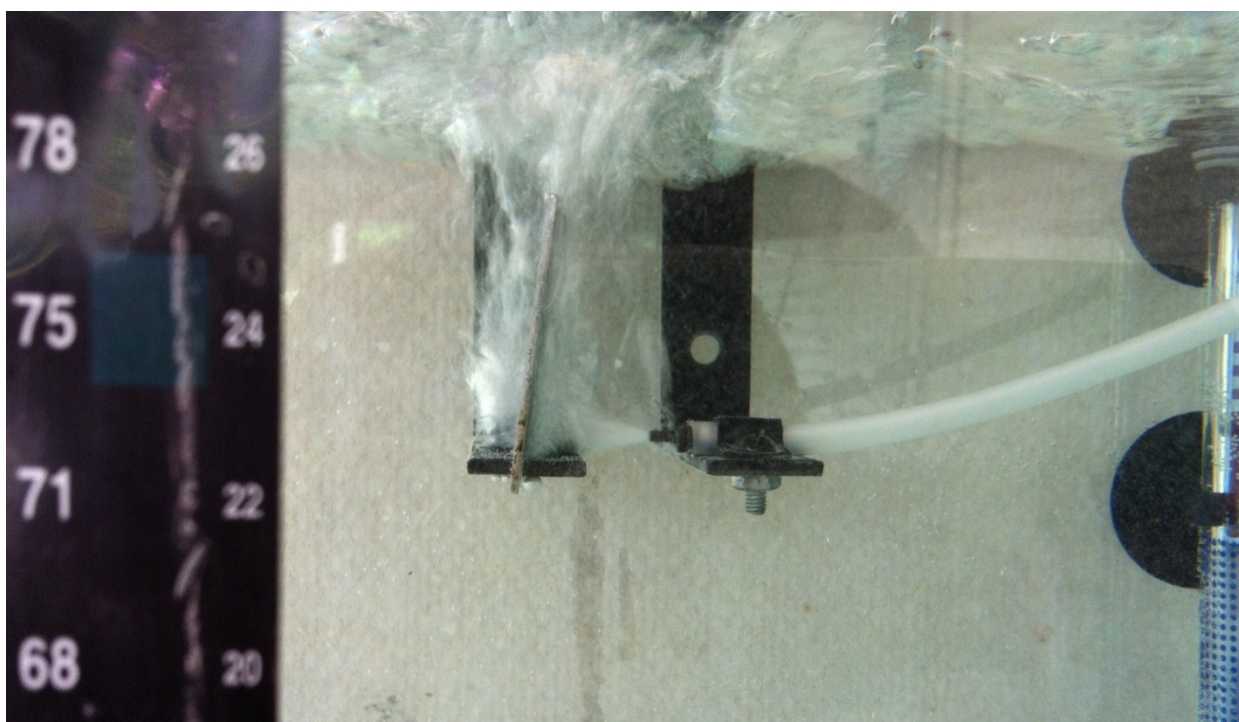


Figure 5.1
 I_2 MP Test Apparatus

In addition to the New York laboratory testing, the I_2 MP was field tested using actual warm sea water at the NELHA site in Kona, Hawaii. 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 (see Figure 5.2 for indoor assembly) consisted of one of six different metallic samples contained within a clear PVC pipe with pumped 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 one inch in diameter and clear for observation. The indoor test assembly had five of the six tubes infused using the I₂MP. 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 5.2. 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. Since 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.



Figure 5.2
NELHA Test Assembly

5.2 FIELD TESTING

The field demonstration was performed onboard the SDTS home ported in Port Hueneme, California. A schematic diagram of the shipboard demonstration I_2 infusion device has been provided in Figure 2.1. For the shipboard demonstration, the heat exchangers supporting LPAC HX No. 1 and No. 2 were selected (see Figure 5.3). Both HXs were cleaned using the I_2 CP protocol while only the No. 1 HX was maintained using the I_2 MP protocol. The LPAC No. 2 HX served as a control. All significant events, including the cleaning operations and the installation of the I_2 MP equipment, were timed in order to determine ease of implementing this technology. The demonstrations were performed in accordance with the following steps:

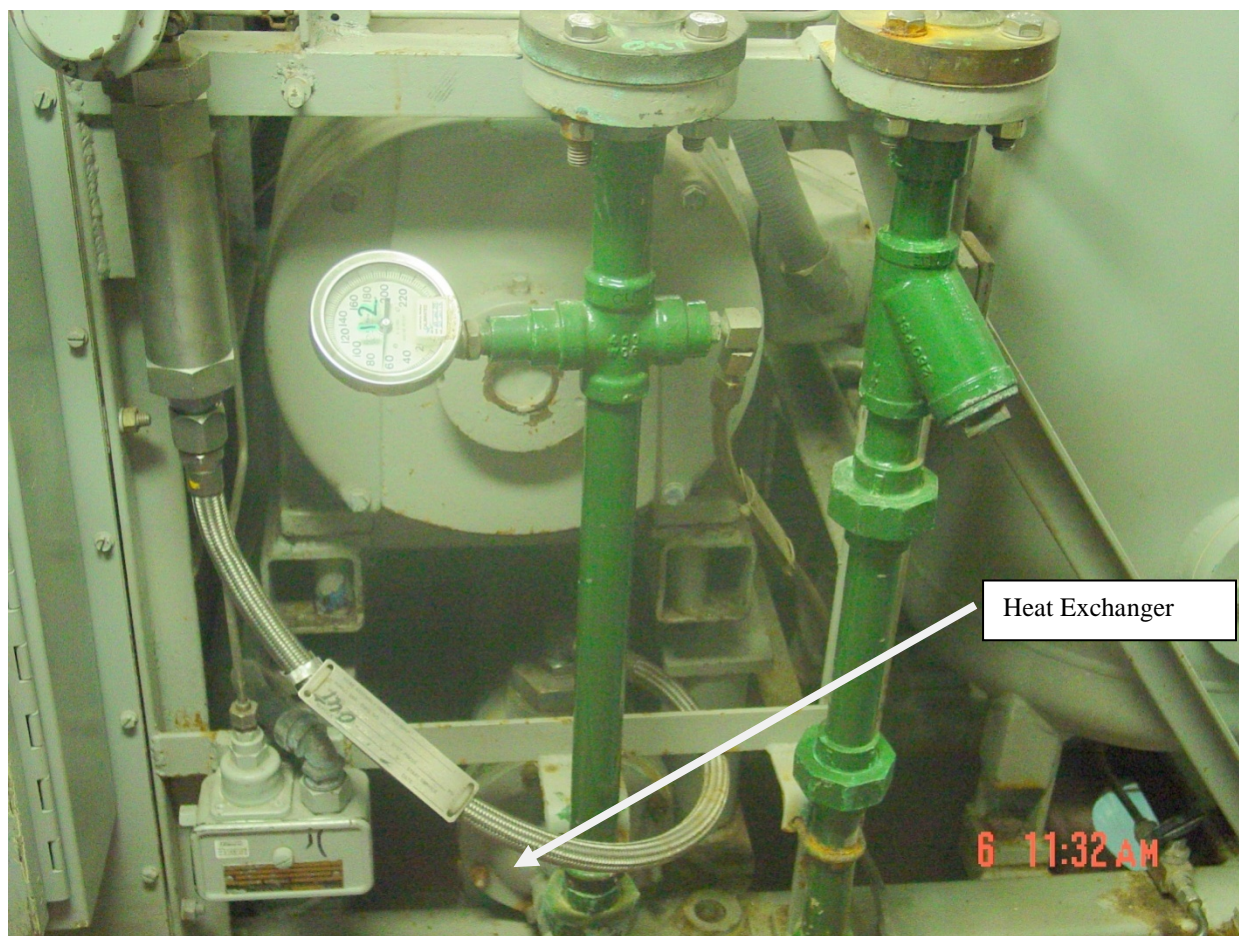


Figure 5.3
Low Pressure Air Compressor No. 1 Heat Exchanger

I_2 CP

- Before initiating the cleaning, inlet pressure and both inlet and outlet seawater temperatures were recorded for the HXs to be cleaned. These are the primary indicators of foul formation.
- Before the cleaning, a sample of cleaning fluid was obtained for analysis of pH, iodine

and heavy metals.

- A full I₂CP was performed on both exchangers. The project team performed the cleanings under the observation of the ship's crew. The exchangers were isolated, pressurized, and drained of water. The cleaner was injected into the heat exchangers and the cleaning fluid re-circulated for an hour. The exchangers were then continuously infused with iodinated air to agitate the fluid.
- Following the cleaning, the inlet pressure and both inlet and outlet seawater temperature were recorded.
- After the cleaning, the quantity of waste cleaning chemical was recorded. Samples of the waste cleaning fluid were analyzed for pH, iodine, and heavy metals.
- The I₂CP equipment was removed from the ship following the cleaning.

I₂MP

- Prior to installing the equipment, water samples from the previously cleaned HX were analyzed for pH, TOC, and heavy metals.
- The I₂MP equipment was installed on the previously cleaned LPAC No. 1 HX. The I₂MP system was mounted near the exchanger and the iodinated air-line was connected to the seawater inlet line at the flexible hose connection. The I₂MP system was also connected to the ship's low-pressure air system. The infusion device injected iodinated air into the seawater supply stream for 5 minutes every hour of the day.
- The SDTS operated under its normal schedule.
- A SDTS crewmember was responsible for system monitoring and maintenance. Every two hours pressure and temperature measurements were collected from the operational HX.
- Periodically, water samples were collected by the project team. Samples were collected during infusions and during periods without infusion. These samples were analyzed for pH, TOC, heavy metal, and concentration of total iodine.
- The project team changed the I₂ cartridge approximately monthly.
- At the completion of the demonstration, the project team visually inspected the I₂MP equipment, and recorded the pressure drop and temperature change across both HXs.

The measurements and test methods identified in Table 5.2 were used during the shipboard demonstrations. To ensure accuracy and reliability of the collected data, all samples were analyzed at an independent certified laboratory using EPA methods. For all cases, duplicate samples were provided to the lab. These samples were not identified to the lab as duplicates. In addition, the project team retained a third identical sample in case of an analysis problem. Any duplicate sample results outside the test procedures limit of accuracy was investigated. Water samples were collected from sampling ports installed both upstream and downstream from the demonstration HXs. To ensure accuracy, two members of the project team independently took the measurements from calibrated ship's gages. The two identical readings were compared to ensure that they were within the readability of the applicable ship's gage.

Table 5.2
Demonstration Measurement Techniques

Measurement	Test Method
Acidity in pH readings	SM 18-21 4500-HB(00)
Concentration of Cu, Pb, Ni, Ti and Zn (mg/L)	EPA 200.7 Rev 4.4
Concentration of total iodine in water in ppb	<u>Inductively Coupled Plasma-Mass Spectrometer</u> (EPA 6020A)
HX water pressure in psi	Calibrated ship's gage (calibrated per MIP Series 9802)
HX water temperature in degrees F	Calibrated ship's gage (calibrated per MIP Series 9802)
Quantity of cleaners used in gallons	Calibrated measuring container
Time in minutes and seconds	Stopwatch
TOC	EPA 9060

6.0 PERFORMANCE ASSESSMENT

In this section, our results are broken down into three parts. In the first part, laboratory results are discussed. This testing was primarily conducted to verify that the I₂ 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; to qualitatively demonstrate the difference in the warm seawater fouling rate between an infused and non-infusion tube; to qualitatively verify that I₂ infusion does not harm seawater algae; to verify that infusion does not result in an increase in the metal erosion rate; and finally, to verify that the I₂ kills bacteria that can cause foul formation. The final part discusses the results from the shipboard demonstration. In this part, we repeat the metal erosion and bacteria kill testing. We 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 6.1, the results from the laboratory cleaning fluid testing as described in paragraph 5.1 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 I₂CP 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 I₂CP 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 I₂CP is compatible with existing shipboard systems and its use will result in a less hazardous waste as compared to current acid cleaning procedures.

Table 6.1
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]

In regard to the iodine vapor perfusion metallic coupon bench testing described in paragraph 5.1, as indicated by the metallurgical testing and scanning electron microscopy performed by Lit Labs, 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. See Appendix B for a copy of the report summary. The non-metallic coupons testing also described in paragraph 5.1 similarly indicated little material disruption. Total dissolved and suspended solid testing indicated little change as shown in Table 6.2.

Table 6.2
Non-metallic TDS and TSS Erosion Test

	I₂ infused	Ambient air
TSS	81 mg/l	75.3 mg/l
TDS	20,500 mg/l	19,600 mg/l

Unfortunately, the testing results from the NELHA facility were not as complete as we had originally outlined in our 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 two 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 25th, 2012. During this test period, we did, however, confirm that the I₂ infusion did not appear to retard algae growth in the outdoor test assembly as shown in Figure 6.1. We also confirmed that even with an inadequate water flow rate, visual indications showed a reduction in bio-fouling (see Figure 6.2 and 6.3) 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. Thus, the full extent of the fouling differences that would occur during a period that is more representative of a Navy shipboard HX cleaning cycle (i.e. 6 to 12 months) could not be shown.

After November, 2012, all of water samples from the NELHA testing indicated that little iodine elution was occurring. Whereas water samples from the SDTS indicate a 30 ppb typical iodine presence in the water effluent, the samples from the Makai site indicate less than 3 ppb. Additionally, due to the bio-fouling that occurred in a number of the tubes and the length of exposure to this foul, metallurgical and Scanning Electron Microscopy studies were not able to be completed due to the significant presence of a number of organic and non-organic contaminants. Based on the lack of valid results, the project team decided to use Cu Ni ship's piping components from the SDTS for the metallurgical examination specified in the Demonstration Plan.

Although the initial testing results as indicated on Figures 6.1, 6.2 and 6.3 showed positive results for the infused tubes as to foul retardation and algae non-inhibition, problems first

occurring in November 2012, make all subsequent data suspect. Therefore, the project team does not consider the later data to be valid and we have not included it in this final report.



Figure 6.1
Algae Growth in Outside Infused Tube



Figure 6.2
Bio-fouling in Indoor Un-infused Tube

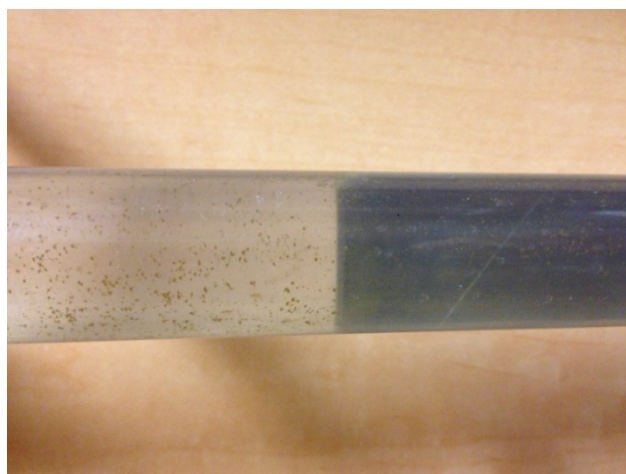


Figure 6.3
Bio-fouling in Indoor Infused Tube

During the testing at NELHA, water samples were periodically drawn from both the infused and non-infused tubes and sampled for pH, DO, total iodine, heavy metals, and bacteria. In addition, photographs of the tubes were taken. For pH, dissolved oxygen, heavy metal, and iodine content, these samples were taken during the infusion process from the downstream sampling port (above the coupon). Chemical/physical sampling results are provided in Tables 6.3 through 6.5. The total iodine results are indicative of the minimal iodine sublimation into the effluent water stream. The low metal elution is indicative of minimal surface metal ion stripping due to the iodinated bubble/metallic surface interaction. Due to prior testing of the technology, these were the results we expected.

The biological sampling consists of identifying the presence of bio-fouling related microbes within the water stream since they constitute the basis of bio-fouling in many oceanic environments. To confirm the presence and therefore the possibility of bio-fouling through microbial formation, the water stream of the two Ti tubes were tested for the primary species responsible for bio-fouling and Microbiological Induced Corrosion. In Table 6.6, the microbe presence is recorded in terms of the number of Colony Forming Units (cfu) per mil. The sample analysis was performed by the Special Pathogens laboratory in Pittsburgh, PA. These samples were collected during both infused and non-infusion periods. These tests showed that the microbes necessary for foul formation were present in the Pacific Ocean seawater used for the demonstration. During infusion, the bacterial counts within the seawater collected at the sampling port were reduced by 50 %

Table 6.3
Dissolved Oxygen and pH

Sample	Sample Date	pH (unit less)	DO (mg/l)	DO (% Saturation)	DO (Temp. °C)
After Infusion	7/1/13	8.21	6.47	95.9	25.2
During Infusion	7/1/13	8.2	6.68	98.8	25.2

Table 6.4
Total Iodine Sublimation

Sample	Sample Date	Total iodine
Infused Ti Tube	11/01/2012	327 ppb
Non-Infused Ti Tube	11/01/2012	325 ppb

Table 6.5
Heavy Metal Elution

Metal Ion	Brass NInf* Inf**	Hastalloy Ninf Inf	CuNi 90/10 Ninf Inf	Titanium II Ninf Inf	Stainless 316 Ninf Inf
Copper µg/l	12 10	10 10	10 10	10 10	10 10
Lead µg/l	10 10	10 10	10 10	10 10	10 10
Nickel µg/l	10 10	10 10	10 10	10 10	10 10
Titanium µg/l	50 50	50 50	50 50	50 50	50 50
Zinc µg/l	20 20	20 20	20 20	20 20	20 20

* NInf(Non infused) ** Inf(Infused)

Table 6.6
Bacterial Presence (cfu/ml)

Sample	Sample Date	Slime former	Acid Producing	Iron reducing	Total Heterotrophic Plate Count*
Infused Ti Tube	11/01/2012	350,000	50,000	9000	6500
Non-Infused Ti Tube	11/01/2012	350,000	50,000	9000	13,000

*All samples were taken prior to infusion in both tubes for the purpose of standardization except for total plate count.

The shipboard demonstration was initiated in March, 2103 and continued through January, 2014. Since 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, OR, the exchangers were relatively clean at the start of the demonstration period. We 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, we also observed no change 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 heat exchangers and were performed within 3.5 hours creating less than five gallons of hazardous waste per exchanger.

An integral part of this shipboard demonstration was the safety of the I₂MP infusion protocol in regard to HX materials and iodine sublimation into seawater. In Table 6.7, results from a downstream water sample analysis for metals, I₂, 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 6.7
Results of Water Sampling during Shipboard Demonstration

	Cu (µg/l)	Pb (µg/l)	Ni (µg/l)	Ti (µg/l)	Zn (µg/l)	I₂ (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 I₂CP 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 6.4 and 6.5, 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.

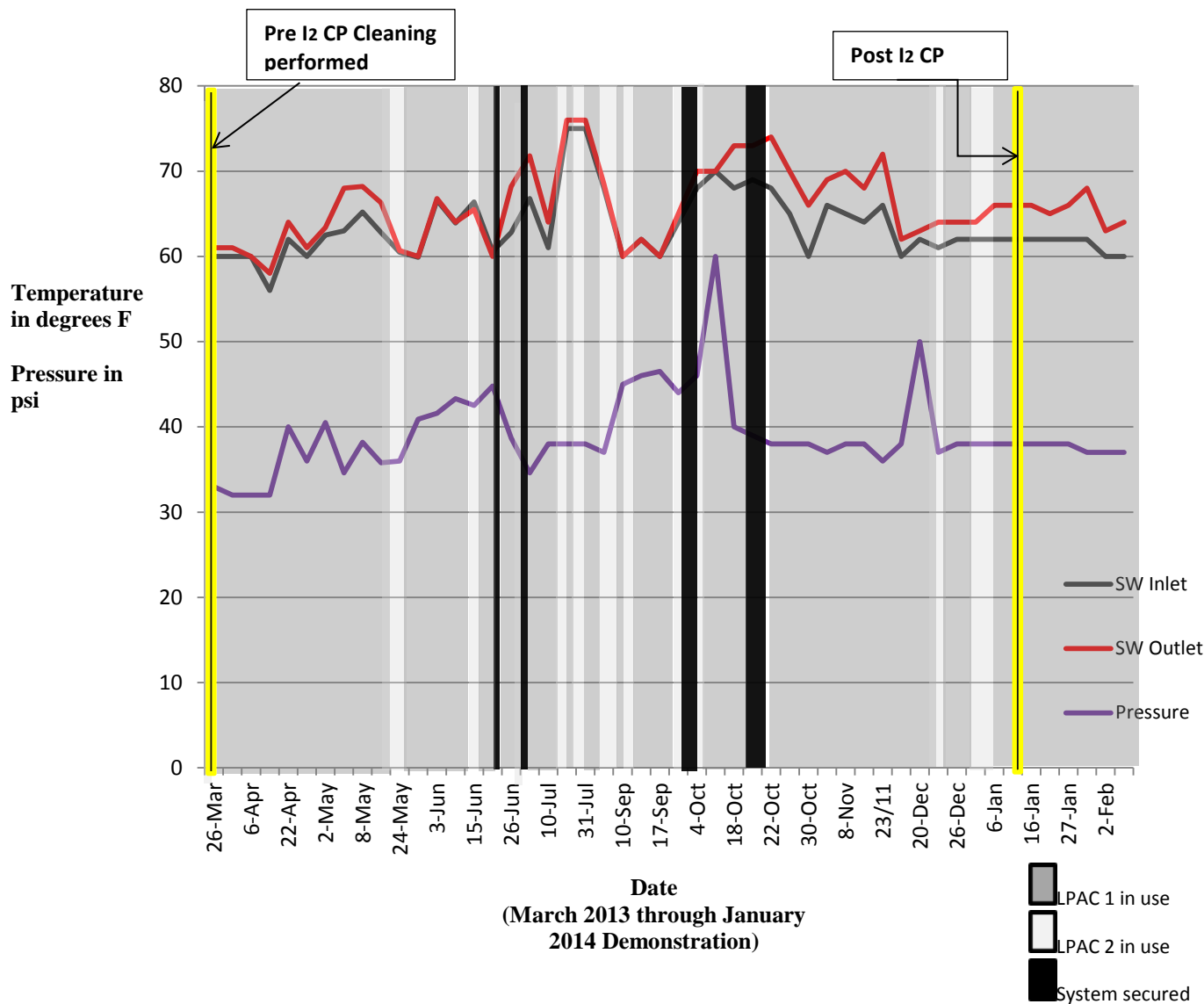


Figure 6.4
Inlet and Outlet Temperatures and Inlet Pressure for LPAC No.1

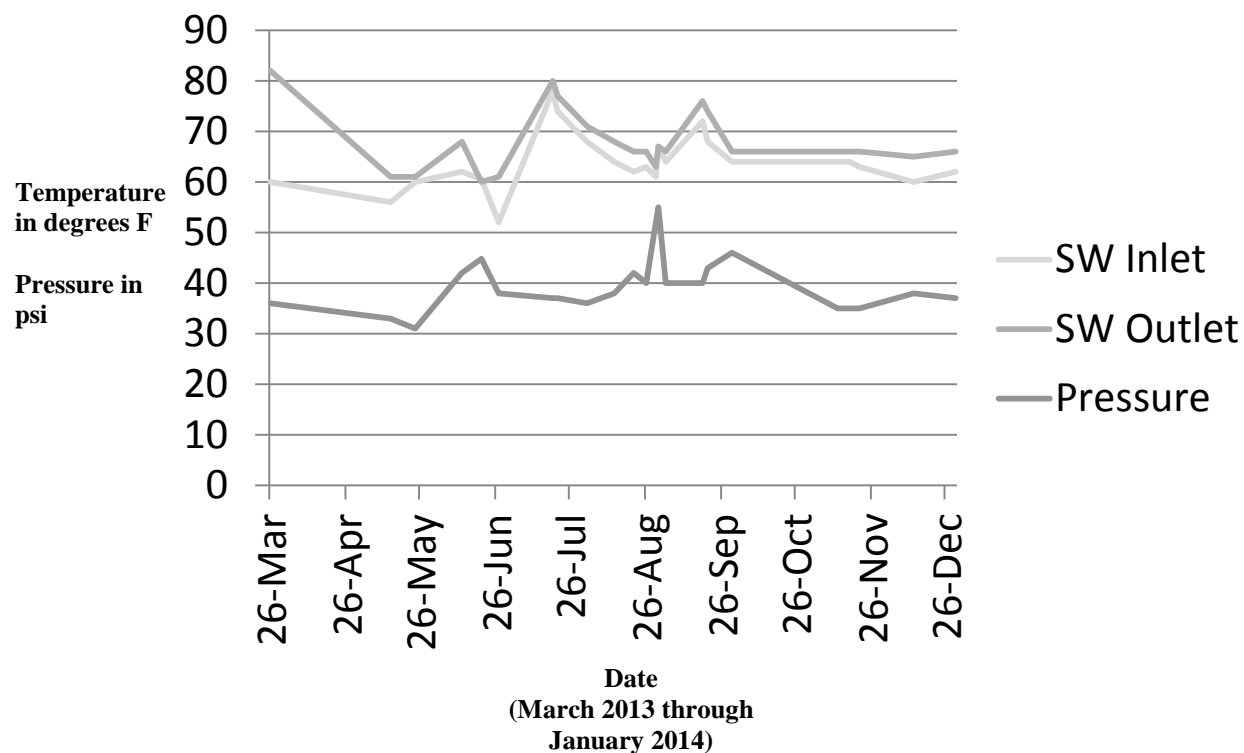


Figure 6.5
Inlet and Outlet Temperatures and Inlet Pressure for LPAC No.2

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 a 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 heat exchanger 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. Figures 6.6, 6.7, and 6.8 show significant sea grass and mud in LPAC No. 1, but little biological fouling. Similar results were found for LPAC No. 2. The heat exchangers 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.

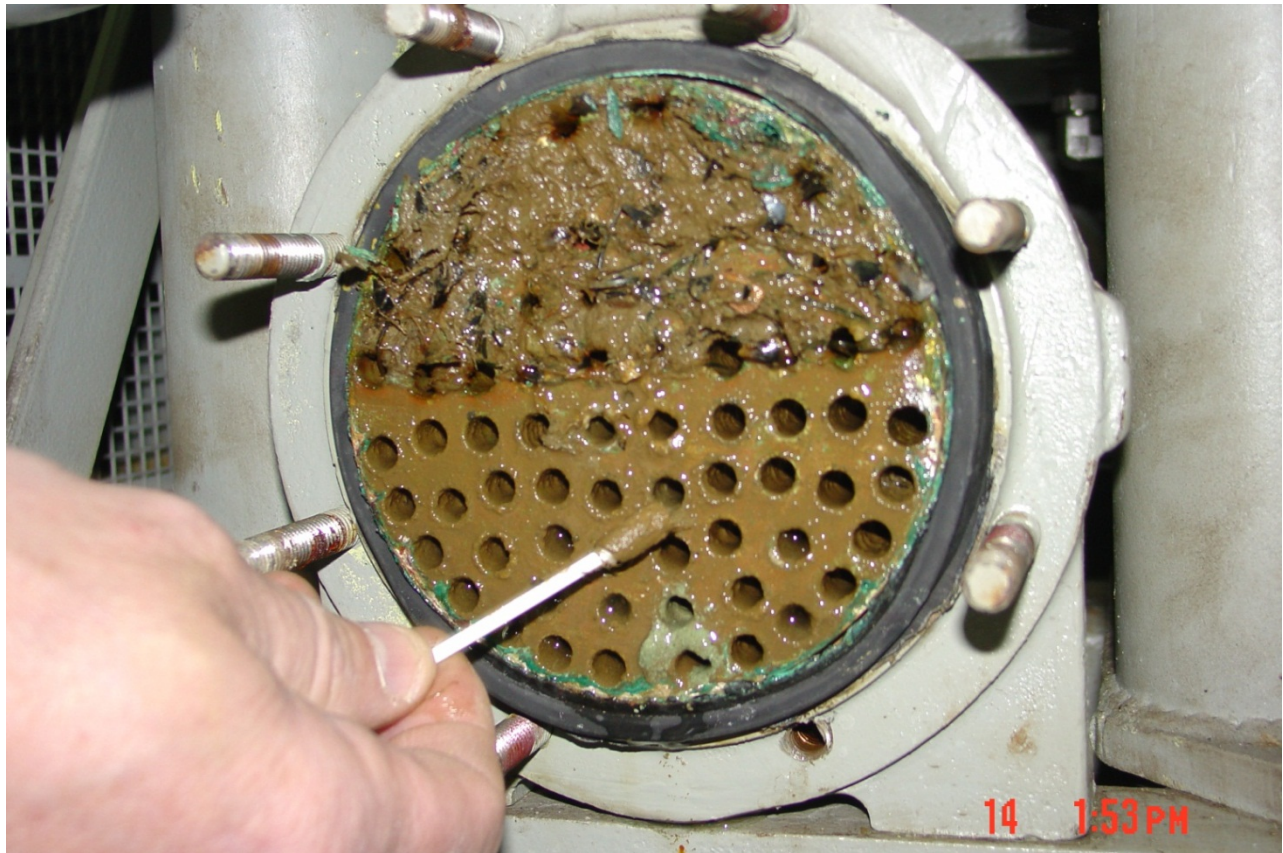


Figure 6.6
LPAC No. 1 HX Tubes Prior to Removing Sea Grass

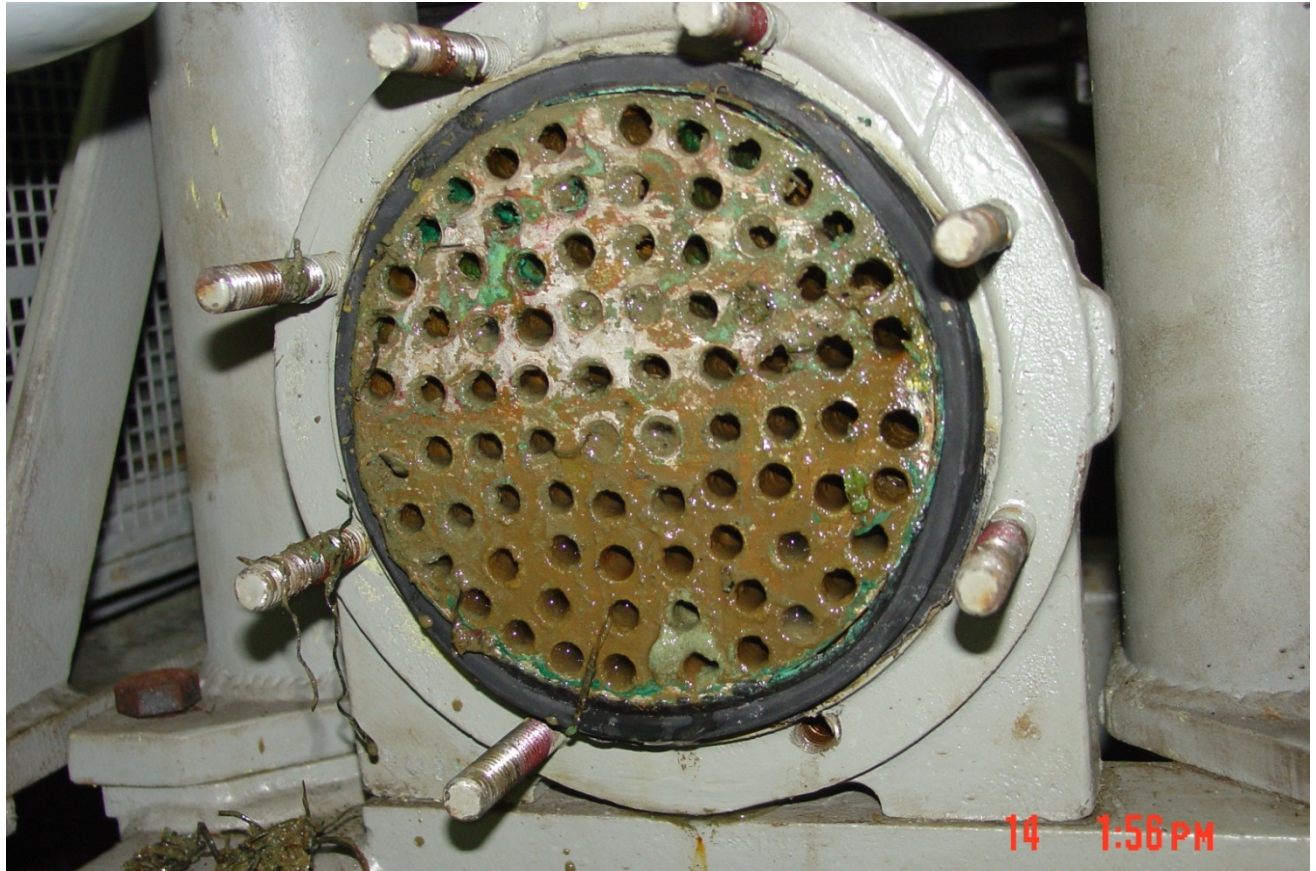


Figure 6.7
LPAC No. 1 HX Tubes After Removing Sea Grass



Figure 6.8
LPAC No. 1 Sea Grass

During the final cleaning, samples of the cleaning solution were analyzed for TOC, TSS, TDS, metal elution and pH. Samples were collected both at the start and completion of the cleanings. As shown in in Table 6.8, the analysis for heavy metal elution confirmed that the I₂CP protocol resulted in less heavy metal elution than typically occurs with the current Navy procedure. The higher TOC, TDS and TSS values found in the post cleaning solutions are indicative that organic and inorganic materials were removed during the cleanings. We cannot, however, say for certain that this removed material was foul since we know that both HXs contained significant amounts of sea grass and mud.

Table 6.8
Results of I₂CP Cleaning Solution Analysis

Mg/l	Cu	Pb	Ti	Zn	Ni	pH	TOC	TDS	TSS
LPAC 1 Pre	271	2.8	<.5	18.8	64.8	<2	3780	425	16800
LPAC 1 Post	715	24.8	.53	887	299	<2	8410	780	34800
LPAC 2 Pre	33.2	.08	<.5	3.38	4.61	<2	3290	235	17400
LPAC 2Post	277	7.56	<.5	131	106	2.18	2260	1550	24700

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 heat exchanger saw very little use. Ideally, the demonstration would have been continued until such time that the ship needed to perform a HX cleaning. Since the ship normally cleans the exchangers every 3 to 6 months, the project was able to show, however, that use of the I₂ bubble infusion technology did achieve our most important goal, namely extending the period between cleanings by 50%.

7.0 COST ASSESSMENT

7.1 COST MODEL

Employing the I₂CP and I₂MP for cleaning and maintaining heat exchangers 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 heat exchangers 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 I₂CP is that unlike the current process, the I₂CP 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 I₂CP 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, we expect a typical DoD shipboard heat exchanger to be cleaned approximately once every two years. This is significantly longer than the reported six 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 that this demonstration indicated that a 50% increase in the period between cleanings is reasonable, for this cost analysis we will assume an average of three years between cleanings when employing the I₂ bubble infusion technology.

For this cost analysis, we will make the cost comparison using the life cycle costs for employing the I₂CP and I₂MP technologies over the expected 15 year service life of the I₂ 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 7.1, the cost difference between the two cleaning methods is summarized. These costs are based on cleaning the LPAC heat exchangers. 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 I₂CP costs identified in the table represent our 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 I₂MP to extend the period between cleanings must also be considered.

Table 7.1
Cost Comparison between I₂CP and Current Cleaning Procedure

I₂CP			
Direct Environmental Activity Process Costs			
Start-Up (One-time)		Operation & Maintenance (Per cleaning event)	
Activity	\$	Activity	\$
Equipment purchase	\$1200.00 For LPAC HX size	Labor to operate equipment	\$300.00
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	\$3,200
Equipment installation	\$100	Utilities (Electrical)	Nominal Cost
		Hazardous waste disposal costs	\$1,200
		Cleaning chemicals	\$1,200
		Consumables and supplies	\$200

Besides the cleaning costs discussed above, we must also consider the costs of the I₂MP. Since most DoD operated ships have no system to maintain heat exchanger cleanliness (i.e. no chlorination system), the costs for the I₂MP represents new additional costs. These costs are identified in Table 7.2. The I₂MP system can serve multiple HXs, however, the cost estimate below assumes one system per HX.

Table 7.2
Costs to Install and Operate a Typical I₂MP System on a DoD Vessel

I₂MP			
Direct Environmental Activity Process Costs			
Start-Up (One-time)		Operation & Maintenance (Annual)	
Activity	\$	Activity	\$
Equipment purchase	\$1,200.00 (For installation on (1) LPAC exchanger)	Labor to operate equipment	Zero additional cost since it will be performed by ship's personnel
Equipment installation	\$600.00 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, we will compare costs using a present value analysis methodology that takes into account using the I₂MP throughout the equipment life cycle and the completion of numerous cleaning evolutions. For this analysis, we will assume that the I₂MP 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 I₂MP and I₂CP 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 (7 cleanings during life-cycle) and 3 years for the new method (4 cleanings during life-cycle). For the analysis, we will assume an interest rate of 3%. Since 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 I₂MP equipment is estimated based on this equipment becoming a commercial item. Currently, each system is custom manufactured. Labor costs for the I₂CP is estimated based on actual times and representative fully burdened labor rates for the required trades at Naval Base Ventura County. Material and hazardous wastes 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, thus saving approximately \$16,300 or about 50% of the costs when both the I₂CP and I₂MP processes are employed over the service life of the I₂ 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. Thus, the potential savings for installing the I₂ bubble infusion technology on all the HXs on a Navy ship is significantly greater than reported above.

8.0 IMPLEMENTATION ISSUES

The proprietary I₂ 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 I₂ 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 which 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, PA. 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, we hope to present our results to the warrant holder(s).

During our meeting with the Code 924 technical experts, they expressed the opinion that the I₂ 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 could be made. The project team does not expect a final Navy decision on whether or not to proceed with the I₂ 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 I₂ bubble infusion technology are currently being initiated. The technology is undergoing study at the Undersea Naval Warfare Center in Newport, RI 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 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 NAVFAC 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

Points of Contact

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
Bruce Holden	NAVFAC EXWC Environmental Department 1100 23rd Ave Code EV11 Port Hueneme, CA 93043	(805) 982-6050 bruce.holden@navy.mil	Principal Investigator
Gene Griffin	NAVFAC EXWC Environmental Department 1100 23rd Ave Code EV11 Port Hueneme, CA 93043	(805) 982-2267 gene.griffin@navy.mil	Assistant Principal Investigator
Michael Radicone	I ₂ Air Fluid Innovation, Inc. 14 Vallywood Dr. Huntington Station, NY. 11746	(516) 850-3727 mradicone@yahoo.com	President of Equipment Supplier
Momar Seck	Naval Surface Warfare Center, Carderock Division Wastewater Management Branch, Code 633 9500 MacArthur Blvd Bethesda, MD 20817	(301) 227-5225 (301) 227-5549 momar.seck@navy.mil	Technology Integration Lead
Dr. K. James Hay	US Army Construction Engineering Research Laboratory 2902 Newmark Dr. Champaign, IL 61826	(217) 373-3485 kent.j.hay@usace.army.mil	Army Lead
Michael Wolfe	Naval Surface Warfare Center, Port Hueneme Division 4363 Missile Way Port Hueneme, CA. 93043	(805) 228-0886 michael.wolfe@navy.mil	SDTS Project Engineer
Joseph Scharf	Naval Surface Warfare Center, Carderock Division-Ships Systems Engineering Station Code 924 5001 South Broad St. Building 4 Philadelphia, PA 19112	(215) 897-1056 <u>joseph.scharf @navy.mil</u>	NAVSEA Salt Water Piping Systems Technical Expert

Appendix B

Scanning Electron Microscopy and Metallurgical Results

Long Island Testing Laboratories, Inc.

Specialists in Aerospace Materials Testing, Since 1985
243-A Wyandanch Avenue, North Babylon, New York 11704
Phone (631) 643-6792, (800) 300-8176, Fax (631) 643-5628
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METALLURGISTS - ANALYSTS

Accredited



Certification No.: **A40946** 1 of 1

To:	DATE : August 9, 2012
12 Air Fluid Innovation, Inc.	P.O. No. : 71012
14 Valleywood Drive	MATERIAL: ---
Huntington Station, NY 11746	SPEC. No. : ---
ATTN.: Michael Radicone	IDENTITY : (1) Titanium Grade 2, (2) Cu-Ni 90/10, (3) Hastelloy C 276, (4) Stainless Steel 316, (5) Bronze

Results of test:

SEM/EDS Analysis & Metallographic Evaluation of iodine vapor infused samples:

Introduction:

Five items that were subjected to 6 hours of continuous iodine vapor infusion in a saltwater bath at 20 psi through a 1 mm nozzle were submitted for evaluation. The infusion was directed at a fixed point with the bubbles allowed to move up the surface. Half the sample was covered in plastic wrap to prevent exposure. Customer wants us to examine the exposed and unexposed areas nearest the impact point. Scanning Electron Microscopy (SEM) & Energy Dispersive X-ray Spectroscopy (EDS) analytical techniques along with metallography were suggested by the customer for the evaluation.

SEM/EDS Evaluation:

The 5 samples were evaluated by Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) analytical techniques. SEM evaluation disclosed no significant changes in the surface texture and morphology in the 'Exposed' and 'Unexposed' areas of the five samples. However the Cu-Ni sample shows some surface layer. See the enclosed SEM views.

The EDS spectra from the 'Exposed' and 'Unexposed' areas show the presence of some external contaminants in both the areas. Presence of zinc (Zn) was noted in all the samples, including the non-copper base samples at both the exposed and unexposed areas. Customer should review the enclosed EDS spectra and try to identify the source of these external contaminants.

Metallographic Evaluation:

The 5 samples were cross-sectioned at the junction of the exposed and unexposed area and microscopically examined for any microstructural changes at the impacted surface. Metallographic evaluation of the five etched samples did not show any significant differences in the microstructure of the exposed and unexposed areas. See the enclosed addenda of the metallographic views.

The foregoing is a true copy of our records from the tests of this material

T. Rao Tipirneni, President

Samples will be retained only for 30 days after this report date. No responsibility is assumed for losses due to interpretation relative to our impartial reports. Liability otherwise is limited to value of services rendered. Recording of false, fictitious or fraudulent statements or entries on this document may be punished as a felony under federal law. Also the test report shall not be reproduced except in full, without our written approval. Test results marked with an (X) have been performed by a qualified outside source.

Appendix C

Cornell Mastitis Study

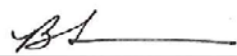
STUDY REPORT:

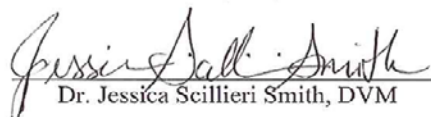
Evaluation of the Germicidal Activity and the Associated Iodine Residue of i2Vapor Perfusion Technology

Prepared by:

Dr. Frank Welcome, Mr. Brad Rauch and Dr. Jessica Scillieri Smith

 12/20/13
Dr. Frank Welcome, DVM, MBA Date

 12/20/2013
Brad Rauch, MS, PMP Date

 12/20/13
Dr. Jessica Scillieri Smith, DVM Date

Quality Milk Production Services
Cornell University, Animal Health Diagnostic Center, College of Veterinary Medicine,
Ithaca, New York, USA

Prepared for:

Mr. Mike Radicone
14 Valleywood Dr.,
Huntington Station, NY 11746



There was a large difference between the rinsate iodine concentrations of the treatment groups. All rinsate samples obtained from the 1.0% iodine treatment had concentrations of iodine greater than 2900 ppb, where all the rinsate samples from the i2VP treatment group had concentrations less than 250 ppb. The mean concentrations were 3370 and 198 ppb for 1.0% iodine and i2VP, respectively. The comparison between these means had a p-value <.0001.

Disinfection rates of liquid volume varied depending on the organism. *E.coli* and *Staphylococcus aureus* seemed to be the most resilient to disinfection by i2VP treatment, where *Streptococcus uberis* and *Prototheca* were more susceptible. It should be noted that this was not a replicated portion of the trial and was conducted only to provide descriptive insight into the effect of bubbling a liquid volume containing high populations of organisms.

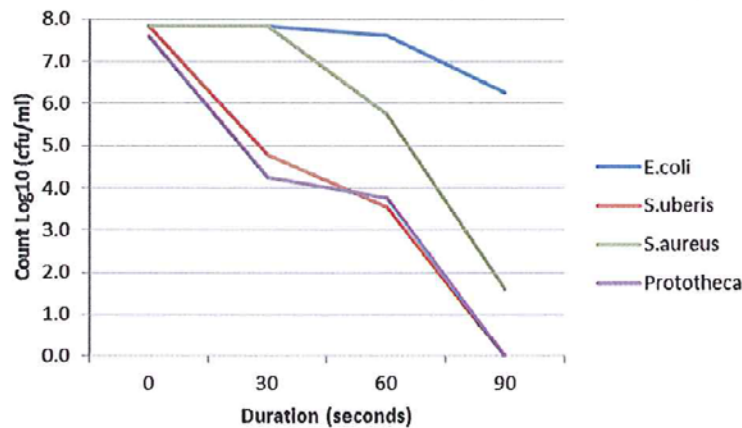


Figure 1. Reduction in organism counts, overtime, as a result of bubbling liquid volume with I₂ vapor.

4. Summary

A newly developed disinfectant technology called the i2 Vapor Perfusion was compared to traditional disinfection with 1.0% iodine dip. The comparison was aimed at germicidal activity on four mastitis-causing organisms and the resulting concentration of iodine residue that could be recovered from the teat surface. While the i2VP was not as effective as the 1.0% iodine dip in reducing organism populations, it did significantly reduce the populations compared to the negative control. In addition, the iodine residue that resulted from the disinfection with the i2VP was approximately 1/20th of the residue produced by 1.0% iodine dip. The results of this experiment show that the i2VP has the ability to significantly reduce mastitis-causing organism populations, while leaving little iodine residue on the teat surface. In addition, significant disinfection can be obtained in liquid volumes, but the rate of kill is likely variable for each organism. Further investigation into various applications of the i2VP in food production is recommended.