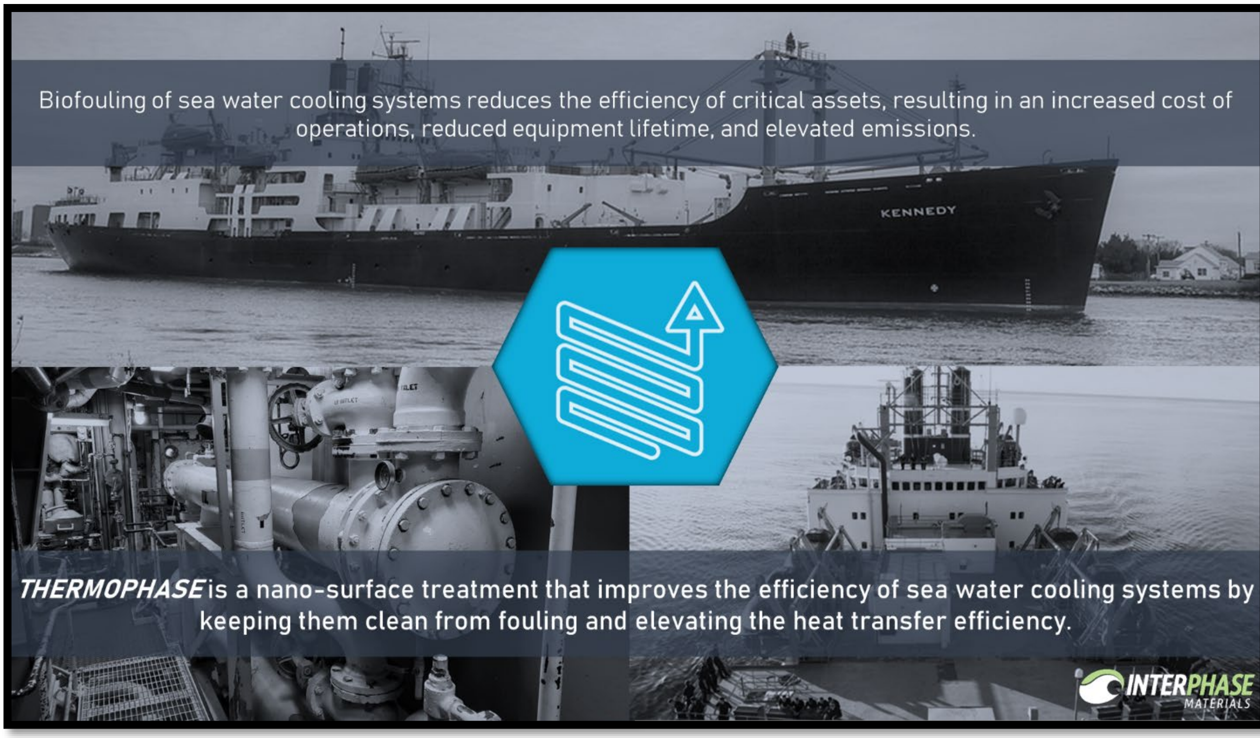
Biofouling Prevention Demonstration on Seawater Cooling System

Final Report

August 11, 2022



INTERPHASE MATERIALS | LCE LIFE CYCLE ENGINEERING | U.S. Department of Transportation Maritime Administration

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Name: Dr. Noah Snyder
Phone: (814) 282-8119
Email: NoahSnyder@InterphaseMaterials.com

Acknowledgements

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Executive Summary

Biofouling on seawater cooled systems reduces the effectiveness of critical systems such as heating, ventilation, and air conditioning (HVAC) plants and engines, resulting in reduced energy efficiency, increased emissions, and unnecessary maintenance costs. Funded by MARAD's META program, Interphase Materials worked with the Massachusetts Maritime Academy and Life Cycle Engineering to demonstrate the effectiveness of its biofouling reducing nano-surface treatment solution, THERMOPHASE. During this project, Interphase Materials applied THERMOPHASE to a demonstration chiller and installed test coupons in an auxiliary seawater cooling system strainer. Following 115 days in operation, a significant reduction in biofouling was observed in both the test coupons and inside the condenser of the demonstration chiller. In parallel, Life Cycle Engineering evaluated the status of the seawater cooled assets for both current and future energy efficiency studies. The inability to collect reliable data from the seawater cooled chillers inhibited the calculation of baseline efficiency metrics for the system. The results of this project are likely to assist with the commercialization of THERMOPHASE in the maritime industry where it is expected to improve the energy efficiency of vessels.

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Chapter 1: Background

Project Overview

Massachusetts Maritime Academy (MMA) partnered with Interphase Materials, Inc. (IPM) to use the Maritime Environmental and Technical Assistance (META) funding to support a demonstration of Interphase Materials' nano-surface treatment, THERMOPHASE, on the TS KENNEDY's seawater cooling system with the goal of improving efficiency through biofouling prevention. One of META's primary focus areas is reducing vessel and port air emissions. Biofouling is a common problem for marine vessels which reduces efficiency for both propulsion and seawater cooling systems leading to increased vessel emissions.

Biofouling is the accumulation of organisms such as barnacles and algae on wetted surfaces. Beyond the operational impact of biofouling, the International Maritime Organization has targeted the control of a ships biofouling in order to prevent the transfer of invasive aquatic species [1]. Biofouling occurs on numerous ship locations including seawater cooling systems which are used for applications such as heating, ventilation, and air conditioning (HVAC), engine cooling, and refrigeration container (reefer) cooling. Heat exchangers used in these cooling systems are especially prone to reduced performance caused by biofouling due to their high surface areas, small openings, and the low thermal conductivity of biofilms.

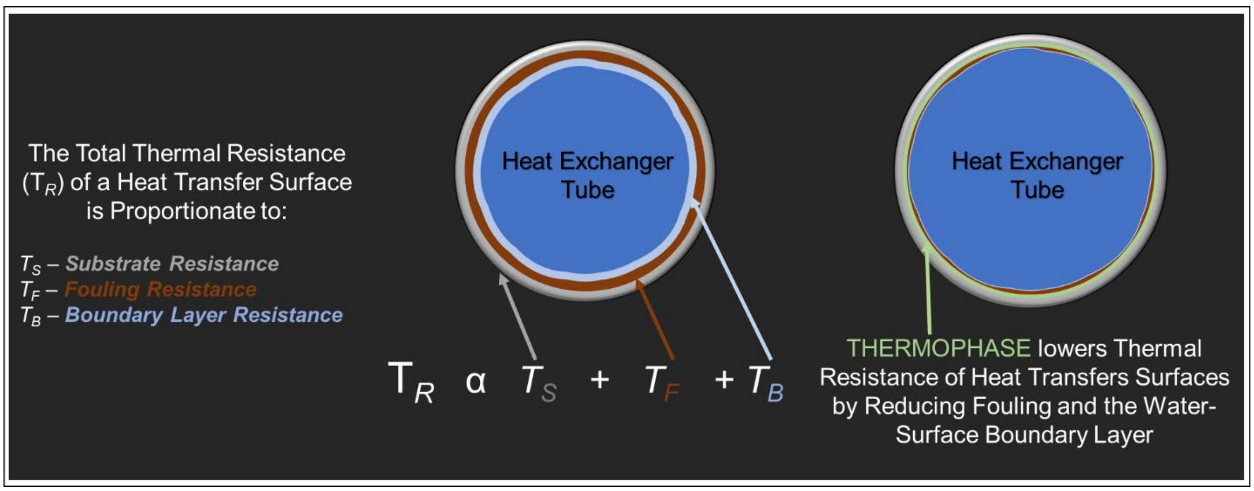

Figure 1. THERMOPHASE Mechanism of Action. The total thermal resistance of a heat transfer surface (T_R) is proportional (α) to the sum of the substrate resistance (T_S), the fouling resistance (T_F), and the boundary layer resistance (T_B). THERMOPHASE is believed to improve heat transfer via reducing both the fouling and the boundary layer resistances.

Interphase Materials has developed a proprietary surface treatment (THERMOPHASE) which functions by mitigating biological fouling (algae, barnacles, etc.), reducing inorganic fouling (scale and corrosion by-products), and improving the heat transfer properties of heat exchanger components (e.g., condensers in HVAC units) (see **Figure 1** for an overview of the THERMOPHASE mechanism of action). THERMOPHASE is a specially formulated solution that creates a single molecular layer coating on the surface of the heat exchanger. The coating is theorized to increase the efficiency of heat exchangers via two separate mechanisms. Firstly, by reducing the biofouling accumulation on a heat transfer surface, the thermal resistance due to fouling (T_F) is reduced. Secondly, it is hypothesized that THERMOPHASE also reduces the boundary layer resistance (T_B). The boundary layer resistance, also known as the laminar boundary layer, is created from the formation of water monolayers on the heat transfer surfaces[2]. THERMOPHASE alters the solid-liquid interface, and this change is believed to be the reason for previously observed increases in heat transfer efficiency, even on clean components. As a results of biofouling reduction and heat transfer increases, IPM believes THERMOPHASE is a high-reward, near-term technology that has the potential to improve the efficiency, decrease the ownership costs, and improve overall performance of maritime vessels.

THERMOPHASE Development

Interphase Materials (IPM) has been developing THERMOPHASE since 2016 (see **Figure 2** for a complete timeline of development). IPM was founded in 2015 in Pittsburgh, PA after launching from the University of Pittsburgh. The first technology IPM developed was originally created with the intent to reduce biofouling on brain implants to improve neural prosthetic technology.

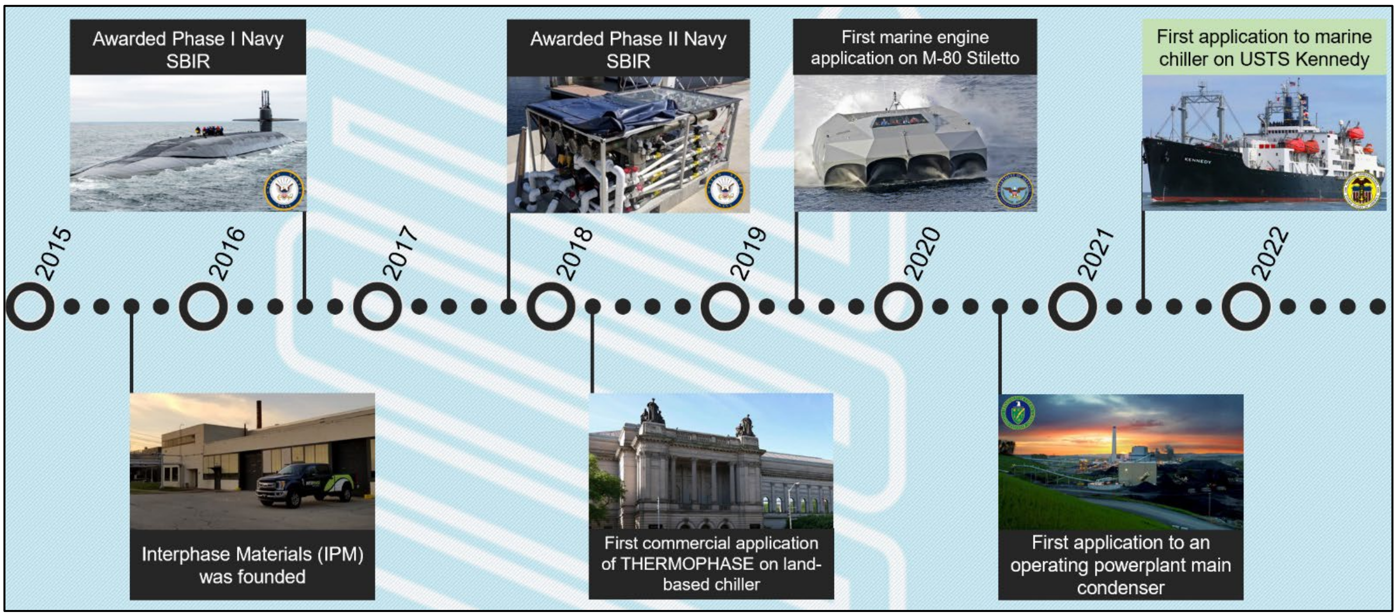

Figure 2. Timeline of THERMOPHASE Development.

In 2016, the U.S. Navy awarded IPM a Phase 1 Small Business Innovative Research (SBIR) contract to develop a solution for reducing biological fouling in marine heat exchangers (Topic # N161-41-0110, Contract # N00024-16-P-4092). During the Phase 1 SBIR, IPM created THERMOPHASE, a biocide-free chemical material that covalently binds to the surface of heat exchanger components to reduce the accumulation of biological organisms. IPM discovered early during heat transfer testing that THERMOPHASE appeared to increase the heat transfer of heat exchangers, even those free from fouling. Due in part to this discovery, the U.S. Navy awarded IPM a Phase 2 SBIR contract in 2017 to continue upon the development of THERMOPHASE. At the time of this report, the Navy Phase II SBIR is active with a period of performance expected to conclude in October of 2022.

Following the initial success of the U.S. Navy SBIR development, IPM began transitioning the technology to land-based commercial applications. In 2018, IPM applied THERMOPHASE to a land-based chiller plant at the Carnegie Museum of Natural History in Pittsburgh, PA. Since that application, IPM has continued applications to land-based chillers in several states including, Pennsylvania, New York, Illinois, Texas, Nebraska, Massachusetts, and Louisiana.

In 2019, as part of a Phase 3 SBIR awarded by the Rapid Reaction Technology Office, IPM applied THERMOPHASE to the seawater cooling system of a Caterpillar engine onboard the M-80 Stiletto. This marked the first time THERMOPHASE had been applied to an operating marine system. The following year, the Department of Energy funded IPM to apply THERMOPHASE to the first power plant condenser system at the Longview Power Plant in Maidsville, West Virginia.

With the support of this project, IPM applied THERMOPHASE to the first marine chiller onboard the TS KENNEDY using a practical commercial application system. IPM worked together with the Maritime Administration (MARAD) and Life Cycle Engineering (LCE) to perform this demonstration of THERMOPHASE on-board the TS KENNEDY at Massachusetts Maritime Academy. This demonstration included coupon testing at key locations in the seawater cooling system, an assessment of the TS KENNEDY's seawater cooled assets and a demonstration application of THERMOPHASE to a reefer heat exchanger.

Objective

The Massachusetts Maritime Academy and Interphase Materials believe that a demonstration of THERMOPHASE on a surface ship's seawater cooling system is the next critical step in transition and integration of their technology into the maritime industry. The goal of this project is to demonstrate THERMOPHASE's benefits when applied to shipboard seawater cooling assets. Massachusetts Maritime Academy and Interphase Materials believe that the benefits of the antifouling surface treatment are well aligned with META's objective of improving the efficiency of domestic maritime industries. To achieve these goals the team have identified the following technical objectives for this phase I project:

I. **Demonstrate ability of THERMOPHASE to reduce biofouling under typical ship conditions**
II. **Determine baseline performance of seawater cooled assets**
III. **Perform Return on Investment calculations**

Project Task Summary

During a 12-month period of performance, Interphase Materials, in collaboration with the Massachusetts Maritime Academy and Life Cycle Engineering, tested THERMOPHASE onboard the TS KENNEDY. The testing included the application of THERMOPHASE to a demonstration heat exchanger, biofouling coupon analysis, and an assessment of the critical cooling components of the test vessel.

TS KENNEDY Demonstration Platform

The TS KENNEDY, a former commercial freighter and current training ship for the Massachusetts Maritime Academy, was used a demonstration ship for this project. The ship initially launched in 1967 and became a training ship in 2001. The TS KENNEDY is 160 m long, has a range of 10,000 nautical miles, and contains 8 decks. IPM worked with the Massachusetts Maritime Academy crew to select an ideal demonstration heat exchanger. As can be seen in Figure 3, a Seahorse model chiller unit manufactured by Carrier located on Frame No. 145 of the Upper Tween Deck (Figure 3A) was used as a test component. There are two Seahorse chillers located on the Tween deck that serve to provide refrigeration of the food storage (Figure 3B). For this demonstration Seahorse chiller #2 (starboard) was selected for application of THERMOPHASE (Figure 3C) and chiller #1 (port) was used as a control since both units are operated when the ship is active.

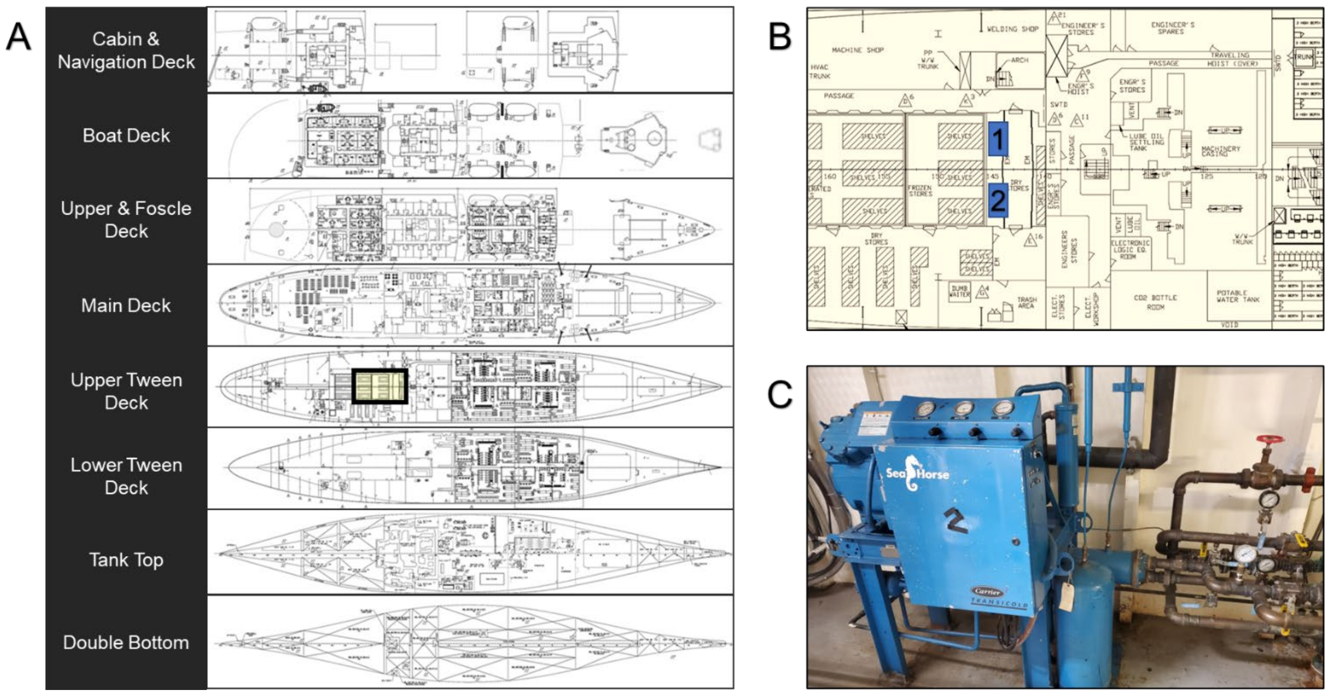

Figure 3. TS KENNEDY Test Component Location.

TS KENNEDY Summer Cruise

The TS KENNEDY departed on Summer Cruise within this project's period of performance (weekly destination tracks can be seen in **Figure 4**). The cruise started on May 29th in Buzzards Bay, Massachusetts. The initial cruise through the end of June was operated by the Massachusetts Maritime Academy. The cruise following July was operated by the Texas A&M Maritime Academy.

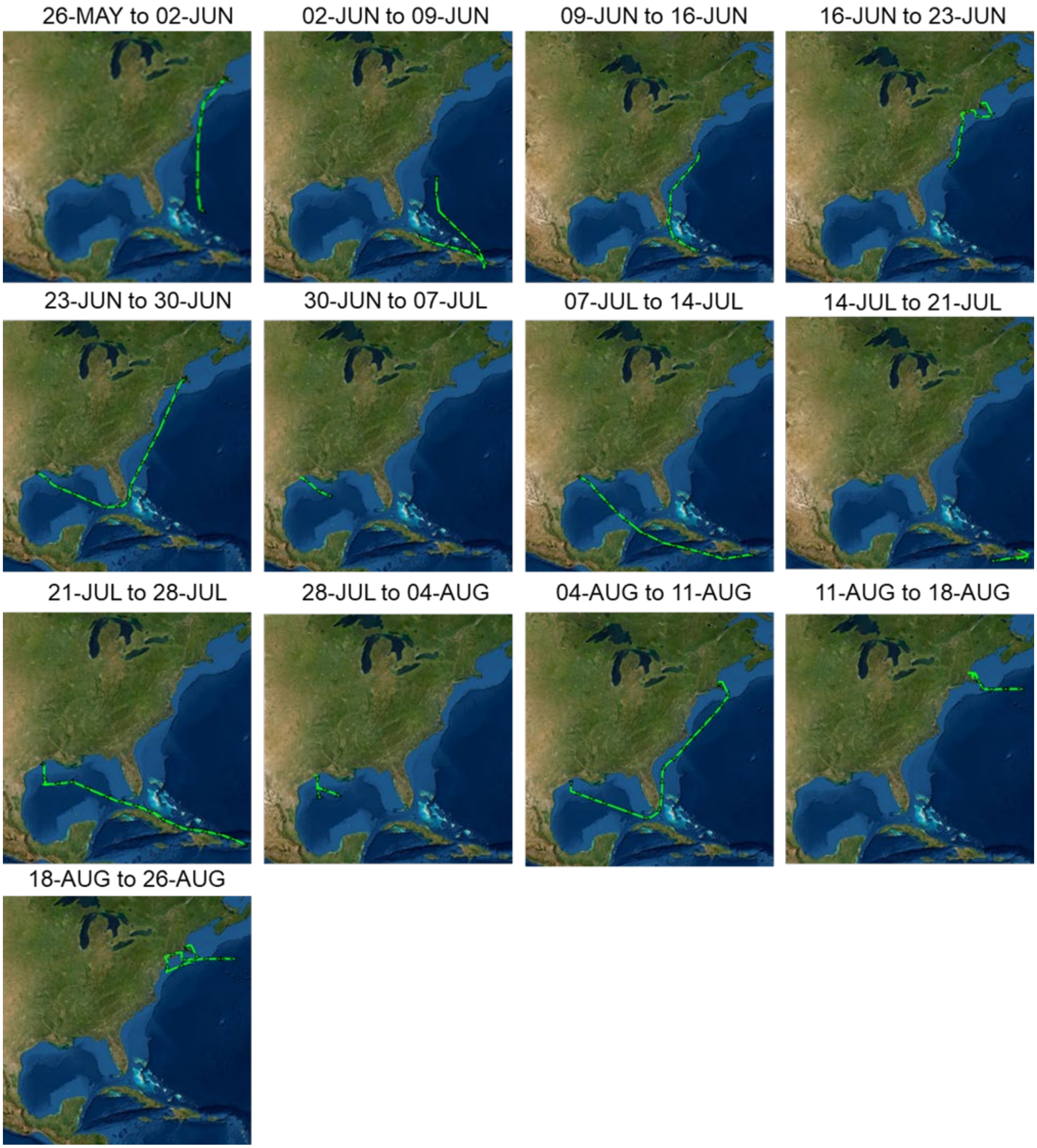

Figure 4. TS KENNEDY Summer 2021 Cruise.

Chapter 2: Biofouling Assessment

Task Overview

Not including Task 0, the completed project had four tasks (as can be seen in Figure 5). Task 1 was focused on demonstrating the fouling reduction properties of THERMOPHASE. In Task 2, efficiency data was collected from the TS KENNEDY's seawater cooled assets and, in Task 3, the fouling data was integrated with the efficiency information to evaluate the return on investment (ROI). Finally, in Task 4, a Phase II test plan was created for future evaluation of THERMOPHASE.

Task	Description	Deliverable
Task 0: Project Management	Reporting, internal meetings, and communications with customers/partners	Final Deliverable Report containing results
Task 1: Acquire fouling data on test vessel	Install and evaluate samples in sea water systems, image key components before and after test, and treat reefer oil cooler	Results to test hypothesis about fouling reduction properties of IPM product
Task 2: Acquire component efficiency from sea water cooled assets	Collect and monitor efficiency data from test vessel on critical assets [Life Cycle Engineering]	Results to test hypothesis about efficiency improvements of IPM Product
Task 3: Integrate fouling and efficiency data to prepare ROI	Correlate fouling data from Task 1 and efficiency data in Task 2 to create performance improvements ROI	ROI for maritime industry by vessel class and cumulative impact to U.S.
Task 4: Phase II Test Plan Creation	Use Lessons learned to create a test plan for treating additional sea water cooled assets during 2021/2022 maintenance period with assessemtn in 2022	

Figure 5. Task Overview.

Timeline

The project was officially awarded on April 27th, 2021 with an initial end date of May 31st, 2022. The detailed initial project timeline by task can be seen in Figure 6. A two month no-cost extension was completed to ensure time for the completion of the Final Report.

	Month											
Task	1	2	3	4	5	6	7	8	9	10	11	12
Task 0: Project Management	1	1	1	1	1	1	1	1	1	1	1	1
Task 1: Acquire fouling data on test vessel		1	1	1	1	1	1	1	1	1		
Task 2: Acquire component efficiency from sea water cooled assets		1	1	1	1	1	1	1	1	1		
Task 3: Integrate fouling and efficiency data to prepare ROI									1	1	1	1
Task 4: Phase II Test Plan Creation											1	1

Figure 6. Project Task Timeline.

Budget

The project had a total funding magnitude of $200,000.00. The funding mechanism was through an amendment of an existing Cooperative Agreement between the Department of Transportation Maritime Administration, Office of Environment & Innovation, Maritime Environmental and Technical Assistance, and the Massachusetts Maritime Academy. The project cost included a $158,738 firm-fixed price subcontract to Interphase Materials to conduct and oversee the work. The project was completed within the initial budget.

Team

In addition to oversight from MARAD, the team consisted of the Massachusetts Maritime Academy, Interphase Materials, and Life Cycle Engineering. The summary of the team roles can be found in Figure 7. The Massachusetts Maritime Academy is the owner and operator of the TS KENNEDY and assisted with installation of the Interphase Materials THERMOPHASE technology. Interphase Materials is the inventor and owner of THERMOPHASE and led the installation and biofouling evaluation of the THERMOPHASE technology. Life Cycle Engineering collected information regarding the seawater cooled assets from the Massachusetts Maritime Academy and THERMOPHASE performance data from Interphase Materials to assess the benefits of the technology to the maritime industry.

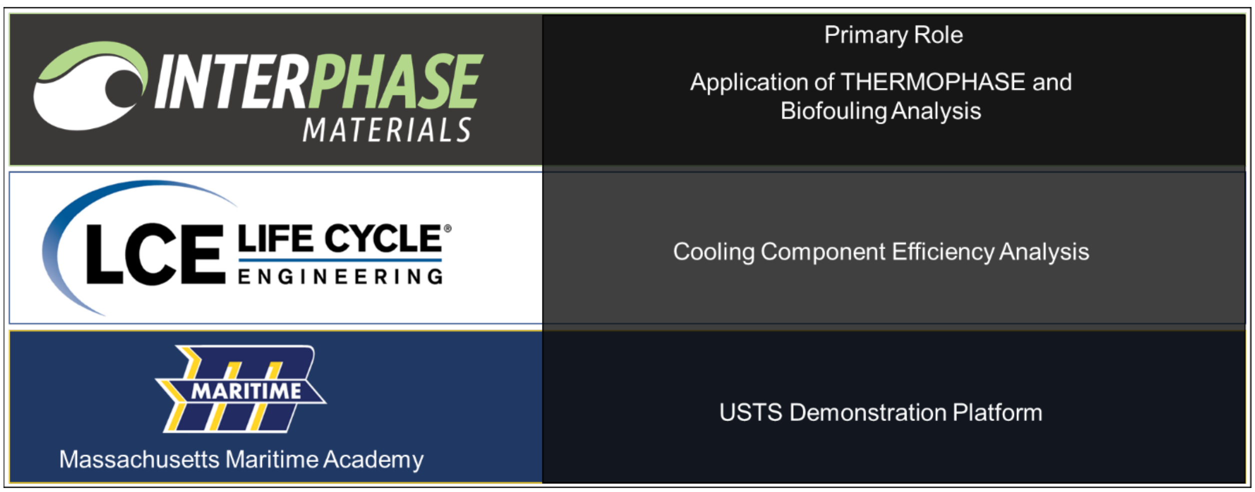

Figure 7. Project Team Primary Roles.

Treatment of TS KENNEDY Heat Exchanger

Following conversations with the Massachusetts Maritime Academy team, a Carrier Seahorse refrigeration plant was chosen as an ideal site for the demonstration. The plant was chosen as it contains two identical chillers in parallel that are in continuous use on the ship. Prior to the application of THERMOPHASE, the Massachusetts Maritime Academy team cleaned and drained both chillers. On May 17th, 2021 Interphase Materials applied the THERMOPHASE technology to Seahorse chiller #2 onboard the TS KENNEDY, prior to the ship getting underway for Summer training cruises (see previous section for asset description). To assist with the application, an engineer from Life Cycle Engineering was on-site. In addition, crew members and students from the Massachusetts Maritime Academy assisted with the application. To perform the THERMOPHASE application, Interphase Materials connected a Goodway descaling system to Seahorse Refrigeration Plant #2 and flushed the proprietary THERMOPHASE solution through the tube-side of the condenser for 60 min. During the application process, metal test coupons were treated by suspending the samples in the reservoir of the descaling system. Images of the system and the coupons suspended in the reservoir can be seen in Figure 8. The coupons were removed from the reservoir and used for biofouling and quality control assessment as described below.

Figure 8. THERMOPHASE Treatment Test Setup.

As an important note, the application system did not include any descaling chemical. Interphase Materials uses the Goodway descaler system solely to flush the THERMOPHASE technology through the heat exchanger, no cleaning is occurring during this step. Following the application, both chillers in the refrigeration plant were used during a summer cruise until they were inspected in September of 2022.

Installation of Biofouling Test Coupons

For biofouling assessment, metal coupons were installed in a seawater strainer (within the seawater cooling system that supplies the Carrier Seahorse refrigeration plant) by fastening the coupons to the side of the strainer cage (see Figure 9). Pristine, 'untreated', coupons and THERMOPHASE 'treated' coupons from the application described above were installed. Four different types of coupons were evaluated in this step including: 90/10 CuNi, 70/30 CuNi, 316 stainless steel, and titanium (unalloyed, commercially pure). A stainless steel biomesh coupon was initially included but the samples were removed from analysis due to damage to the coupons during the test. In addition, admiralty brass and 304 stainless steel coupons were treated during the THERMOPHASE application, but these samples were not installed into the strainer for fear of decreasing the performance of the strainer during operation.

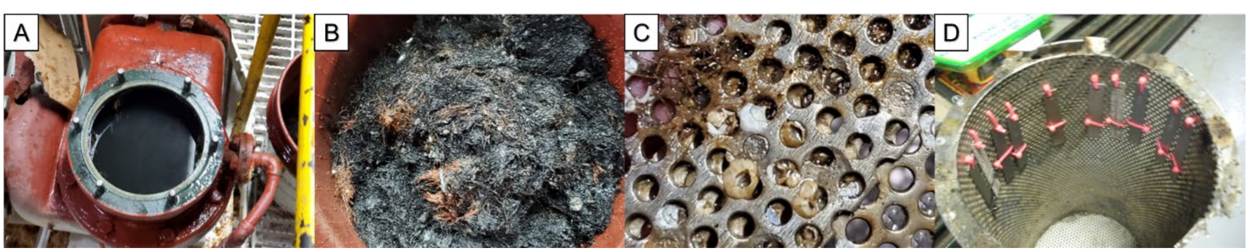

Figure 9. Biofouling Coupon Strainer Installation. The seawater strainer (A) was inspected prior to the summer cruise and contained an accumulation of sea waste (B). The presence of microfouling and macrofouling were apparent on the walls of the strainer (C). The coupons were suspended to the walls of the strainer (D).

After the TS KENNEDY returned to the home of the Massachusetts Maritime Academy in Buzzards Bay, Massachusetts, the coupons were removed from the strainer and imaged immediately on September 9th, 2021. At that time the coupons had been installed in the system for 115 days.

Coupon Contact Angle Measurement

To ensure that the THERMOPHASE application was effective, a set of coupons from the application reservoir were evaluated for changes in surface energy. In general, samples that have been treated with THERMOPHASE have a higher contact angle than pristine surfaces. A more recent biocide-free strategy for preventing biofouling is to the creation of hydrophobic coatings to deter the adhesion of organisms [3].

Contact angle is a useful measurement to evaluate the hydrophilicity or hydrophobicity of a sample. By convention a hydrophilic sample contains a contact angle less than 90°, a hydrophobic sample has a contact angle between 90° and 120°, while a super hydrophobic sample has a contact angle greater than 120°. The contact angle is the measurement of the angle between the surface and the droplet (as is depicted in Figure 10). Different alloys have varying surface energy and therefore different contact angles. As an example samples with more polar functional groups exposed on the surface (such as CuNi samples) will have lower contact angles compared to more nonpolar surfaces like stainless steel alloys.

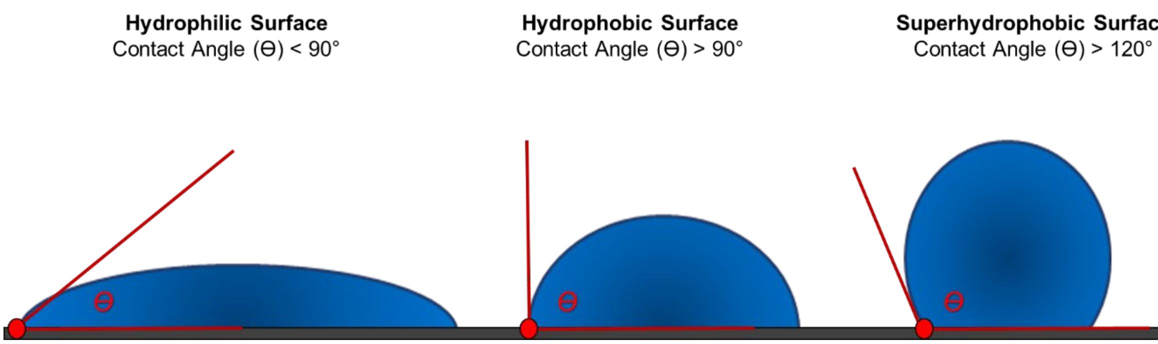

Figure 10. Contact Angle Schematic.

In IPM facilities, surface energy was quantified using the static (i.e. sessile drop) contact-angle measurement method [4]. Droplets of water were pipetted onto the pristine and 'treated' samples prepared in Task 1, and the contact angle was measured by imaging with IPM's custom built contact-angle goniometer. A goniometer is a special tool with a flat stage and a camera to accurately measure the contact angle of a droplet. The contact angle measurements were compared using a one-way analysis of variance (ANOVA) with a post-hoc Tukey HSD (Honestly Significant Difference) test (see an example of the droplet test and imaging in Figure 11).

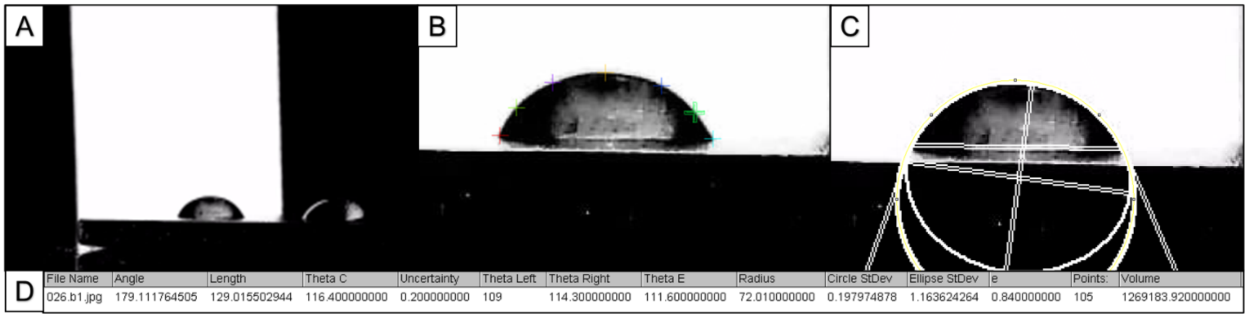

Figure 11. Contact Angle Imaging Methodology. The contact angle was measured using a combination of a custom-built goniometer and ImageJ image processing. Firstly, a 10 µL water droplet was manually pipetted onto a sample mounted on the goniometer stage and imaged (A). Using ImageJ, seven points were manually selected along the edge of the droplet, including the interface point between the droplet and the surface (B). The ImageJ Contact Angle processing plugin then measures the contact angle (C) and reports the findings in a summary table (D).

Image Analysis of Biofouling Coupons

For biofouling analysis of the coupons installed in the seawater strainer, a simplified image analysis approach was taken. In brief, coupons were imaged immediately following removal from the strainer. The images were then aligned and converted to grayscale images. Following conversion to the grayscale images, the background metallic substrates appear 'white' while the fouling accumulation appears 'black'. Therefore, the more white pixels an image has, the more the background metal surface is still visible. Conversely, the darker the picture, the more the sample has been covered by bioaccumulation. Using the ImageJ software, the gray values were calculated and averaged across an equal area of the samples. The 'gray value' ranges from 0 to 255 where 0 is a fully 'black' pixel whereas 255 is a fully 'white' pixel.

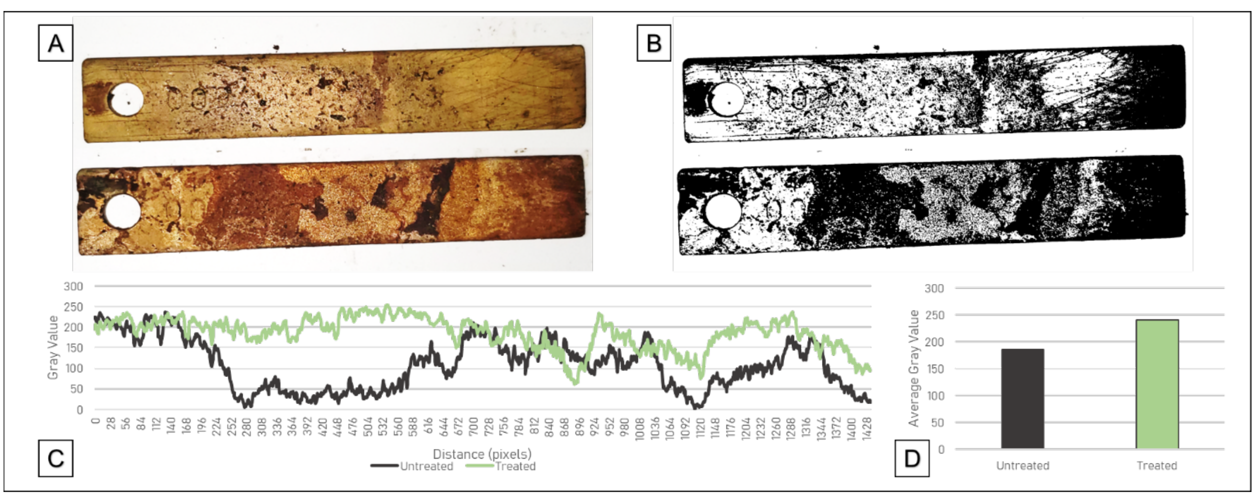

Figure 12. Image Analysis of Biofouling Coupons. Biofouling coupons from the seawater strainer were removed and imaged under the same light conditions (A). The images were then digitally converted to grayscale images where a value of 0 is a black pixel and a value of 255 is a white pixel (B). The value of each pixel varies across the distance of the samples and can be used to determine the location of fouling on the sample (C). All pixels in the image were averaged to determine the overall 'gray value', where a lower gray value represents a more fouled sample.

Borescope Analysis

In addition to removing and imaging the coupons from the seawater strainer, Interphase Materials collected Borescope images in the Seahorse chillers during the September 2021 visit. When Interphase Materials arrived in September, the chillers had been drained and the end plates were removed. The borescope was inserted into several tubes in each chiller and video was recorded. Images from these recordings were used for further analysis to be discussed in the Results section.

THERMOPHASE Treatment Quality Control

Using the contact angle methodology described previously, Interphase Materials is confident that the application to the Seahorse chiller was successful. As can be seen in Figure 13, the contact angle increased following the THERMOPHASE application for all of the coupons.

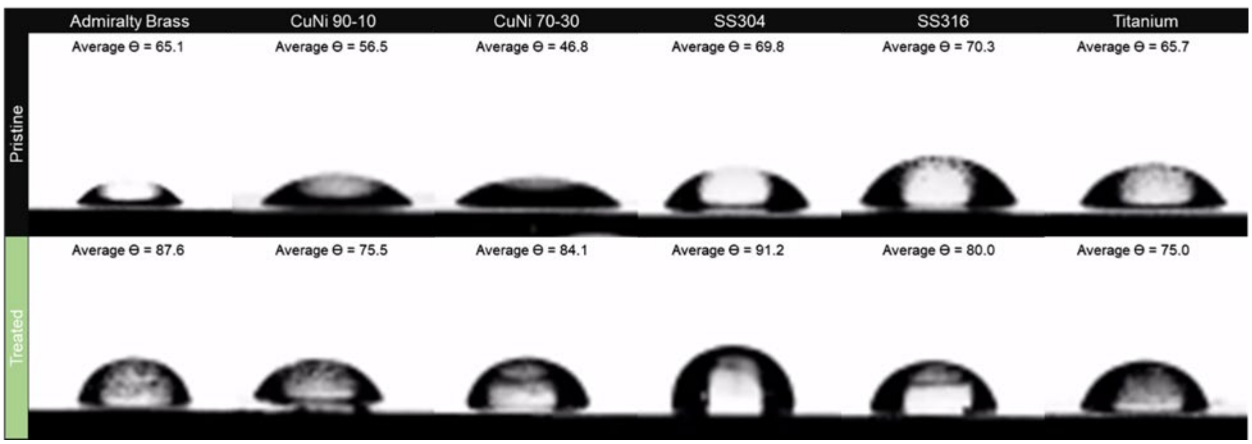

Figure 13. Coupon Contact Angle Following THERMOPHASE Treatment.

For each of the alloys evaluated, the contact angle increase was significantly different (see Figure 14 for a bar plot summarizing the results). Based on the convention defining hydrophilicity versus hydrophobicity, only the THERMOPHASE-treated SS304 sample is considered to have a hydrophobic surface. The greatest

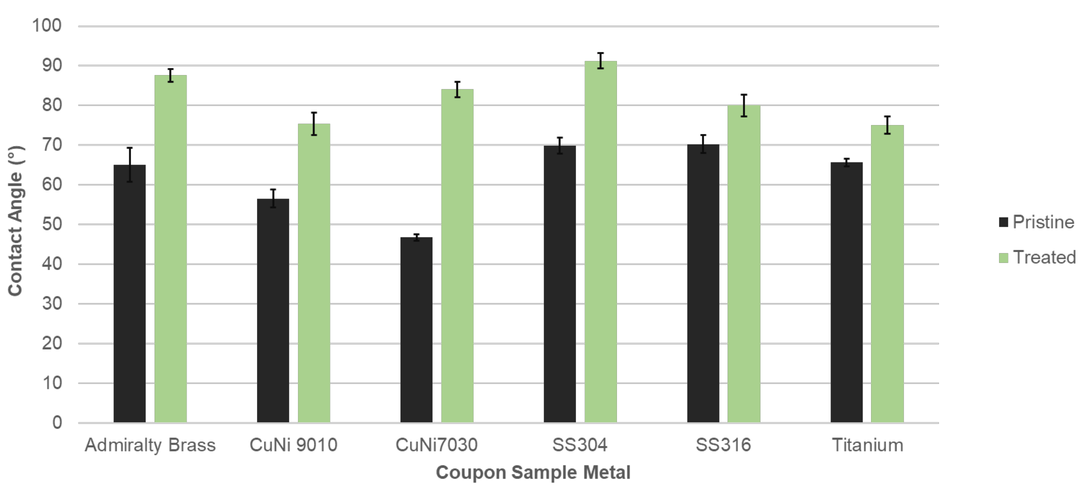

Figure 14. Contact Angle Comparison Following THERMOPHASE Treatment.

change was observed with CuNi 70-30 with a ~ 37° increase in contact angle following the treatment. Conversely, a 10° increase in treatments to the SS36 and Titanium represent the smallest observed change.

THERMOPHASE Biofouling Reduction Demonstration on TS KENNEDY

Significant fouling occurred on the samples installed in the seawater strainer. As can be seen from the coupon images, the type and extent varied across the samples (see Figure 15). Macroscopic fouling (two barnacles) was observed on the untreated titanium. Beyond the barnacle growth on the titanium sample the type of fouling was not classified.

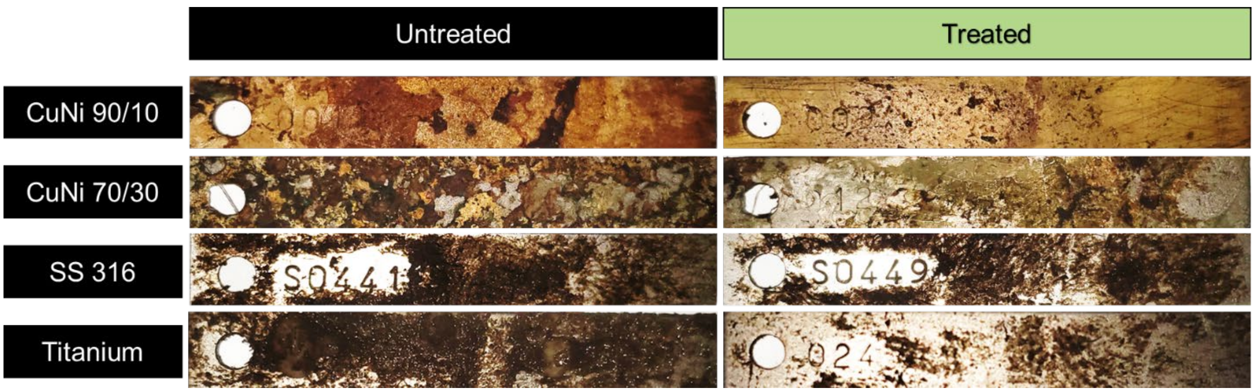

Figure 15. Biofouling Images on Coupons.

To quantify the fouling coverage on the samples, the 'gray value' method described above was used. In all alloys, the THERMOPHASE coupons showed a reduced degree of fouling compared to the untreated samples using the 'gray value' as a basis of fouling (see Figure 16). The greatest difference was observed between the titanium samples with a greater than four-fold difference. Interestingly, the titanium samples had one of the lowest contact angle differences as shown above.

In addition to observing fouling reduction on the coupons used in the strainer test, there was significant fouling differences observed in the borescope images of the chillers. Firstly, when viewing the tube sheets of the chillers, it appeared that there was less build-up on the tube sheet of the THERMOPHASE treated chiller (see Figure 17).

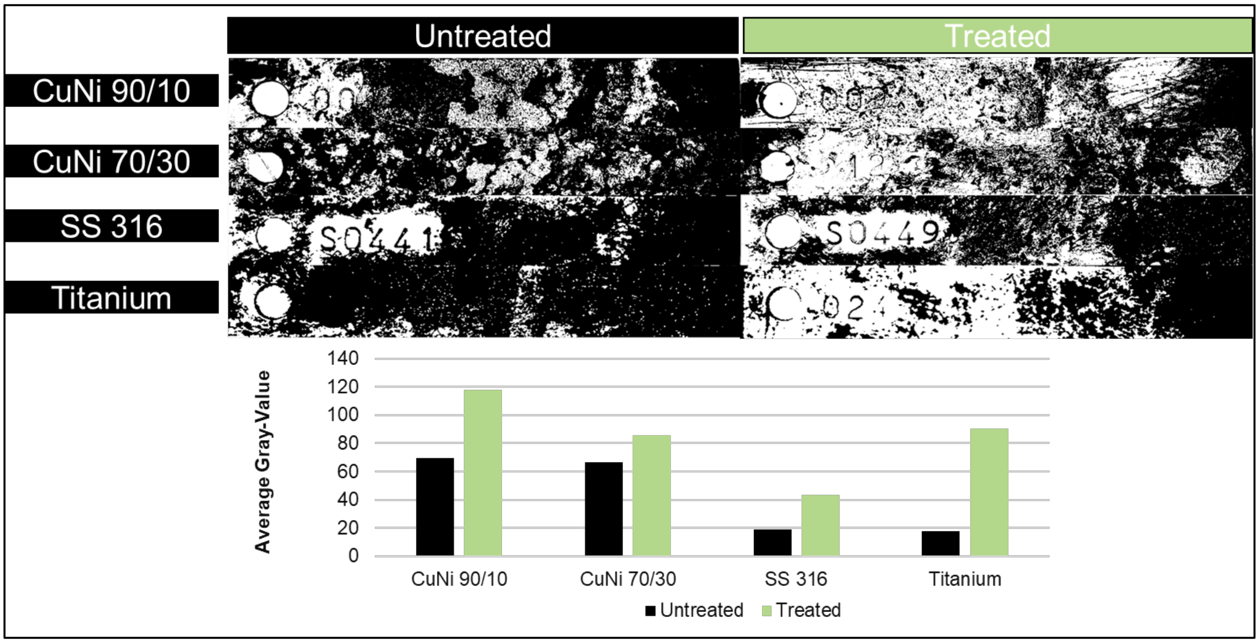

Figure 16. Biofouling Coupon Image Analysis Summary. The average gray value is calculated by averaging each gray value for the entire coupon area (0 is a white pixel and 255 is black pixel).

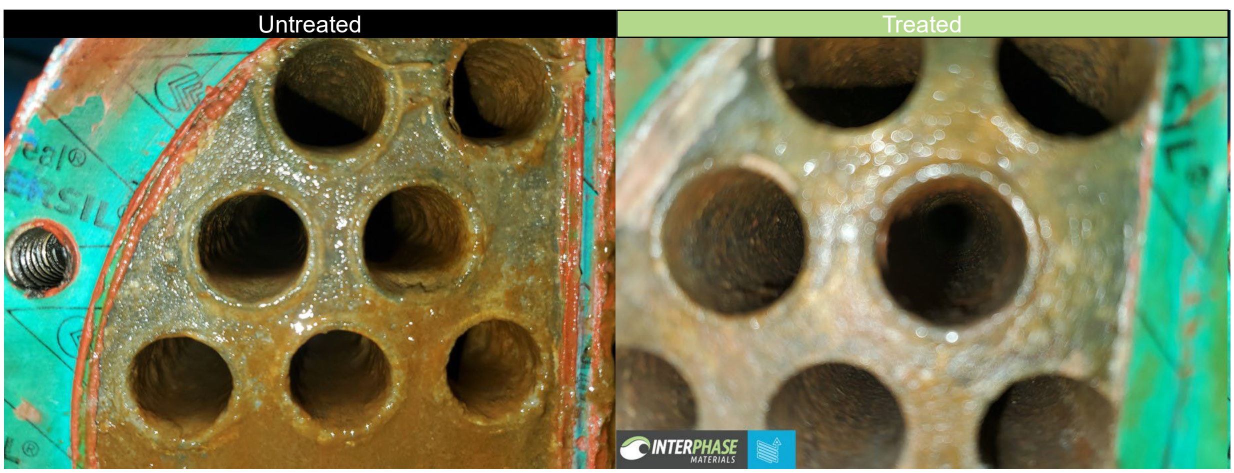

Figure 17. Tube Sheet Side-By-Side Comparison.

Images from inside the length of the tubes showed a more pronounced effect (see Figure 18). The borescope of the treated chiller tubes shows clear rifling on the inner wall of the tubes (which is a feature of commonly used 'enhanced' chiller tubes). However, the fouling build-up of the untreated tubes 'mask' any ability to recognize the tube rifling. These images suggest a minimum fouling of ~ 1 mm in diameter based on the dimensions of the rifling.

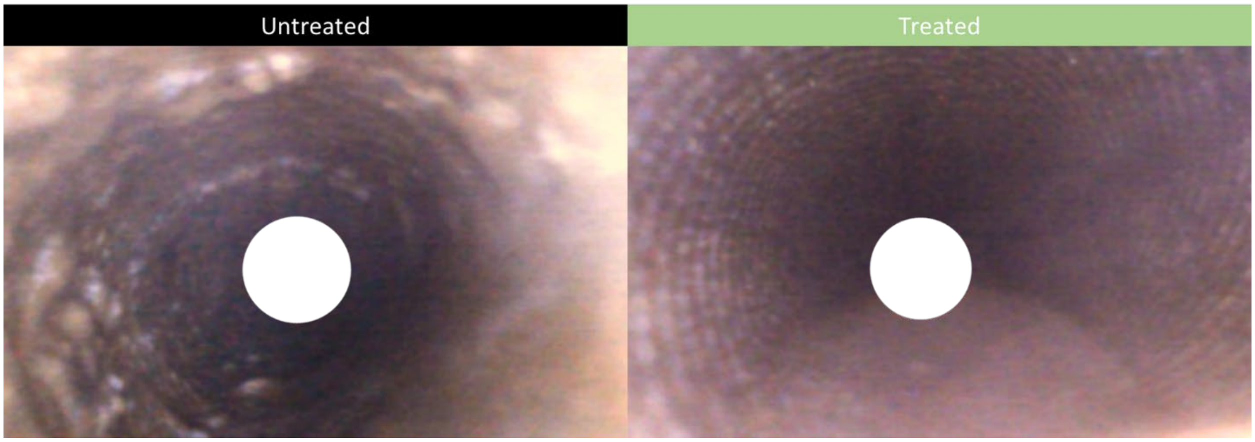

Figure 18. Biofouling in USTS Heat Exchanger Comparison.

As a quick method of quantification, a linear profile image analysis technique was used to quantify the gray-values along a given line. The same line was drawn on the same portion of each image. In this case the more ‘white’ (and higher value) corresponds to fouling in the image. The untreated has a 30%-40% lower gray-value indicating more fouling on the surfaces of the tube. This linear profile methodology could be used to extract further information about the fouling on the system (e.g. depth, uniformity, etc.); however, additional data would be necessary for calibration of the method.

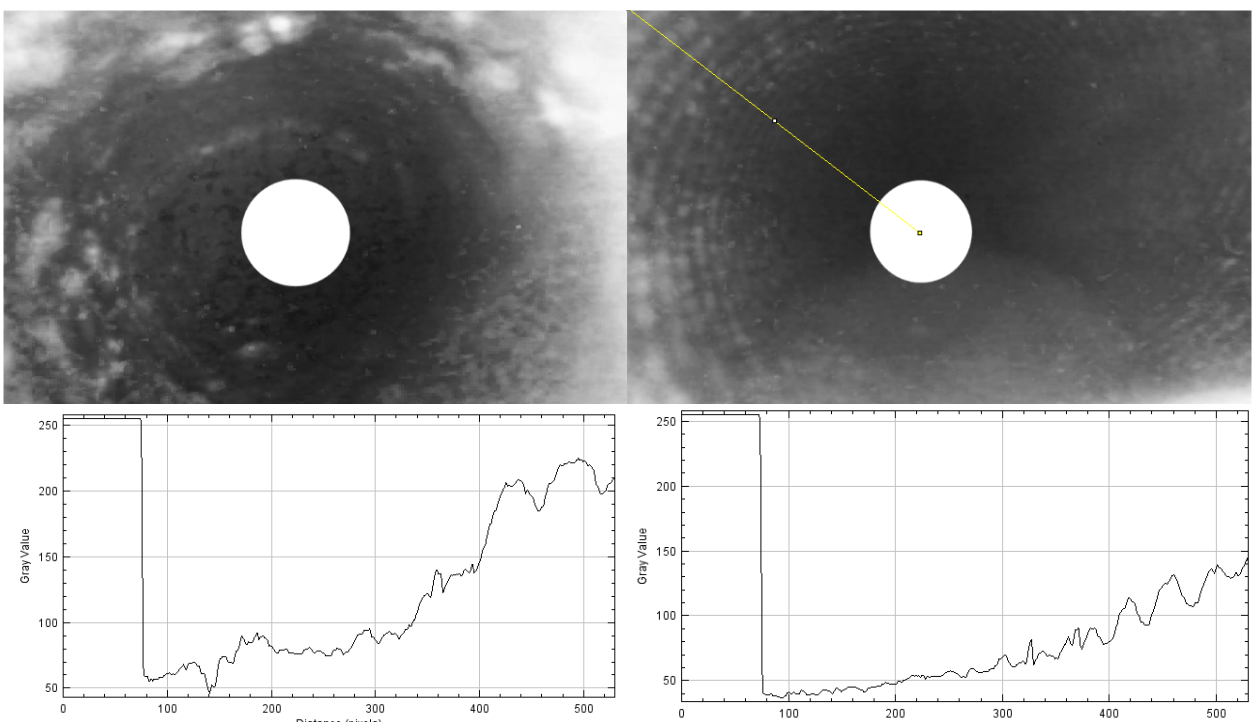

Figure 19. Borescope Image Analysis.

Chapter 3: TS KENNEDY Efficiency Assessment

Inspection of Seawater Cooled Assets

Life Cycle Engineering worked with the Massachusetts Maritime Academy to collect and evaluate information from the seawater cooled assets. The focus was primarily on the Seahorse refrigeration and the main AC plant. The three air conditioning chilled water plants located in the Auxiliary Machinery Room (AMR) were surveyed. One air conditioning plant is a SMARDT SHB046-1HG07-F2HHBA-F2AVBA-BCO plant with a nominal capacity of 130 tons. The plant refrigerant is R-134A. This plant has a modern display system that provides chilled water flow, seawater and chilled water inlet and outlet temperatures, and motor loading information. The temperature instrumentation could not be accessed but based on the wiring appears to be thermocouples or possibly RTDs. The flowmeter is an Onicon model F-3104-211. The two remaining air conditioning plant in the AMR are Carrier model 30HXC186R—640BA-1 Each air conditioning plant has two compressors. The plant refrigerant is R-134A. These plants have been retrofitted with a Carrier Comfort Link Navigator display system. It is likely that the display system provides chilled water flow, seawater and chilled water inlet and outlet temperatures, and motor loading information. The temperature instrumentation could not be accessed but based on the wiring appears to be thermocouples or possibly RTDs. The flowmeter is an Onicon model F-3104-211. One of the chilled water plants located in the main machinery space was also surveyed. The plant is probably original to the ship, and uses R-12 for the refrigerant. The instrumentation on the R-12 plant is minimal, and temperatures are indicated with analog gauges that cannot be read with significant accuracy. These plants cannot be used for a future THERMOPHASE performance evaluation without adding to and modifying the existing instrumentation. Using the R-12 plants for performance evaluation is not recommended.

Seahorse Refrigeration Plant Assessment

The two T/S Kennedy refrigeration plants are typical shipboard units with copper-nickel shell and tube heat exchangers. The seawater to each unit is provided by an auxiliary seawater system. Performance design information for each refrigeration unit is from chapter 5 of the Refrigeration Plant Technical Manual is as follows:

Condenser Water Temperature In	90 ºF
Condenser Water Temperature Out	100 ºF
Saturated Condensing Temperature	105 ºF
Saturated Suction Temperature	-22 ºF
Cooling Capacity	5.3 tons
Power Input	17.2 hp
Condenser Water Flow	35 gpm

The condenser water flow is controlled by a pressure regulating valve. The seawater flow is controlled to maintain constant refrigerant outlet conditions. If heat exchanger fouling is present, the seawater flow is increased to maintain the constant refrigerant outlet conditions. The heat transfer remains approximately constant as fouling increases until the maximum seawater flow is reached. At maximum seawater flow, as fouling increases, the refrigerant outlet temperature begins to increase.

The instrumentation on each refrigeration plant, although typical for a shipboard installation, is limited. There are condenser outlet temperature gauges for each unit. To determine the seawater inlet temperature, a gauge in the Engine Room has to be used. There is no seawater flowmeter installed. The refrigerant lines do not have temperature gauges permanently installed. There is no practical way to analyze refrigeration plant performance using the installed instrumentation.

The design refrigerant heat dissipation during normal operation is the 5.3 ton (63,600 BTU/hr) plant capacity plus the motor heat load. The motor load is 17.2 hp. The motor heat dissipation is calculated as

$$17.2\ \text{hp} \cdot \frac{1}{0.9\ \text{efficiency}} \cdot 2545\ \text{BTU}\cdot\text{hr}^{-1} \cdot \text{hp}^{-1} = 48{,}151\ \text{BTU/hr}\ .$$

Smardt Chilled Water Plant Assessment

The Smardt air conditioning plant is located in the TS Kennedy Auxiliary Machinery Room (AMR). Existing shipboard temperature, flow, and power measuring instrumentation is used to gather data on chilled water flow, seawater inlet and outlet temperature, chilled water inlet and outlet temperature, and chilled water plant power usage. The Carrier chilled water plants installed in the same space do not have power measuring instrumentation installed. These plants therefore do not have adequate instrumentation to make monitoring these plants worthwhile.

The older chilled water plants located in the Engine Room have limited instrumentation. The older chilled water plants are poorly suited for performance testing due to the limited and relatively imprecise installed instrumentation.

The collected data was used to calculate each air conditioning plants chilled water tonnage and the horsepower required per ton of air conditioning. The horsepower per ton of air conditioning is a measure of chilled water plant efficiency. As the seawater side of the condenser fouls, there will be an increase in the horsepower per ton of air conditioning.

The Smardt air conditioning chilled water plant on the training ship Kennedy was monitored during the summer of 2021. During this time, performance data was recorded. Specifically, the inlet and outlet seawater temperature, the inlet and outlet chilled water temperature, the chilled water flow rate, and the Smardt plant power consumption were recorded twice daily. The raw data recorded is contained in table 1.

THERMOPHASE Heat Transfer Impact Estimate

A limited fouling factor calculation for the refrigeration plant condenser is possible. The performance of the heat exchanger is defined by the equation

$$Q = U \cdot A \cdot \Delta T$$

where Q is the total heat transferred, U is the heat transfer coefficient, A is the heat transfer area, and ΔT is the temperature difference across the heat exchanger.

The information on the heat exchanger (an Acme/Ketema MHX 1005A-2P) is limited. The manufacturer was contacted, and the heat transfer area of the heat exchanger is proprietary. Per reference 1, Table 11-2, a typical heat transfer coefficient for refrigerants ranges from 50 to 150 BTU/hr-ft^2-ºF. Calculation are performed using the midpoint of the range, 100 BTU/hr-ft^2-ºF. Appendix A contains calculated heat exchanger fouling factors for untreated seawater surfaces based on data taken from the TS Kennedy tests. Appendix A also contains calculated heat exchanger heat transfer coefficients.

The heat transfer coefficient will vary based on seawater flow and fouling. It is known based on published information that the heat exchanger manufacturer uses a fouling factor of 0.005 hr-ft^2-ºF/BTU. Appendix A documents that a fouling factor of approximately 0.005 is reached on an untreated heat exchanger after 4 months in service.

Refrigeration plant power consumption remains essentially constant as seawater flow throughout the condenser increases. After maximum seawater flow is reached and fouling increases, the refrigerant plant power consumption begins to increase. Based on the calculated fouling factors and heat transfer coefficients contained in Appendix A, it appears that after 3 to 4 months the heat exchanger will have fouling greater than the design condition. It is believed that after 4 to 5 months untreated TS Kennedy refrigerant plants will begin to have increased refrigerant discharge temperatures due to heat exchanger fouling, and therefore will begin to exhibit an increase in power consumption.

The performance calculations are prepared as follows, and the results are shown in table 1. Symbols used in this calculation are:

Q	heat removed from the chilled water (BTU/hr) -
T_{swi}	inlet seawater temperature (ºF)
T_{swo}	outlet seawater temperature (ºF)
T_{cwi}	inlet chilled water temperature (ºF)
T_{cwo}	outlet chilled water temperature (ºF)
LMTD	log mean temperature difference (ºF)
V	volumetric flow rate (gallons per minute (gpm))
C_p	specific heat at constant pressure (BTU/lb ºF) (1.0 BTU/lbºF for water)

The purpose for recording this data was to prepare a performance baseline, and to see if the energy efficiency of the chilled water plant deteriorated over time.

Information and calculations from ARI 550/590, "2020 Standard for Performance Rating of Water-chilling and Heat Pump Water-heating Packages Using the Vapor Compression Cycle" was used.

The chilled water plant is modeled as a single heat exchanger. This is appropriate since the vapor compression cycle merely forces the energy to flow from the cold side of the heat exchanger to the hot side. Heat exchanger fouling would be expected only on the seawater side of the condenser. The refrigerant loop should have minimal fouling, and the fresh water side of the evaporator also would not be expected to have significant fouling.

The calculation of the energy (Q) transferred is:

$$Q = \mathrm{C_p} \cdot (\mathrm{T_{cwi}} - \mathrm{T_{cwo}}) \cdot V \cdot (8.3\ \mathrm{lb/gal}) \cdot (60\ \mathrm{min/hr}) \cdot (1200\ \mathrm{BTU/hr/ton})$$

Q divided by the chilled water plant energy input yields a measure of efficiency, calculated in horsepower per ton. The use of horsepower per ton does not reflect the fact the seawater cooling water temperature cooling the chilled water plant can vary greatly. To correct for this, a measure of the temperature difference between the chilled water and the seawater is needed. A reasonable measure is the log mean temperature difference (LMTD) used in heat exchanger performance calculations. LMTD is described as follows:

Assuming that the air conditioning plant acts as a heat exchanger, generic heat exchanger has two ends (which we call "A" and "B") at which the hot and cold streams enter or exit on either side; then, the LMTD is defined by the logarithmic mean as follows:

$$LMTD = (\Delta T_A - \Delta T_B)/ \ln(\Delta T_A/\Delta T_B)$$

where ΔT_A is the temperature difference between the two streams at end *A*, and ΔT_B is the temperature difference between the two streams at end *B*. With this definition, the LMTD can be used to find the exchanged heat in a heat exchanger:

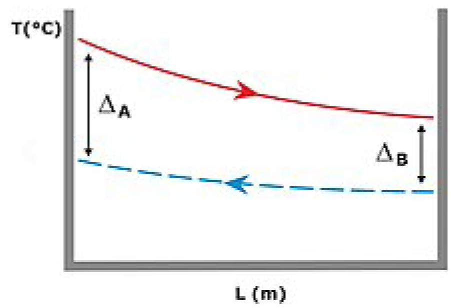

Figure 20. The LMTD illustrated in a countercurrent temperature profile

Life Cycle Engineering ROI Assessment

The results of the refrigeration plant condenser THERMOPHASE treatment were encouraging. The treated condenser showed significantly less fouling than the untreated condenser onboard the TS Kennedy. .Based on calculated fouling coefficients, it appears that after several months of operation, an untreated TS Kennedy refrigeration will have design level fouling. Based on testing, the THERMOPHASE treated TS Kennedy refrigeration plant will require less power to operate than an untreated unit after several months in use. It should be noted that significantly less cleaning will be required with THERMOPHASE treated seawater condensers. Reduced cleaning requirements will reduce operating costs.

As shown in table 1, there was a very limited amount of Smardt air conditioning plant data collected during the two summer T/S Kennedy voyages. Repeated attempts to gather more data have been unsuccessful.

The limited amount of data collected is for an untreated air conditioning plant seawater cooled condenser. There is not enough data available to show Kennedy chilled water condenser performance degradation. A proper test will require the collection of several months data to show plant degradation. Of course, an air conditioning plant treated with THERMOPHASE is expected to show reduced fouling.

Table 1

SMARDT PLANT OPERATING DATA

Date	Time	CW Inlet T (ºF)	CW Outlet T (ºF)	SW Inlet T (ºF)	SW Outlet T (ºF)	Flow Rate (GPM)	Power (kW)	Tonnage	Horsepower/Ton	Delta T A	Delta T B	LMTD	Horsepower/Ton ºF
6/5/2021	0815	50	40.5	82.9	93.9	239	71.4	94.79	1.01	43.9	42.4	43.15	2.34E-02
6/5/2021	1500	49.9	40.7	83.4	94.1	235	75	90.26	1.11	44.2	42.7	43.45	2.56E-02
6/6/2021	0810	48.8	40	82.9	93.2	236	82	86.71	1.27	44.4	42.9	43.65	2.90E-02
6/7/2021	0905	49.1	40	81.6	86.9	236	65	89.66	0.97	37.8	41.6	39.67	2.45E-02
6/7/2021	1500	50.1	39.8	82.1	87.8	241	70.4	103.64	0.91	37.7	42.3	39.96	2.28E-02
6/8/2021	0957	49	39.8	82.5	78.8	241	66.2	92.57	0.96	29.8	42.7	35.86	2.67E-02
6/8/2021	1500	49.7	40	81.8	87.4	241	72	97.60	0.99	37.7	41.8	39.71	2.49E-02
6/9/2021	0850	48.4	41	81.8	87.3	241	75	74.46	1.35	38.9	40.8	39.84	3.39E-02
6/13/2021	0947	49	40	83.4	89.2	293	72.4	110.09	0.88	40.2	43.4	41.78	2.11E-02
6/13/2021	1337	49.5	40	83.9	90.1	290	79.7	115.02	0.93	40.6	43.9	42.23	2.20E-02
6/14/2021	0815	48.8	40	86.5	89	295	73.7	108.38	0.91	40.2	46.5	43.27	2.11E-02
6/14/2021	1325	48.2	40.5	82.2	89.1	292	74.3	93.87	1.06	40.9	41.7	41.30	2.57E-02
6/15/2021	0825	48.1	40	82.7	87.6	293	73	99.09	0.99	39.5	42.7	41.08	2.40E-02
6/15/2021	1315	48.8	40	82.7	88.1	293	76.1	107.65	0.95	39.3	42.7	40.98	2.31E-02
6/16/2021	0820	47.5	39.8	82	86.5	288	64	92.58	0.93	39	42.2	40.58	2.28E-02
6/16/2021	1315	48	40	82	86	288	62	96.19	0.86	38	42	39.97	2.16E-02
6/17/2021	0815	47	40	72.2	76.2	288	45	84.17	0.72	29.2	32.2	30.68	2.34E-02
6/17/2021	1350	47.5	40	71.5	76.1	288	46	90.18	0.68	28.6	31.5	30.03	2.28E-02
6/18/2021	0930	47	40	67.2	71.4	288	35.2	84.17	0.56	24.4	27.2	25.77	2.17E-02
6/18/2021	1320	48	40	66.4	70.2	288	36.4	96.19	0.51	22.2	26.4	24.24	2.09E-02

PHASE II Test Plan (Task 4)

During this project, the biofouling reduction properties of THERMOPHASE were demonstrated on the TS KENNEDY. Preventing biofouling may be a significant enough value proposition to the maritime industry for commercialization in this market; however, to understand the benefits to energy efficiency and environmental emissions in the maritime industry, a data-centric demonstration is needed. While this may be feasible to complete onboard the TS KENNEDY, a reliable source of future data and a robust historical data set may be challenging. A potential work plan has been created for a Phase II effort that would demonstrate the energy efficiency and environmental impact of THERMOPHASE (as seen in Figure 21). To ensure an effective demonstration, it would be essential for a data set to be produced with the appropriate variables for at minimum a 12 month historical time period prior to vessel selection. This would limit the risk of installing THERMOPHASE on a vessel without data reporting capabilities.

Task	Description	Deliverable
Task 0: Project Management	Reporting, internal meetings, and communications with customers/partners	Final Deliverable Report containing results
Task 1: Pre-Application Assessment of Marine AC Plant	Initial Assessment of Pre-Existing Data	At minimum 12 month historical opertional analysis of AC plant efficiency
Task 2: THERMOPHASE Application to Marine AC Plant	Application of THERMOPHASE to Marine AC Chiller	Installation of THERMOPHASE on AC plant chiller
Task 3: Biofouling and Efficiency Analysis of Marine AC Plant Following THERMOPHASE Application	Analysis of Biofouling Coupons and Real-Time AC Plant Data	Monthly analysis of marine ac plant opertional efficieny and biofouling coupon results

	Month											
Task	1	2	3	4	5	6	7	8	9	10	11	12
Task 0: Project Management	1	1	1	1	1	1	1	1	1	1	1	1
Task 1: Pre-Application Assessment of Marine AC Plant	1	1										
Task 2: THERMOPHASE Application to Marine AC Plant			1									
Task 3: Biofouling and Efficiency Analysis of Marine AC Plant Following THERMOPHASE Application			1	1	1	1	1	1	1	1	1	

Figure 21. Phase II Work Plan and Timeline.

Chapter 4: Conclusions and Future Work

Objective Review

The goal of this effort was to further demonstrate benefits of THERMOPHASE for the maritime industry. IPM established three objectives at the onset of this project.

Objective 1 was to demonstrate the ability of THERMOPHASE to reduce biofouling under typical conditions. IPM observed a reduction of biofouling in both test coupons installed in the seawater strainer as well as the borescope images comparing the treated and untreated Seahorse chillers. Furthermore, THERMOPHASE was applied in 1 hr using commercially available pumping equipment. This practical application helps to support a pathway towards adoption in the maritime industry, and marks the first marine application using commercial equipment to date.

Unfortunately, due to a lack of reliable data from the AC plant chillers Objectives 2 and 3 were less conclusive. Objective 2 was to determine the baseline performance of seawater cooled assets. While we were able to inspect the AC plant seawater cooled systems, there was not sufficient data available from any of the inspected systems to create a quantitative baseline efficiency of the chillers. As expected, the Seahorse chiller was not outfitted with sufficient data acquisition systems. The purpose of the Seahorse chiller application was to prove the THERMOPHASE application process and to demonstrate biofouling reduction, a lack of data collection was anticipated. However, the team had hoped to find data reporting capabilities in either of the Carrier chillers or the Smardt chiller in the AMR. Unfortunately, while there was significant instrumentation installed on the Smardt chiller, we were unsuccessful in data retrieval. The instrumentation was not stock on the system and we were unable to find a reliable method or professional to acquire the data.

The completion of Objective 3 suffered due to the lack of data available on the TS KENNEDY. Our goal was to use the baseline performance of the seawater cooled assets, combined with the biofouling data collected, to prepare an ROI estimate that we felt confident could be confirmed in further testing. However, without the ability to baseline the system, there was little engineering analysis that could be done beyond the current understanding of THERMOPHASE' impact to chillers and heat exchangers. The team was able to show that the THERMOPHASE application significantly reduced the fouling factor after 4 months. In principle, this should provide energy efficiency improvements that could be confirmed with on a system that monitors and reports the necessary data.

Lessons Learned

One of the primary goals of this project was to advance THERMOPHASE in order to benefit the maritime industry. We believe that we have moved closer towards this goal; however, the lack of data availability restricts a baseline performance assessment that could have further prepared THERMOPHASE for the next steps in testing. While a measured efficiency gain was never the intent of this project, the demonstration on the Seahorse chiller was to prove the application method, the team was hopeful that we could establish a baseline on the TS KENNEDY that could be used in a second more quantity test. Without this data, it would be challenging to see conclusive improvements via an application to one of the chillers in the AMR. IPM recommends that before an efficiency demonstration is done, a ship would need to have reliable data reporting as a stand operational process. In other words, a demonstration would be much more likely to produce conclusive results if there was a historical record of chiller performance in tact, and the ability to continue that reporting. Regardless, however, the decision to treat the chiller in May 2021 was a good opportunity to show the benefits of the THERMOPHASE to reducing biofouling and should be useful to recruit a future demonstration site now that the application method has been proven.

Summary

In Summary, this project reports the first ever long-term biofouling reduction demonstration of THERMOPHASE onboard an operational vessel, a significant milestone in the development of this technology. While the TS KENNEDY may not be ideal for demonstrating the energy efficiency impact of the technology, this test represents a vital step towards the commercialization of THERMOPHASE. Furthermore, the biofouling reduction properties alone make this a valuable project. The remaining questions is not whether the technology improves energy efficiency, but by how much. If the visual evidence in this report is an indicator, which it would be logical to assume that it does, then the impact to the energy efficiency and environmental sustainability of the maritime industry could be significant. Based upon these results Interphase Materials will begin to commercialize THERMOPHASE in the maritime industry and will be seeking the appropriate channel partners. In parallel, Interphase Materials will be looking for vessels with onboard data reporting capabilities that my be interested in partaking in a data-centric case study.

References

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Appendix A – Calculated Fouling and Heat Transfer Coefficients

Calculated Fouling Factors

Months	Fouling Thickness (mm)	Fouling Factor (m2K/W)	Fouling Factor (ft^{2}-ºF-hr/BTU)
0	0	0	0
1	0.3725	0.0003	0.0015
2	0.7304	0.0005	0.0030
3	1.0743	0.0008	0.0044
4	1.4046	0.0010	0.0057
5	1.7221	0.0012	0.0070
6	2.0270	0.0015	0.0083
7	2.3201	0.0017	0.0095
8	2.6016	0.0019	0.0106
9	2.8721	0.0021	0.0117
10	3.1320	0.0023	0.0128
11	3.3817	0.0024	0.0138
12	3.6216	0.0026	0.0148
13	3.8521	0.0028	0.0157
14	4.0735	0.0029	0.0166
15	4.2863	0.0031	0.0175
16	4.4907	0.0032	0.0184
17	4.6871	0.0034	0.0192
19	5.0572	0.0036	0.0207
20	5.2314	0.0038	0.0214
21	5.3988	0.0039	0.0221
22	5.5596	0.0040	0.0227
23	5.7141	0.0041	0.0233
24	5.8625	0.0042	0.0240
25	6.0051	0.0043	0.0245

26	6.1422	0.0044	0.0251
27	6.2738	0.0045	0.0256
28	6.4003	0.0046	0.0262
29	6.5219	0.0047	0.0267
30	6.6387	0.0048	0.0271
31	6.7508	0.0049	0.0276
32	6.8586	0.0049	0.0280
33	6.9622	0.0050	0.0284

Heat Transfer Coefficient Estimate

Months	Fouling Factor	Clean Heat Transfer Coefficient	Overall Heat Transfer Coefficient
	(ft^{2}-ºF-hr/BTU)	(BTU/hr-ft^2-ºF)	(BTU/hr-ft^2-ºF)
0	0	100	100
1	0.00152216	100	86.78928547
2	0.002984634	100	77.01410466
3	0.004389765	100	69.49383856
4	0.005739799	100	63.53321128
5	0.007036898	100	58.69613033
6	0.008283137	100	54.69520863
7	0.00948051	100	51.33335754
8	0.010630934	100	48.47090347
9	0.011736249	100	46.00609894
10	0.012798223	100	43.86306727
11	0.013818557	100	41.98407088
12	0.014798884	100	40.32439592