ESTCP
Cost and Performance Report

(WP-200902)

Demonstration of a Centrifugal Separator and Ultrafiltration Membrane System for the Treatment of Shipboard Bilgewater

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ESTCP

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COST & PERFORMANCE REPORT
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TABLE OF CONTENTS

Page

EXECUTIVE SUMMARY ES-1

1.0 INTRODUCTION 1
- 1.1 BACKGROUND 1
- 1.2 OBJECTIVES OF THE DEMONSTRATION 2
- 1.3 REGULATORY DRIVERS 3

2.0 TECHNOLOGY 5
- 2.1 TECHNOLOGY DESCRIPTION 5
  - 2.1.1 Self-Cleaning Strainer 6
  - 2.1.2 1st Stage 6
  - 2.1.3 2nd Stage 7
- 2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY 8

3.0 PERFORMANCE OBJECTIVES 11

4.0 SITE/PLATFORM DESCRIPTION 13
- 4.1 TEST PLATFORM/FACILITIES 13
  - 4.1.1 NSWCCD Oily Wastewater Laboratory 13
  - 4.1.2 Shipboard Test Vessel 13
- 4.2 SITE-RELATED PERMITS AND REGULATIONS 14

5.0 TEST DESIGN 15
- 5.1 LABORATORY TESTING 15
- 5.2 SHIPBOARD EVALUATION 15

6.0 PERFORMANCE ASSESSMENT 17
- 6.1 LABORATORY EVALUATION 17
  - 6.1.1 System Inspection 17
  - 6.1.2 Performance Evaluation 17
  - 6.1.3 Performance Metric Results Overview 17
- 6.2 SHIPBOARD PERFORMANCE ASSESSMENT 18
  - 6.2.1 Installation 18
  - 6.2.2 Troubleshooting and Trial Runs 18
  - 6.2.3 Deployment 19
  - 6.2.4 Homeport Ship Visit 20
  - 6.2.5 Conclusions and Recommendations 21

TABLE OF CONTENTS (continued)

Page

7.0 COST ASSESSMENT 23

8.0 IMPLEMENTATION ISSUES 25
8.1 TRANSITION IMPACTS 25
8.2 LESSONS LEARNED 25
8.3 TECHNOLOGY TRANSFER PLANS 26

9.0 REFERENCES 27

APPENDIX A POINTS OF CONTACT A-1

LIST OF FIGURES

Page

Figure 1. 3-gpm AAE/CINC combined system at AAE's factory. 2
Figure 2. Simplified shipboard setup of the AAE/CINC combined system. 5
Figure 3. NSWCCD AAE/CINC combined system setup front view..... 5
Figure 4. CINC OWS. 7
Figure 5. Ceramic membrane structure. 8
Figure 6. NSWCCD oily wastewater laboratory..... 13
Figure 7. Shipboard influent, midpoint, and effluent samples. 19

LIST OF TABLES

Page

Table 1. Laboratory evaluation objectives. 11
Table 2. Performance evaluation test conditions. 15
Table 3. Performance evaluation effluent quality results. 17

ACRONYMS AND ABBREVIATIONS

AAE	Aircraft Appliances and Equipment
AEPC	afloat environmental program coordinator
AFFF	aqueous film forming foam
APPS	Act to Prevent Pollution from Ships
CFR	Code of Federal Regulations
COTS	commercial-off-the-shelf
CWA	Clean Water Act
DoD	U.S. Department of Defense
EMI	electromagnetic interference
EPA	U.S. Environmental Protection Agency
ESH	Environmental Safety and Health
ESTCP	Environmental Security Technology Certification Program
gpm	gallons per minute
HASP	Health and Safety Plan
HP	horsepower
IMO	International Maritime Organization
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environmental Protection Committee
MPA	marine propulsion assistant
MTBF	mean time between failure
NAVFAC	Naval Facilities Engineering Command
NAVSEA	Naval Sea Systems Command
NAVSEA 05P5	Naval Sea Systems Command, Shipboard Environmental Engineering Directorate
NDS	NAVSEA Design Supplement
nm	nautical mile
NSWCCD	Naval Surface Warfare Center, Carderock Division
NVR	Naval Vessel Rules
OCM	oil content monitor
OOC	out of commission
OPA	oil pollution abatement
OPNAVINST	Chief of Naval Operations Instruction
OWHT	oily waste holding tank
OWS	oily water separator

P&ID	piping and instrumentation diagram
ppm	parts per million (volume)
psi	pounds per square inch
SGT-HEM	silica gel treated N-hexane extractable material
TIAP	Technology Identification and Assessment Process
UF	ultrafiltration
UNDS	Uniform National Discharge Standards
USCG	United States Coast Guard
WOT	waste oil tank
WP	Weapons Systems and Platforms

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EXECUTIVE SUMMARY

In accordance with the Office of the Chief of Naval Operations Instruction (OPNAVINST) 5090.1C, Navy vessels must limit oily waste discharges to less than 15 parts per million (ppm) under normal shipboard operating conditions. Newer bilgewater practices and ship design have led to higher concentrations of emulsified oils. The majority of existing Navy oily water separators (OWS) cannot effectively treat this emulsified bilgewater.

The Aircraft Appliances and Equipment Limited (AAE)/CINC Industries Combined System, an advanced two-stage treatment (OWS) system designed to treat bilgewater, was evaluated under laboratory and shipboard conditions. The first stage is a centrifugal separator (CINC separator) designed to remove bulk oil and larger oil droplets. The second stage is a ceramic ultrafiltration (UF) membrane designed to treat emulsions and finer oil droplets. Oily wastewater processed by a ship's OWS must contain less than 15 ppm oil in order to discharge overboard.

The performance objectives for the laboratory and shipboard evaluations were to demonstrate effluent quality, efficiency of the CINC separator, and water content of the waste oil. System reliability as well as operation and maintenance requirements were also determined during these evaluations.

The laboratory evaluation showed that the AAE/CINC Combined System was effective at producing an effluent with less than 15 ppm oil-in-water when processing non-emulsified and mechanically emulsified bilgewater with influent oil concentrations ranging from 0.02% to 100%. The AAE/CINC Combined System could not consistently produce a dischargeable effluent when processing oily water and aqueous film forming foam (AFFF). When exposed to oily water and liquid detergents, the system would go into recirculation minutes after starting a test. Bubbles in the effluent that formed from the detergent caused the Navy-approved ET-35N oil content monitor (OCM) to alarm. Oil break through was observed during the second mixed liquid detergent test. The system was unable to meet effluent criteria during the first oily water and chemicals (bleach, acetone, and paint thinner) test. However, the system was able to meet effluent criteria during the second mixed chemicals test. Oil was observed to break through the system when processing oily water and powdered detergent.

The CINC separator could not meet the test's requirement of removing at least 80% of the influent oil during the laboratory evaluation. The CINC separator would typically remove 40%-46% of the injected oil in an oily water mix and near 0% of the injected oil in an oily water and detergent mix.

Over the course of the laboratory evaluation, waste oil generated from the AAE/CINC Combined System had an average water content of 90%, not meeting the test's maximum allowable water content limit of 20%.

Four performance, one design, and three equipment failures occurred during the laboratory evaluation.

The laboratory evaluation results indicated that the AAE/CINC Combined System was an easily operated OWS. Overall, maintenance activities were easy to carry out. The system's touch screen control panel enhanced the simplicity of some of the maintenance activities.

The CINC separator could not meet some of the test's requirements during the shipboard evaluation.

During the shipboard evaluation, water content of the waste oil could not be measured due to the system's piping configuration. Program modifications were made to reduce the amount of water in the waste oil; however it was still likely that water content of the waste oil was over 20%.

Three performance, one design, and five equipment failures occurred during the shipboard evaluation. The failures of the membrane feed pump were by far the most significant failures. After upgrading the membrane feed pump with more robust components, the pump functioned reliably.

During the shipboard evaluation, the AAE/CINC Combined System could not be operated without support from Naval Surface Warfare Center, Carderock Division (NSWCCD) prior to upgrading the membrane feed pump. After membrane feed pump modifications were carried out, ship's force reported that the system was easy to use. Corrective maintenance actions were difficult to perform due to the compact design of the system.

1.0 INTRODUCTION

1.1 BACKGROUND

In accordance with the Office of the Chief of Naval Operations Instruction (OPNAVINST) 5090.1C, Navy vessels must limit oily waste discharges to less than 15 parts per million (ppm) under normal shipboard operating conditions [1]. The Navy has adopted environmental equipment to comply with this restriction. Most Navy ships are equipped with an oil pollution abatement (OPA) system. The oily water that collects in bilges and other locations is pumped to an oily waste holding tank (OWHT). The wastewater in the OWHT is then pumped to an oily water separator (OWS) where it is treated. Separated waste oil is sent to the waste oil tank (WOT) for storage until shore side disposal. An oil content monitor (OCM) measures the OWS effluent's oil concentration to determine if it is within regulatory limits and acceptable for overboard discharge. If the oil concentration is too high, the effluent is recirculated back to the OWHT for retreatment.

Commercial-off-the-shelf (COTS) OWS systems are being designed and certified to meet International Maritime Organization (IMO) Marine Environmental Protection Committee (MEPC).107(49) and United States Coast Guard (USCG) 46 Code of Federal Regulations (CFR) 162.50 for processing oily wastewater. Manufacturers are presenting shipbuilders with these certified systems as viable options for use onboard new and future Navy ship classes such as CVN-78, DDG-1000, and LCS. However, these COTS systems may not satisfy Navy's environmental and operational requirements. In order to acquire effective and efficient OWS systems and allow the unrestricted operation of Navy ships with minimal ship impact or life cycle cost, these COTS systems must be identified, assessed, and tested for their impact on and applicability for use onboard Navy ships. To address these requirements, Naval Sea Systems Command, Shipboard Environmental Engineering Directorate (NAVSEA 05P5) tasked the Wastewater Management Branch of the Environmental Quality Division at the Naval Surface Warfare Center, Carderock Division (NSWCCD Code 633) to implement the Shipboard OPA Technology Identification and Assessment Process (TIAP) to explore commercial OWS treatment technologies.

The Aircraft Appliances and Equipment Limited (AAE)/CINC Industries Combined System is a 3-gallons per minute (gpm) two-stage separator. The system's first stage bulk oil separator is a centrifugal separator. It consists of a rotating drum housed in a cylinder, with a drive motor mounted above the unit. Centrifugal forces (100 – 2,000 g's) are generated by the rotor's rotation, amplifying density differences between water and oil and causing the two phases to separate. The second stage is a single ultrafiltration (UF) ceramic membrane polishing loop. The first stage effluent flows into a feed tank, which supplies the secondary UF polishing stage. The ceramic membrane's pores allow water molecules to pass through the membrane, whereas most oil molecules are retained. The concentrate is periodically bled from the circulating feed stream and discharged to the WOT for shore side disposal.

Under the TIAP program, Code 633 has conducted a Technology Assessment and Analysis of Alternatives on the AAE/CINC Combined System [2, 3]. This technical report describes the laboratory and shipboard evaluations for the 3-gpm AAE/CINC Combined System.

The effort to evaluate the AAE/CINC was funded by the Environmental Security Technology Certification Program (ESTCP) Weapons Systems and Platforms (WP) Program Area in conjunction with NAVSEA 05P5 leveraged funding. ESTCP is the U.S. Department of Defense's (DoD) environmental technology demonstration and validation program. The primary goal of ESTCP is to identify and demonstrate promising, innovative and cost-effective technologies and methods that address DoD's high-priority environmental requirements [4].

1.2 OBJECTIVES OF THE DEMONSTRATION

The overall objective was to demonstrate the AAE/CINC Combined OWS centrifugal separator and UF membrane system's performance when processing DoD shipboard generated oily waste and validate the system's ability to meet discharge requirements. The AAE/CINC Combined System as it was set up at AAE's factory is shown in Figure 1. Maintenance requirements were also determined during this evaluation. The following are the specific technical objectives of the project:

- Demonstrate the performance of the centrifugal separator and UF membrane system in treating shipboard generated oily waste by measuring key effluent quality parameters and validating the system's ability to meet discharge requirements;
- Demonstrate the level of operator involvement by documenting time required for routine operation and maintenance; and
- Identify and detail ship integration issues.

Figure 1. 3-gpm AAE/CINC combined system at AAE's factory.

1.3 REGULATORY DRIVERS

The need for shipboard bilgewater treatment for military vessels is driven by existing and anticipated future regulations. Without treatment, military operations in littoral waters and foreign waters could be restricted by the limited bilgewater holding capacity of the ship. The Clean Water Act (CWA) of 1977 prohibits the discharge of oil in a harmful quantity into all waters within 12 nautical miles (nm) of the U.S. coast or in any waters that may affect natural resources of the Exclusive Economic Zone [5]. U.S. Environmental Protection Agency (EPA) regulations state that a harmful quantity of oil is defined as a discharge that violates applicable water quality standards or causes a sheen to appear on the water surface. In general, a concentration in excess of 15 to 20 parts ppm oil may be sufficient to cause a sheen.

The Act to Prevent Pollution from Ships (APPS) implements the stringent oil and oily waste discharge requirements of Annex I of the International Convention for the Prevention of Pollution from Ships (MARPOL) [6]. Annex I of MARPOL requires that the oil content of the overboard discharge does not exceed 15 ppm [7]. Annex I requirements do not apply strictly to warships, but party states (including the U.S.) are required to establish standards for their warships that require such ships to conform as closely as practicable with the international standard without compromising operational effectiveness.

U.S. Navy policy on oil and oily waste discharge is outlined in OPNAVINST 5090.1C, Environmental and Natural Resources Program Manual [8]. OPNAVINST 5090.1C implements the requirements of the APPS and complies with the CWA. Navy policy states that ships shall not discharge oily waste that will produce a sheen within 12 nm of the U.S. Additionally, Navy ships equipped with an OWS and OCM shall attempt to limit oil and oily discharges to 15-ppm oil worldwide.

Anticipated regulations concerning bilgewater discharges will be imposed under the Uniform National Discharge Standards (UNDS) [9]. DoD and EPA are jointly developing the UNDS standards to regulate liquid discharges from Armed Forces vessels. It is expected that the UNDS bilgewater standard will require Navy ships be equipped with a USCG certified OWS system. USCG rule, 46 CFR 162.050, establishes OWS system performance, testing, and certification requirements [10]. 46 CFR 162.050 references system certification requirements that were developed by the IMO under MEPC.107(49) resolution. MEPC.107(49) established OWS system test specifications, such as simulating realistic influent conditions (i.e., the liquid should contain seawater, oil, grease, and emulsions that are likely to be found in vessel bilge compartments), more stringent than had been previously required under MEPC.60(33).

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2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

The AAE/CINC Combined System provides continuous separation in two stages using the principles of centrifugation and UF to separate oil from bilgewater. A self-cleaning strainer prior to both stages removes finer solid particles. Bulk oil and larger oil droplets are removed in the first stage. Finer oil droplets and emulsified oil are removed in the second stage. The first stage is a centrifugal liquid-liquid separator. The centrifuge separates oil and water by amplifying the density differences between the two. The second stage utilizes a ceramic membrane module to remove emulsions and finer oil droplets. Separated oil and self-cleaning strainer flushes are discharged to a WOT. An OCM (provided by the user) measures the residual oil content before deciding if the system effluent is clean enough to discharge overboard. Figure 2 depicts a simplified shipboard setup of the AAE/CINC Combined System. Figure 3 shows the system as it was installed in the laboratory.

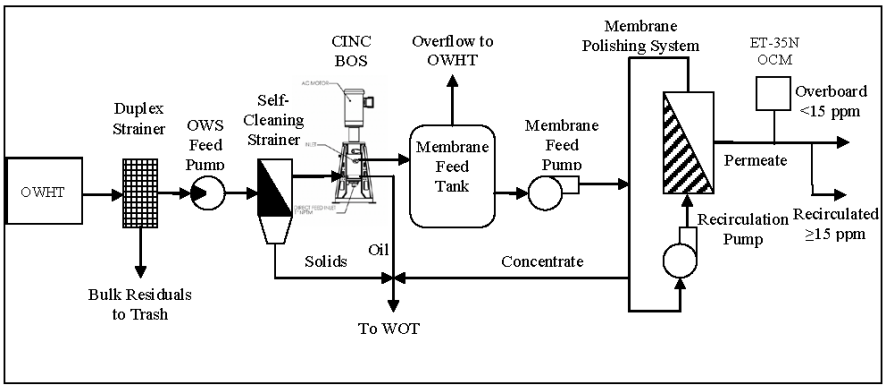

Figure 2. Simplified shipboard setup of the AAE/CINC combined system.

Figure 3. NSWCCD AAE/CINC combined system setup front view.

2.1.1 Self-Cleaning Strainer

Prior to the 1st stage, the oily water passes through a Ronningen-Petter Disc Cleaning Filter/Self Cleaning Filter Model 400 (DCF 400) equipped with an 800-micron element. The self-cleaning strainer removes contaminants that can cause membrane face plugging, such as lint and fibers. This model of self-cleaning strainer provides 112 square inches (in^2) of filtration surface area. Contaminants that gather on the filter element are scraped off by a spring-loaded cleaning disc that travels up and down the inside of the filter element. The self-cleaning strainer requires 80 pounds per square inch (psi) of air pressure to actuate the cylinder with the attached spring-loaded cleaning disc and potable water to flush contaminants through the strainer outlet. The contaminants and flushing fluid are discharged to the WOT. The frequency of self-cleaning was factory set to occur every 12 minutes or when the differential pressure between the inlet and outlet of the filter exceeded 5 psi.

2.1.2 1st Stage

After passing through the self-cleaning strainer, fluid enters the CINC centrifugal separator (model V-05 Clean-In-Place). The CINC is a liquid-liquid separator that separates liquids by exploiting differences in their respective densities. Figure 4 illustrates the bilgewater's flow path through the centrifugal separator, depicting how oil and water are separated. This model has a maximum hydraulic rated capacity of 6-gpm. The separator consists of a rotating drum housed in a cylinder, with a 2 horsepower (HP) Baldor electric drive motor mounted above the unit. Bilgewater is fed directly through an inlet at the bottom of the rotor and flows up into the rotor assembly. This direct feed design minimizes the formation of mechanical oil-in-water emulsions by limiting the wastewater's contact with the exterior of the rotating rotor. Centrifugal forces (100 – 2,000 g's) are generated by the rotor's rotation, amplifying density differences between water and oil and causing the two phases to separate. As the rotor rotates, the heavier water phase is forced to the outer edge of the rotor, a vortex space forms along the rotor shaft, and the oil phase is formed in between. Weirs are located at the top of the rotor such that the lighter oil phase flows out through the center of the rotor, and the heavier water phase exits near the outer edge. The adjustability of the rotor speed and the heavier water phase weir diameter allow the unit to be optimized for separating oil and water. The oil/water interface remains in the same location regardless of the ratio of the two phases, allowing the unit to handle influent oil concentrations ranging from 0-100%. As the bilgewater in the OWHT is processed, the bilgewater flowing to the separator will transition from a mostly water phase, to an intermediate oil/water emulsion mixture, and finally to a bulk oil phase. Throughout this transition, the effluent exiting the light phase outlet (oil) will increase. Enough water will be retained in the CINC separator in order to sustain the oil/water interface and prevent oil from exiting the water outlet.

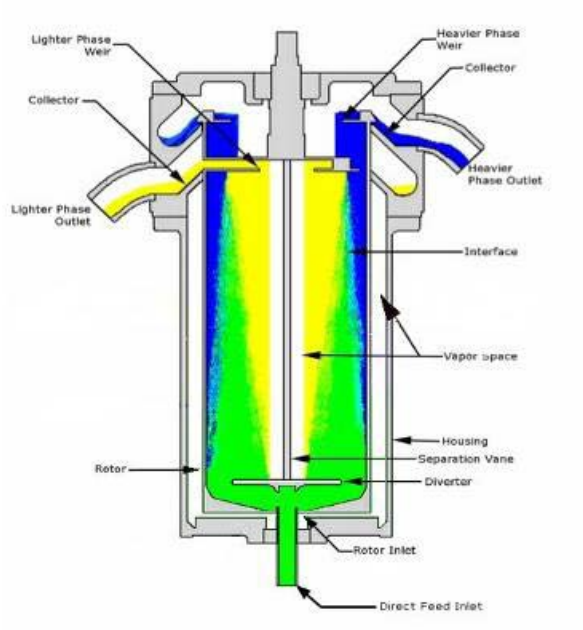

Figure 4. CINC OWS.

The fact that the CINC separator is not fully flooded during operation and contains air means that no backpressure can exist at the outlets. Any restriction at the oil or water exits will cause liquid to back up into the machine. Separated oil therefore must be gravity drained to the WOT.

2.1.3 2nd Stage

The second stage consists of a recirculation loop with a single Corning cross-flow ceramic UF membrane to separate emulsified oil. The measured volume of fluid the membrane loop can hold is 7 gallons. The ceramic UF membrane's pores allow water molecules to pass through the membrane but reject oil. The nominal pore size of the membrane is 5 nanometers. The membrane has an external diameter of 5.66 inches and a length of 34 inches. The membrane's substrate is composed of the mineral Mohite.

As oily water flows through the membrane, the water passes through the membrane coating and permeates through the substrate to the outer diameter of the membrane module. The concentrated oily waste continues through the membrane passageways and exits at the end of the membrane, to be recirculated in a loop by the centrifugal recirculation pump, as shown in Figure 5. The centrifugal recirculation pump is a 1500 series horizontal fiberglass Fybroc pump driven by a 10 HP Baldor Electric motor, model number JMM3714T. The pump operates at 200-300 gpm. The recirculation action of the pump creates cross-flow conditions in the membrane that reduce the accumulation of oil and other substances on the membrane surface. This decreases the fouling rate of the membrane.

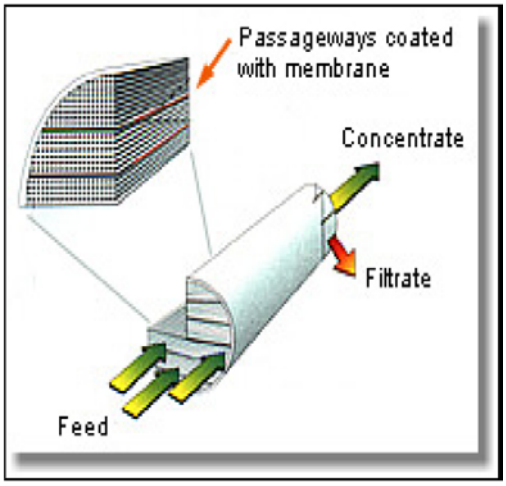

Figure 5. Ceramic membrane structure.

The Combined System will automatically bleed out 0.3 gallons of concentrate to the WOT once every 10 minutes. During this period of time, 30 gallons of permeate will exit the system. This equates to a volume reduction factor of 100.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Regulatory compliance and policy drive the implementation of bilgewater treatment systems aboard Armed Forces vessels. As these regulations and policies become more restrictive, the existing systems are no longer an option for new ship designs, and ships may be required to upgrade their existing systems. In 2004, IMO adopted new 15-ppm OPA system certification test procedures [6]. These testing procedures, entitled MEPC.107(49), established more stringent requirements, such as more realistic influent conditions (i.e., conditions of the sample bilgewater used to test system performance) than what had been previously required and extended testing durations. Additionally, in 2007, the U.S. Navy updated its policy to remove a contingency that allowed oily discharges of up to 100-ppm oil outside 12 nm from land if operating conditions prevented the ship's OWS from reducing the oil concentration to below 15-ppm oil. An effective and efficient shipboard treatment system that satisfies the regulations and policy will allow ships more freedom to travel within restrictive waters for longer periods of time, to enter restrictive waters with little notice and preparation, and to reduce pier side oily waste disposal costs.

Current parallel-plate separators installed throughout the Fleet only provide single stage treatment and may have difficulty treating emulsified bilgewater to the 15-ppm limit. Additionally, onboard storage capacity is insufficient to hold the untreatable bilgewater. This condition could result in emulsified oil being discharged to the environment above discharge limits. The AAE/CINC Combined System offers the DoD a separator that is potentially capable of producing a discharge that satisfies the current and anticipated discharge requirements in an effective and efficient manner while minimally impacting the ship. The system was designed for use on a military vessel and for the processing of DoD-specific bilgewater.

The CINC centrifugal separator is significantly smaller and lighter than the current parallel-plate separators used throughout the Fleet. Additionally, the centrifugal separator should provide a

reduction in maintenance and operational manpower requirements. The self-cleaning ability of the CINC separator should reduce the maintenance manpower burden. Existing parallel-plate separators require time-consuming and cumbersome maintenance operations to clean the plates and often result in reassembly errors that reduce the effectiveness of the separator.

The AAE/CINC Combined System's membrane module is based on proven technology used onboard other Navy Combatants. These systems have proven that cross flow ceramic UF membrane technology is effective in producing a discharge that meets the regulatory and policy discharge requirements when processing military generated bilgewater as secondary treatment.

Commercial OWS treatment systems are now being designed and certified in accordance with MEPC.107(49) and USCG requirements. However, these certification tests use fluids not typically found onboard DoD ships. Typical technologies used by the commercial systems include, but are not limited to, multi-stage gravity coalescence, absorption filters, and biological systems.

Multi-stage gravity coalescers rely on coalescence and gravity to separate oil from water. These systems have many of the same disadvantages as those of the existing parallel-plate separators found throughout the Fleet. While a number of these types of systems have received MEPC.107(49) and USCG certification, questions remain regarding their ability to effectively treat emulsified bilgewater and their reliability over an extended operating period. It is believed that there is a high potential for the secondary coalescer to clog with sludge, resulting in unacceptable effluent oil concentration.

A number of manufacturers offer absorption polishers as a secondary treatment stage following a conventional primary coalescence separator. However, these systems may require frequent absorbent media replacement to ensure that the discharge remains below 15-ppm oil. Media replacement can be difficult to accomplish correctly by shipboard personnel. Improperly packed media can be prone to short-circuiting and channeling.

Biological treatment systems are able to remove small oil droplets, emulsions, and dissolved oils from the bilgewater. However, the presence of concentrated detergents or solvents can kill the microorganisms that are integral to the system's operation. Additionally, the microorganisms have a limited shelf life, are sensitive to temperature fluctuations, and require a continual stream of nutrients and oil to survive.

While the AAE/CINC Combined System's initial acquisition cost may be higher than some available commercial systems, the anticipated long-term operating cost associated with cleaning the coalescers and replacing spent absorbent media could be higher than the cost associated with purchasing and maintaining the AAE/CINC Combined System. Additionally, the other commercially available systems could be challenged by special military requirements. The AAE/CINC Combined System was designed to operate in the confined spaces found onboard Armed Forces vessels, be operated and maintained by military personnel, and process the unique fluids used by the military. Finally, the AAE/CINC Combined System needs to be tested to MEPC, military vibration, and military electromagnetic interference (EMI) requirements. Military shock testing is not required for the system. The designated location for the AAE/CINC

Combined System onboard DDG class ships is considered unmanned and thus not required to be tested to military shock standards. The commercial units would require upgrades to meet these requirements, increasing their initial acquisition costs.

3.0 PERFORMANCE OBJECTIVES

Table 1. Laboratory evaluation objectives.

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Effluent quality	Effluent sample analysis data as specified by: EPA 1664	95% of the effluent samples are less than or equal to 15 ppm oil-in-water	The system failed to meet this criterion.
		100% of the effluent samples are less than or equal to 100 ppm oil-in-water	The system succeeded in meeting this criterion.
	Effluent sample analysis by: The ET-35N OCM	ET-35N OCM makes the decision to discharge effluent 95% of the time	The system failed to meet this criterion.
Primary separator efficiency	OWS system intermediate samples (CINC effluent) analysis by: EPA 1664	At least 80% of the influent oil is removed by primary CINC centrifugal separator	The system succeeded in meeting this criterion based on EPA 1664.
	Flow rate of oil discharged from CINC separator is compared to the flow rate of oil injected into the system		The system failed to meet this criterion based on flow rate measurements.
Minimize water content of the retained oil	Water content of the waste oil	100% of the waste oil discharged contain less than 20% water by volume	The system failed to meet this criterion.
System alarms and warnings functions as designed	Activate warnings and alarms	All system alarms, indicators, and sensors function as designed	The system succeeded in meeting this criterion.
System reliability	Component failure data Documentation of equipment deficiencies and failures	Mean time between failure (MTBF) greater than 400 hours with a confidence interval of 90%	The system failed to meet this criterion.
Qualitative Performance Objectives			
Level of operator involvement	Record daily labor hours required for routine operation, maintenance, and repair.	Lower manpower requirement than existing 10NP + 5-gpm OWS system.	The system succeeded in meeting this criterion.

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4.0 SITE/PLATFORM DESCRIPTION

4.1 TEST PLATFORM/FACILITIES

4.1.1 NSWCCD Oily Wastewater Laboratory

The AAE/CINC Combined System was purchased for full-scale evaluation at NSWCCD's Oily Wastewater Laboratory, shown in Figure 6. NSWCCD engineers have used the laboratory to test experimental equipment designs and commercial systems. The laboratory contains holding tanks, treatment systems, and support equipment designed to simulate shipboard contaminants and conditions. All utilities were provided for the AAE/CINC Combined System, including oil-free air, water, power and low-pressure air. The laboratory facility meets all criteria as a test site and provides controlled feed composition, controlled feed volume, and the required utilities to test the equipment and simulate shipboard conditions, while providing access to experienced bilgewater technicians and engineers. The laboratory has been accepted by the USCG as a Designated Facility for performing approval testing of pollution prevention equipment for compliance with the standards and regulations contained in IMO Resolution MEPC.107(49) and 46 CFR 162.05, as promulgated under the APPS (33 U.S.C. 1901 et seq.) [11].

Figure 6. NSWCCD oily wastewater laboratory.

4.1.2 Shipboard Test Vessel

USS MITSCHER (DDG-57) was chosen as the testing platform for the shipboard evaluation. USS MITSCHER is an Arleigh Burke (DDG-51) class destroyer commissioned in 1994. The shipboard evaluation followed the laboratory evaluation to determine if the system could process contaminants of actual bilge water. The shipboard evaluation demonstrated the system's ship impact, integration, and ability to meet discharge requirements in a real world setting. The full-scale shipboard evaluation determined the system's performance and reliability. Further details regarding DDG-57 can be found in Section 4 of the Final Report.

4.2 SITE-RELATED PERMITS AND REGULATIONS

A Carderock Environmental Safety and Health (ESH) and Naval Facilities Engineering Command (NAVFAC) review of this Laboratory Test Plan was performed. Effluent discharges to the sewer drain were covered under the wastewater discharge permit authorizing discharges to the Blue Plains Wastewater Treatment Plant from NSWCCD. The permit was issued in accordance with the District of Columbia Pretreatment Regulations (DCMR Title 21 Chapter 15) [12]. NAVFAC at Carderock manages the permit. The permit limits the oil and grease content in the disposed effluent to less than 100 ppm. OCMs measured the effluent oil content. If the AAE/CINC Combined System's oil concentration exceeded 15 ppm, the effluent was diverted to the 20,000-gallon WOT located underground for reprocessing by the laboratory's OWS. Reprocessed effluent that exceeded the 100-ppm permit limitation was stored for disposal. Effluent meeting the 100-ppm limit was disposed of via the sanitary sewer. The waste oil from the AAE/CINC Combined System was also discharged to the laboratory's waste oil storage tank.

NSWCCD has a site-wide Health and Safety Plan (HASP) for the laboratories [13]. The Bethesda Site Chemical Hygiene Plan addresses responsibilities, rules and procedures, chemical handling protocol, air sampling, maintenance and inspections, medical surveillance, protective apparel, emergency equipment, records, labels and signs, chemical spill procedures, and training [13].

No special environmental permits are required to operate the treatment system onboard a vessel. AAE will have USCG (46 CFR 162.050) and IMO Resolution MEPC.107(49) Type approval testing conducted. The ship's normal discharge protocols were followed during the test.

5.0 TEST DESIGN

5.1 LABORATORY TESTING

The standard testing regiment (i.e., the Performance Evaluation) consisted of a series of tests using different influent oil concentrations and contaminant levels to determine the OWS performance in the highly variable conditions aboard Navy ships. Table 2 lists the influent conditions and test durations. All testing was carried out at NSWCCD's Wastewater Laboratory in West Bethesda, MD by Code 633. A detailed piping and instrumentation diagram (P&ID) is presented in Section 5 of the Final Report. The AAE/CINC Combined System was subject to each influent condition twice. The Performance Evaluation tests were based on the requirements outlined in the Naval Vessel Rules (NVR) and NAVSEA Design Supplement (NDS) and augmented by additional tests conducted by NSWCCD Code 633 during previous OWS system evaluations [14]. The test fluids identified in the NDS are well-established and have been historically used to evaluate all OWSs. Additional test fluids or conditions were added to the testing regiment as they were identified. Based on system performance results, supplementary testing conditions were added. Although an extensive series of test mixes were considered, not all conditions that the system was exposed to could be accounted for.

Table 2. Performance evaluation test conditions.

Test Number	Test	Test Duration (up to)
1, 9	Oily water	10 hours
2, 10	Oily water	10 hours
3, 11	Oily water & mixed detergent	10 hours
4, 14	Oily water & detergent	10 hours
5, 13	Oily water, mixed detergent, & particles	10 hours
6, 12	Oily water & seawater	10 hours
7, 15	Oily water & aqueous film forming foam (AFFF)	10 hours
8, 16	Oily water & chemicals	10 hours
18,19	OWHT transition test	6 hours
		10 minutes
		30 minutes

After the Performance Evaluation was carried out, three additional tests were conducted. The three additional tests were performed in an attempt to mitigate oil breakthrough observed during the Performance Evaluation and determine system response to a detergent directly observed in use onboard the ship test platform. Further detail regarding additional testing can be found in Section 5 of the Final Report.

5.2 SHIPBOARD EVALUATION

USS MITSCHER (DDG-57) was chosen as the testing platform for the shipboard evaluation. USS MITSCHER is an Arleigh Burke class destroyer commissioned in 1994. The shipboard evaluation was performed after the laboratory test to demonstrate the system's ship impact and integration, effective processing rate, and ability to meet discharge requirements in a real world

setting. The full-scale shipboard evaluation determined the system's performance and reliability. However, the specific performance tests outlined in the NDS were not conducted; rather, the influent conditions and run times were dictated by actual conditions found onboard DDG-57 during the evaluation. A data acquisition system recorded system flow rates, operating time, operating status, system warnings and alarms, effluent oil concentrations, OCM alarms, and diverter valve position. Additionally, system component statuses, such as whether a pump was on or off, were recorded. Operators provided status updates of the system and performed certain equipment repairs. Operators were originally going to record labor hours to operate and maintain the system; however, this task was never performed. Operators were also originally going to perform all routine preventative maintenance; however, these tasks were never carried out. Samples for EPA 1664 analysis were collected by NSWCCD personnel when feasible.

6.0 PERFORMANCE ASSESSMENT

6.1 LABORATORY EVALUATION

6.1.1 System Inspection

Prior to the laboratory evaluation, inspections were carried out. The first inspection occurred at AAE's production facility. The second inspection was an in-house inspection at NSWCCD. System warnings and alarms were tested, risks and concerns were noted, and physical system measurements were made during the inspections. Section 6 of the final report contains further details of the factory and in-house system inspections.

6.1.2 Performance Evaluation

The AAE/CINC Combined System was effective at producing a dischargeable effluent when processing bulk oil, mechanically emulsified oil, and oil emulsified by mixed chemicals (acetone, Stoddard solvent, and bleach). It was not able to produce a dischargeable effluent when exposed to oil with detergents or AFFF. Table 3 summarizes the system's ability to process the various test mixtures. Results highlighted in grey indicate what should be an effluent recirculation condition. Results in white indicate an effluent discharge condition. The deciding factor as to whether or not the system passed a test was based on readings from the ET-35N OCM and results from EPA 1664 analysis. Section 6 of the Final Report goes into further detail of the pass/fail classification.

Table 3. Performance evaluation effluent quality results.

Test #	Test	Pass/Fail	
		Round 1	Round 2
1, 9	Oily water	Pass	Pass
2, 10	Oily water	Pass	Pass
3, 11	Oily water & mixed detergent	Fail*	Fail
4, 14	Oily water & non-ionic detergent	Fail*	Fail*
5, 13	Oily water, mixed detergent, & particles	Fail*	Fail*
6, 12	Oily saltwater	Pass	Pass
7, 15	Oily water & AFFF	Fail	Fail
8, 16	Oily water & chemicals	Fail	Pass
18,19	OWHT transition test	Pass	Pass

*ET-35N OCM alarms signaled due to bubbles or foam in the effluent, not oil breakthrough

6.1.3 Performance Metric Results Overview

Final Discharge (Membrane Permeate) of Performance Evaluation

Based on the acceptance criterion dictating that the ET-35N OCM should make the decision to discharge effluent 95% of the time, the AAE/CINC Combined System failed to meet the system effluent condition requirements. Based on the acceptance criterion dictating that 95% of the effluent samples collected contain an oil concentration of less than or equal to 15-ppm oil as measured by EPA 1664, the AAE/CINC Combined System failed to meet the system effluent oil concentration requirements.

Based on the acceptance criterion dictating that 100% of the effluent samples collected contain an oil concentration of less than or equal to 100-ppm oil as measured by EPA 1664, the AAE/CINC Combined System succeeded in meeting the system effluent oil concentration requirements.

CINC Effluent (Midpoint Discharge)
The system met the acceptance criterion dictating that the CINC centrifugal separator remove at least 80% of the injected oil based on EPA 1664 silica gel treated N-hexane extractable material (SGT-HEM). Removal of the injected oil by the CINC centrifugal separator was also measured by collecting the volume of waste oil discharged by the CINC. The CINC separator did not meet the acceptance criterion based on using this measurement method. Section 6 of the Final Report goes into further detail comparing the methods.

Waste Oil
Based on the acceptance criterion dictating that the average water content of the waste oil be less than 20%, the AAE/CINC Combined System fails to meet the test's waste oil water content requirements.

Operation and Maintenance
The AAE/CINC Combined System was an easily operated OWS. Overall, maintenance activities were easy to carry out. The system's touch screen control panel enhanced the simplicity of some of the maintenance activities. More detailed operation and maintenance information is contained in Section 6 of the Final Report.

System Reliability
Four performance, one design, and three equipment failures occurred during the laboratory evaluation. Section 6 of the Final Report contains further details regarding these failures.

Conclusion and Recommendations
Final recommendation of the AAE/CINC Combined System followed the shipboard evaluation. The shipboard evaluation determined how well the system could process bilge water in real world conditions. Also, the shipboard evaluation yielded crucial data with regard to actual operability, maintainability, reliability, and performance.

6.2 SHIPBOARD PERFORMANCE ASSESSMENT

6.2.1 Installation

The AAE/CINC Combined System was installed onboard DDG-57. All installation work was carried out by AMSEC, a subsidiary of Huntington Ingalls Industries, which specializes in Naval architecture and engineering.

6.2.2 Troubleshooting and Trial Runs

Pierside
After installation, pierside troubleshooting of the system was carried out. Initial testing showed the OWS feed pump could not draw enough suction to deliver fluid from the OWHT. It was

believed that a loose stator housing prevented proper suction from being obtained. After replacing the OWS feed pump, adequate lift of the fluid could be provided. No other issues were discovered and the system successfully processed fluid while operating in recirculation mode.

Underway
Following pierside troubleshooting, NSWCCD personnel rode with DDG-57 during two brief underway events. On the first underway, the AAE/CINC Combined System was successfully operated for over three hours.

On the second underway, the system successfully processed the fluid from the OWHT. Figure 7 shows influent, midpoint, and effluent samples drawn. The influent and midpoint samples are black and opaque. The effluent sample is clear and mostly colorless.

Full details of the EPA 1664 results are in Section 7 of the Final Report.

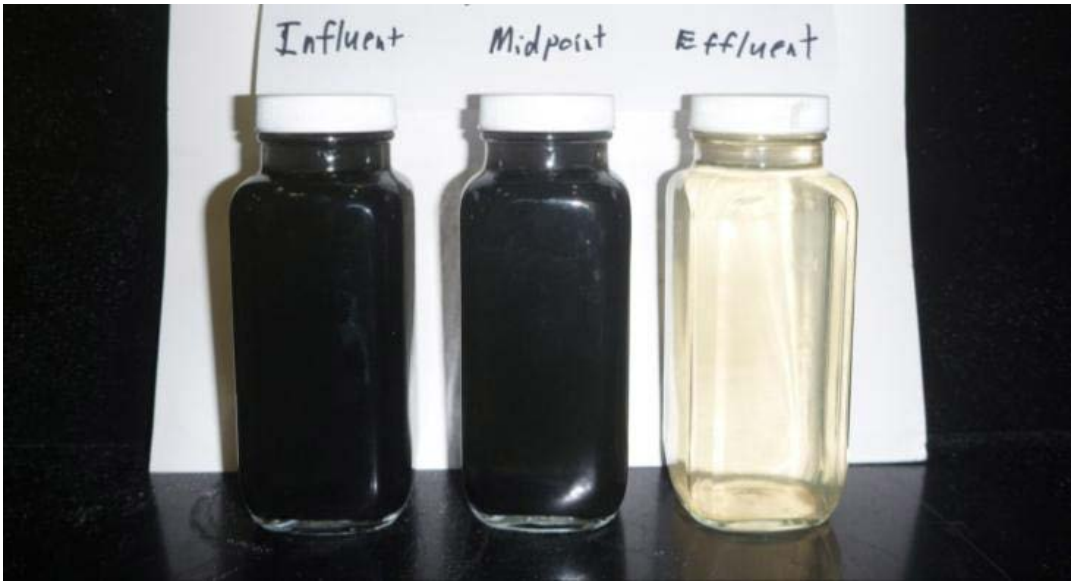

Figure 7. Shipboard influent, midpoint, and effluent samples.

6.2.3 Deployment

Initial Startup Attempts
Shortly after DDG-57 was deployed, ship's force reported that the system's "low membrane loop pressure" alarm would signal upon startup, or the "recirculation loop not charging at startup" warning would signal. After each time the alarm signaled, the system would shut down. When the warning signaled, it indicated the system could not generate the required pressure for the membrane loop to function, resulting in a failure to process.

Ship's force made numerous attempts to process fluid. However upon each startup, the AAE/CINC Combined System would alarm out and shut down or the warning would signal. Additional data showing the repeated startup attempts are presented in Section 7 of the Final Report. After the repeated startup failures, the system was declared out of commission (OOC). NSWCCD made the decision to meet with DDG-57 to diagnose and repair the system.

Ship Rendezvous to Troubleshoot and Repair System
Carderock personnel rendezvoused with DDG-57 to troubleshoot and repair the system. Based on the reports from ship's force about the warnings and alarms, the membrane feed pump was suspected to be the point of failure. After removing the pump from the system and disassembling, it was discovered that the pump's plastic impeller had broken free from an inner bushing that affixed it to the pump motor.

The impeller was repaired by reaffixing the original bushing with a two part epoxy and two press-fit roll pins radiating out from the center the shaft. The pump was reassembled and mounted back on the system after the repair was made. The AAE/CINC Combined System was successfully restarted and began processing fluid.

Second Pump Failure
Shortly after NSWCCD personnel departed DDG-57, the membrane feed pump failed a second time. The recirculation loop not charging at startup warning signaled and the system could not start. This was the first attempt to run the system after NSWCCD personnel left. After failing to start, the AAE/CINC Combined System was declared OOC.

Second Pump Repair
After the second pump failure, alternative pump materials were selected by NSWCCD to increase the pump's robustness. The replacement pump components consisted of a stainless steel (316 SS) impeller, a Viton bell gasket, and a mechanical seal with Viton elastomers. The previous pump components were a plastic (CPVC) impeller and a rubber (EPR) bell gasket. The installation of the replacement parts by ship's force took place in mid-October.

Successful Processing
Immediately after repairing the membrane feed pump, ship's force successfully treated oily waste. During the first run, the system successfully processed the fluid from the OWHT.

The AAE/CINC Combined System was run six times from the time the second membrane feed pump repair took place to the end of deployment. Section 7 of the Final Report shows the data from the other shipboard system runs.

6.2.4 Homeport Ship Visit

DDG-57 was visited by NSWCCD personnel upon return from deployment. Feedback regarding general performance and reliability of the AAE/CINC Combined System was obtained through crew interviews. The AAE/CINC Combined System was inspected and weekly and monthly maintenance activities were carried out.

In addition to the weekly and monthly maintenance performed, a hot flush was carried out. The hot flush had not finished its cleaning cycle prior to NSWCCD personnel departing DDG-57. It was later confirmed by the operator of the system that the hot flush recovered the permeate flow rate to 3 gpm.

After performing preventative maintenance activities, the marine propulsion assistant (MPA) and afloat environmental program coordinator (AEPC) were debriefed. The full trip report is included as Appendix G in the Final Report.

6.2.5 Conclusions and Recommendations

The AAE/CINC Combined System was able to meet the effluent quality performance objective based on EPA 1664 results. All SGT-HEM values for effluent samples collected were less than 15 ppm. A minimum of 95% of samples collected had to have a SGT-HEM value less than 15 ppm in order to pass. All SGT-HEM values for effluent samples collected were less than 100 ppm, meeting the requirement that all SGT-HEM values for effluent samples collected be less than 100 ppm.

Based on the acceptance criterion dictating that the CINC separator remove at least 80% of the influent oil, the system failed to meet the performance objective.

Water content of waste oil sent to the WOT could not be determined due to the piping configuration of the system shipboard. The performance metric states that all waste oil discharged must contain less than 20% water by volume. Software modifications to the self-cleaning strainer were made to reduce the average water content in the waste oil prior to the shipboard evaluation. The software modifications likely significantly reduced the water content of the waste oil compared to the laboratory results, but not to the metrics of the success criteria.

Based on the acceptance criterion dictating that all system alarms, indicators, and sensors function as designed, the system succeeded in meeting the performance objective. All alarms and warnings appeared to have functioned properly during the shipboard evaluation.

Based on the acceptance criterion dictating that the system achieve an MTBF of 400 hours with a confidence interval of 90%, the system failed to meet the criteria.

By far, the most significant failure was the equipment failure of the membrane feed pump. This failure occurred twice. After each failure, the system was declared OOC. After upgrading the membrane feed pump, this failure was no longer observed and the system would reliably start up. Additional details of the failures that occurred are in Section 7 of the Final Report.

A high level of operator involvement was required prior to upgrading the membrane feed pump. Each membrane feed pump repair required it to be removed from the system skid. After the membrane feed pump issues were resolved, ship’s force reported that the level of operator involvement was low.

After upgrading the membrane feed pump, the AAE/CINC Combined System was able to process bilgewater without any major equipment failures. The upgrade consisted of replacing the plastic membrane feed pump impeller, ethylene propylene rubber bell gasket, and mechanical seal with alternative parts that were more chemically and thermally resistant. The alternative parts were a stainless steel impeller, a Viton bell gasket, and a mechanical seal with Viton elastomers. The composition of the original mechanical seal was not known.

Based on the shipboard evaluation, NSWCCD recommended several permanent hardware and system improvements prior to subsequent installations. The most significant modification was the upgrade of the membrane feed pump components. Section 7 of the Final Report further details the recommended changes.

7.0 COST ASSESSMENT

Due to the results of the shipboard evaluation, NSWCCD determined that a cost assessment using the current data would not be representative of the long term use of a fully functional system. A cost assessment was not performed.

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8.0 IMPLEMENTATION ISSUES

8.1 TRANSITION IMPACTS

The AAE/CINC Combined System may be a potential technology to treat bilgewater onboard Navy Combatants. This technology may be suitable as a new install or retrofit. The objective was to evaluate a centrifugal separator and a membrane polisher integrated into a single unit. Laboratory testing warranted further testing shipboard.

The goal was to identify a commercial OWS that could process the highly variable bilge water shipboard and also require minimal operator involvement and footprint. The effective processing rate of the AAE/CINC Combined System was an issue for a ship installation. The system processes bilge water at 3 gpm. Actuation and fluid dumping of the self-cleaning strainer was optimized to reduce water sent to the WOT. The system's programming was modified to optimize actuation and fluid dumping of the self-cleaning strainer. This updated program was successfully demonstrated during the shipboard evaluation. Due to the system's compact design, performing maintenance or repairs on any of the system's pumps was very difficult.

The system demonstrated a low level of operator involvement during the laboratory evaluation. Two major equipment repair events during shipboard deployment required significant effort to diagnose and repair. Other than these two events, ship's force did not report a high level of operator involvement. The system is complex, however the touch screen control panel allows for easy training and operation. The instruction and detail of the Operation and Maintenance manual still requires evaluation as it was under development during the shipboard evaluation.

Implemented equipment will likely be commercially available with custom system adjustments for each ship class, depending on space availability and ship specification. The system tested was full-scale, so there should be no scale-up issues. No proprietary or intellectual property rights issues are anticipated. The system can be purchased by any vessel with the need. The AAE/CINC Combined System purchased for this test was a standard size. Prior to shipboard installation, software modifications were made. During the shipboard evaluation, hardware modifications were made.

8.2 LESSONS LEARNED

Numerous lessons were learned from a mechanical and system software standpoint. Several system modifications were made just prior to and during the shipboard evaluation. Modifications made were based on system failures to either improve robustness or performance. By far, the most important of these modifications was the replacement of the original membrane feed pump components with more robust ones (see Section 7.3.4 of the Final Report). Prior to this modification, the AAE/CINC Combined System repeatedly broke down due to damage to the membrane feed pump. After this modification was performed, ship's force was able to consistently successfully operate the AAE/CINC Combined System. Ship's force reported that the system was never OOC after the membrane feed pump modifications were made.

Program modifications were made to reduce the water content of the waste oil and shut off the potable water valve if the check valve failed to check during membrane backflushing. The

shipboard demonstration showed that the potable water shut off program did, in fact, signal and prevent filling of the OWHT with potable water. The water content of the waste oil was reduced by nearly half by reducing the flushing rate of the self-cleaning strainer. The shipboard demonstration showed that this reduced flush rate did not have any adverse effects on the strainer. Additional program modifications were made to increase the OCM flush time after shutdown and to add a low permeate flow warning to signal to the operator that the membrane needed to be hotflushed.

8.3 TECHNOLOGY TRANSFER PLANS

Further testing of the AAE/CINC Combined System was performed on DDG-57 for the shipboard evaluation. Shipboard testing demonstrated the system's performance under real world conditions with actual bilge water. Laboratory results were favorable for bulk and mechanically emulsified oil but unfavorable for some chemically emulsified oil. For acceptable shipboard system performance, hardware and software modifications were required.

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APPENDIX A

POINTS OF CONTACT

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