Naval Research Laboratory
Washington, DC 20375-5320

NRL/6130/MR—2023/9

Ballast Water Management System Testing on the M/V Cape Washington: Summary of Biological Efficacy (BE) Results

JONATHAN F. GRANT

Battenkill Technologies, Inc.
Manchester Center, VT

STEPHANIE ROBBINS-WAMSLEY
MATTHEW R. FIRST

Marine Biological Engineering Section
Chemistry Division

TIMOTHY P. WIER

Excet, Inc.
Springfield, VA

September 25, 2023

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
25-09-2023

2. REPORT TYPE
NRL Memorandum Report

3. DATES COVERED *(From - To)*
1/1/17 – 9/1/23

4. TITLE AND SUBTITLE

Ballast Water Management System Testing On the M/V Cape Washington:Summary of Biological Efficacy (BE) Results

5a. CONTRACT NUMBER
N0002423WX11171

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Jonathan F. Grant*, Stephanie H. Robbins-Wamsley, Timothy P. Wier**, and Matthew R. First

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
1V58

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
4555 Overlook Avenue, SW
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/6130/MR--2023/9

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Naval Sea Systems Command (NAVSEA)
Washington Navy Yard
1333 Isaac Hull Ave
Washington, DC 20376

10. SPONSOR / MONITOR'S ACRONYM(S)

NAVSEA

11. SPONSOR / MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

*Battenkill Technologies, Inc. 3431 Richville Rd, Manchester Center, VT 05255
**Excet, Inc. 6225 Brandon Ave., #360, Springfield, VA 22150

14. ABSTRACT

Three commercial ballast water management systems (BWMS) were the subject of operational testing by the U.S. Navy on the Ready Reserve Force Vessel M/V Cape Washington. The tests were conducted while pierside in Baltimore, MD over the period between October 2017 and January 2021. As part of this effort, measurements of organisms were made in ballast uptake and treated ballast discharge waters. This report documents the results of these biological efficacy (BE) tests in order to provide public documentation of the observed treatment capabilities. This report does not identify the individual BWMS tested or any of operational assessments other than BE results; here they are identified as BWMS A, BWMS B, and BWMS C. Results from the BE tests show varying performance of filter treatment subsystems used to remove organisms ≥50 µm in size. Both BWMS A and BWMS B were ineffective in removing sufficient quantities of organisms in this size class to meet the regulated discharge standard of 10 living organisms per cubic meter; these two BWMS generally achieved only a 1-log (10x) reduction for this size class of organisms. BWMS C did meet the discharge standard in one test, and nearly met it in the second, showing a much more effective filtration system with at least a 4-log (10,000x) reduction. In the latter two tests, these findings were corroborated via qualitative assessments of ballast water samples obtained before and after the filter where collected particulates were examined via photomicrography.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Matthew First
U	U	U	U	36	**19b. TELEPHONE NUMBER** *(include area code)* (202) 404-4821

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

This page intentionally left blank.

EXECUTIVE SUMMARY

Three commercial ballast water management systems (BWMS) were the subject of operational testing by the U.S. Navy on the Ready Reserve Force Vessel M/V Cape Washington. The tests were conducted while pierside in Baltimore, MD over the period between October 2017 and January 2021. As part of this effort, measurements of organisms were made in ballast uptake and treated ballast discharge waters. This report documents the results of these biological efficacy (BE) tests in order to provide public documentation of the observed treatment capabilities. This report does not identify the individual BWMS tested or any of operational assessments other than BE results; here they are identified as BWMS A, BWMS B, and BWMS C. The BE tests were guided by the same protocols used for land-based type approval testing (the "ETV Protocol") but did not include control tank samples or cleaning of ballast tanks and associated piping. Two of the three BWMS tested had received U.S. Coast Guard (USCG) Type Approval (TA) at the time of the tests, the third had received International Maritime Organization (IMO) TA and was designated as an Alternative Management System (AMS) through the USCG Shipboard Technology Evaluation Program.

The Cape Washington Operational Tests (CWOT) were designed to inform the U.S. Navy of requirements, issues, and concerns associated with shipboard integration of the various technologies used in ballast water management. For each test, the BWMS was installed on a cargo deck just forward of the engine room to allow routing of ballast piping to the treatment system under test. Installation of the BWMS was managed by the ship's Port Engineer, and mariner crew were hired to operate and maintain the system over each test period. Testing with crew operators under shipboard conditions provided more realistic testing than can be accomplished in a land-based test, and has provided some additional insight into ship deployment of commercial BWMS. These tests also provided an opportunity to measure BE performance under shipboard operating conditions. Here the ambient ballasting conditions were in a brackish water environment while the ship was pierside and not underway. However, ballasting operations were entirely conducted using ship's pumps, piping, and ballast tanks which differ from the test environment in land-based type approval testing, and the tests provided experimental data not available to the Navy from shipboard type approval testing.

Over the course of the CWOT, three different commercial treatment systems were evaluated for BE performance, with two replicate BE tests conducted for each system. The BE tests were replicates across the different BWMS in that they directed treated uptake water to the same ballast tank and operated at a target ballast flow rate of 70% of the specified treatment rated capacity (TRC) for the BWMS. Two of the BWMS utilized filtration and ultraviolet (UV) disinfection treatments, while the third BWMS utilized filtration and full stream electrochlorination (EC) disinfection. In each system, the filter was engaged on uptake and designed to remove particles and organisms ≥50 µm in size. For UV treatments, both uptake and discharge waters were exposed to the disinfection treatment. For the EC treatments, the entire ballast was passed through an electrolyzer on uptake, and any residual oxidant during deballast was neutralized through chemical injection at discharge. All systems completed two complete sets of 20 operational test cycles defined in an operational test matrix where the matrix was both representative of Navy ballasting sequences and adapted to the ship constraints and the

capabilities of the individual BWMS. This report documents only the results of the BE test cycles (two ballast uptake and two ballast discharge for each BWMS).

Results from the BE tests (Table 1) show varying performance of filter treatment subsystems used to remove organisms ≥50 µm in size. Both BWMS A and BWMS B were ineffective in removing sufficient quantities of organisms in this size class to meet the regulated discharge standard of 10 living organisms per m^3 (hereafter, org m^{-3}); these two BWMS generally achieved only a 1-log (10x) reduction for this size class of organisms. BWMS C did meet the discharge standard in one test, and nearly met it in the second, showing a much more effective filtration system with at least a 4-log (10,000x) reduction. In the latter two tests, these findings were corroborated via qualitative assessments of ballast water samples obtained before and after the filter where collected particulates were examined via photomicrography.

Table 1. Results summary showing mean (standard deviation) for living organism uptake and treated discharge counts from three BWMS tested on M/V Cape Washington over the period between October 2017 and January 2021.

BWMS and treatments	BE Test Cycle	Ballast Uptake		Treated Discharge	
		≥50 µm live org m^{-3}	≥10 and <50 µm live org mL^{-1}	≥50 µm live org m^{-3}	≥10 and <50 µm live org mL^{-1}
BWMS A Filtration + UV	1	50,754 (± 825)	3,437 (± 191)	8,605 (± 2,608)	7 (± 3)
	2	144,433 (± 3,769)	3,037 (± 875)	12,570 (± 879)	94 (± 10)
BWMS A Filtration + UV	1	99,865 (±4,575)	541 (±49)	4,871 (±584)	4 (±1)
	2	49,315 (±7,100)	117 (±37)	7,224 (±502)	3 (±1)
BWMS C Filtration + EC	1	57,157 (± 4562)	1,170 (± 125)	BDL	BDL
	2	341,342 (± 14,465)	3,483 (± 496)	11.9	BDL

BDL = below detection limit, EC = electrochlorination, org = organism, UV = ultraviolet

The UV disinfection process primarily targets the smaller ≥10 and<50 µm range of organism sizes. Here, variable results were observed for BWMS A in that one test met the discharge standard of 10 live org mL^{-1}, while the second did not. This system demonstrated a roughly 3-log reduction in live organisms as a result of treatment. BWMS B met the discharge standard for this smaller size class in both tests, however the ambient challenge was an order of magnitude lower than presented to the other BWMS. Here the reduction from ambient was approximate 2-log. This system generated frequent treatment alarms and required frequent cleaning of the UV sleeves protecting the lamps to achieve the target UV dose. This suggests that the delivered UV dosage was often less than the target dose.

The EC disinfection process targets any organisms that are present, although the removal of larger organisms in treatment systems with filters also helps lower oxidant demand. This treatment was effective during both replicate BE tests in that the measurement results for the ≥10 and <50 µm size class and one test for the ≥50 µm size class were below the detection limit for the methods as used in type approval testing.

CONTENTS

TABLE OF FIGURES

LIST OF TABLES

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

Term	**Definition**
5CL	Number 5 centerline ballast tank
AIS	Aquatic invasive species
AMS	Alternative management system
BDL	Below detection limit
BE	Biological efficacy
BWMS	Ballast water management system
Chl	Chlorophyll
CWOT	Cape Washington operations test
DO	Dissolved oxygen
DOD	Department of Defense
EC	Electrochlorination
EPA	United States Environmental Protection Agency
ETV	Environmental technology verification
GF/F	Glass fiber filter
h	Hour
IMO	International Maritime Organization
L	Liter
MARAD	Maritime Administration
MERC	Maritime Environmental Resource Center
m^3	Cubic meter
µm	Micrometer
mg	Milligram
mJ	Millijoule
mL	Milliliter
MM	Mineral matter
NAVSEA	Naval Systems Sea Command
NPS	Nominal pipe size
NRL	United States Naval Research Laboratory
NSWC	Naval Surface Warfare Center
NSWCCD	Naval Surface Warfare Center, Carderock Division
NSWCPD	Naval Surface Warfare Center, Philadelphia Division
OMSM	Operations, maintenance, and safety manual

Term	**Definition**
PE	Port Engineer
POC	Particulate organic carbon
ppt	Parts per thousand
PVC	Polyvinyl chloride
TA	Type approval
TOC	Total organic carbon
TQAP	Test quality assurance plan
TRC	Treatment rated capacity
TRO	Total residual oxidant
TSS	Total suspended solids
U.S.	United States of America
USCG	United States Coast Guard
UV	Ultraviolet
UVI	Ultraviolet intensity
UVT	Ultraviolet transmittance

1 INTRODUCTION

1.1 Background

This report provides the results of Cape Washington operational testing (CWOT) of three commercial ballast water management systems (BWMS) performed by the US Navy on the Ready Reserve Force Vessel M/V Cape Washington. The tests were conducted while pierside in Baltimore, MD over the period between October 2017 and January 2021. As part of this effort, measurements of organisms were made in ballast uptake and ballast discharge waters. Specifically, this report documents the results of these biological efficacy (BE) tests in order to provide public documentation of the observed treatment capabilities. This report does not identify the individual BWMS tested or any of operational assessments other than BE results; here they are identified as BWMS A, BWMS B, and BWMS C. The BE tests were guided by the same protocols (discussed below) used for BWMS type approval testing but did not include control tank samples or cleaning of ballast tanks and associated piping. Two of the three BWMS tested had received U.S. Coast Guard (USCG) Type Approval (TA) at the time of the tests, the third had received International Maritime Organization (IMO) TA and was designated as an Alternative Management System (AMS) through the USCG Shipboard Technology Evaluation Program).

The treatment of ballast water on commercial vessels is subject to both international (International Maritime Organization; IMO) and U.S. regulations, where the number of living organisms in the ballast discharge is limited to reduce the transport and delivery of potential aquatic invasive species (AIS). The numeric discharge standards are essentially identical for IMO and the U.S.; both categorize organisms into three size classes: ≥50 µm (nominally zooplankton), ≥10 µm and <50 µm (nominally protists), and <10 µm (two indicator organisms and a pathogen) (Table 2). The key difference between IMO and U.S. regulations is that the U.S. cites "living organisms", whereas IMO cites "viable organisms". However, IMO has only accepted test methods that measure viability for a subset of organisms in the ≥10 and <50 µm size class. Testing for U.S. TA calls for following land-based test protocols published under the U.S. Environmental Protection Agency's (EPA) Environmental Technology Verification (ETV) Program (EPA 2010). While U.S. Navy vessels are not subject to these regulations, they are expected to comply with similar ballast water discharge standards under the Department of Defense Manual (DOD) 4715.06, Volume 3 (DOD 2019). This report summarizes the BE testing regime and observed results from this testing.

Manuscript approved September 12, 2023.

Table 2. Ballast water discharge standards for living/viable organisms in navigable U.S. and International waters. Terminology and organisms identified varies between the US and IMO, where the US considers *living* organisms and the IMO considers *viable* organisms (which are living organisms capable to reproduction). In practice, viability is able to be measured for a subset of organisms ≥10 and <50 µm.

Organization and Standard	**Living Organisms ≥50 µm in Minimum Dimension**[A]	**Living Organisms ≥10 µm and <50 µm in Minimum Dimension**[B]	**Toxigenic *Vibrio cholerae***[C]	***Escherichia coli***	**Intestinal Enterococci**
U.S. Discharge Standard	<10 m^{-3}	<10 mL^{-1}	<1 cfu 100 mL^{-1}	<250 cfu 100 mL^{-1}	<100 cfu 100 mL^{-1}
IMO Regulation D-2 Ballast Water Performance Standard	<10 m^{-3}	<10 mL^{-1}	<1 cfu 100 mL^{-1} or <1 cfu g^{-1} (wet weight zoopl.)	<250 cfu 100 mL^{-1}	<100 cfu 100 mL^{-1}

[A]Nominally zooplankton. [B]Nominally protists. [C]Serotypes O1 and O139. cfu = colony forming unit, IMO = International Maritime Organization, and zoopl. = zooplankton.

1.2 Operational testing purpose and data outputs

The Naval Sea Systems Command 05P (NAVSEA) tasked the U.S. Naval Research Laboratory (NRL) to develop and execute a program to examine the operational characteristics of commercial ballast water management systems. Testing on M/V Cape Washington was designed to provide eight weeks of operational tests in a shipboard ballast environment, where ballast operations with the BWMS were conducted by merchant marine crew. The tests were designed to inform the U.S. Navy of installation requirements, potential operational issues, and technical concerns associated with the shipboard integration of various ballast water management technologies. The tests were overseen by the U.S. Naval Research Laboratory (NRL) and were coordinated through and conducted by the ship owner (U.S. Department of Transportation Maritime Administration - MARAD) and their contracted ship manager (Crowley Government Services, Inc.).

Testing was performed in accordance with the NRL Test Quality Assurance Plan (TQAP), which was developed with input from MARAD, the Port Engineer (PE) for the vessel, the Naval Surface Warfare Center (NSWC) Carderock Division (NSWCCD), and NSWC Philadelphia Division (NSWCPD). NRL and NSWC science team personnel conducted multiple visits to the ship to observe operations and conduct sampling operations. Much of the BWMS installation was performed by the ship's crew with industrial assistance support where required, and technical representatives for each BWMS manufacturer provided operator training, installation support, and commissioning of the equipment.

1.3 Overview of treatment systems

The three BWMS subject to testing are referred to in this report as BWMS A, BWMS B, and BWMS C. Characteristics of the systems, including treatment rated capacity (TRC), treatment methods, and type approval status are provided below in Table 3.

Table 3. Summary descriptions for BWMS tested on M/V Cape Washington

Treatment system	**Treatment rated capacity (TRC)**	**Treatment methods**	**IMO type approval**	**USCG type approval**	**BE results meet discharge standards?**
BWMS A	250 m^3h^{-1}	Filtration (30 µm as tested) + UV	Yes	No – AMS	No
BWMS B	334 m^3h^{-1}	Filtration (40 µm as tested) + UV	Yes	Manufacturer upgraded their field demo unit to USCG approved configuration	No
BWMS C	300 m^3h^{-1}	Filtration (40 µm as tested) + EC	Yes	Yes	Mostly

AMS – USCG alternative management system, BE – Biological efficacy, EC – Electrochlorination, UV – Ultraviolet

2 OVERVIEW OF CAPE WASHINGTON OPERTATIONAL TESTS

2.1 Ballast water treatment test environment

The ship M/V Cape Washington (AKR-9961, IMO 7826178, Figure 1) provides a BWMS test environment to conduct ship ballasting operations. All BWMS testing was performed using ship systems while pierside. This is a Roll-on/Roll-off transport ship in the MARAD Ready Reserve Force, at layberth at the Port Covington Maritime Center in Baltimore's Inner Harbor. Tests typically utilize only one of the ship's ballast pumps and from one to three ballast tanks. Tests are supported by the installation of temporary piping in the engine room, allowing ballast flows to be diverted to and from the adjacent cargo space where the BWMS was installed for the duration of the tests. This configuration allows temporary testing of different treatment systems while allowing a rapid return to normal service arrangements. The selection of ballast tanks used in testing and overboard discharges associated with BWMS testing were reviewed and approved by the ship's management personnel.

Figure 1. M/V Cape Washington (AKR-9961, MARAD photo) serves as the test facility for Navy BWMS testing. Ship displacement is 22,145 t.(light displacement), 53,500 t.(full load). Ship dimensions (in feet) are: length 697', beam 106', draft 38'. Ship speed is 14.7 kts. Image source: MARAD, posted on http://www.navsource.org/archives/09/54/549961.htm.

In accordance with the TQAP, installation of the BWMS was on the No. 01 Cargo Deck (the aft section just forward of the engine room bulkhead on the port side); this space is accessible to motorized vehicles. Connections between the engine room ballast piping and the BWMS as situated in the cargo deck were made via two 8" nominal pipe size (NPS), Class 150 flanges (ballast supply and ballast return) and one 4" NPS Class 150 flange (filter backwash). These piping modifications provided ballast flow from the 12" NPS main ballast piping in the engine room to flanges installed on the engine room forward bulkhead. The 8" NPS piping provided supply and return of ballast water to the BWMS installed in the cargo deck (Figure 2). Filter backwash was sent to the overboard discharge via 4" NPS piping between the flange on the discharge line downstream of the sample port and the 4" NPS flange on the forward bulkhead. Each BWMS included a booster pump to ensure sufficient pressure for discharge of the backwash through this piping. All temporary piping in the engine room and down to deck level in the cargo space was steel, while connections to the BWMS in the cargo space utilized 4" and 8" NPS Schedule 40 polyvinyl chloride (PVC) piping. Compressed air for pneumatic actuators on the BWMS was made available via a connection from the engine room on the forward bulkhead. While each of the ship's two ballast pumps are rated for 700 m^3 h^{-1}, the maximum ballast rate to a BWMS under test was approximately 350 m^3 h^{-1} due to the 8" NPS piping in the cargo deck.

The piping configuration in the cargo space was designed to provide one sample collection port before and two sample collection ports after the treatment system (Figure 2). Water samples from these ports support science team analyses. Two types of sample probes were fabricated for installation based on target sample volumes (i.e., three suitable for large volume [≥ 1 m^3] samples and three for small volume [~10 - 20 L] samples). A return port was included in the filter backwash pipe to allow residual water from sample operations to be pumped into the overboard discharge. For each piping section (supply, return, and backflush), flow sensors (GF

Signet 2551 magmeter) were installed in locations with suitable straight lengths of piping (Figure 2).

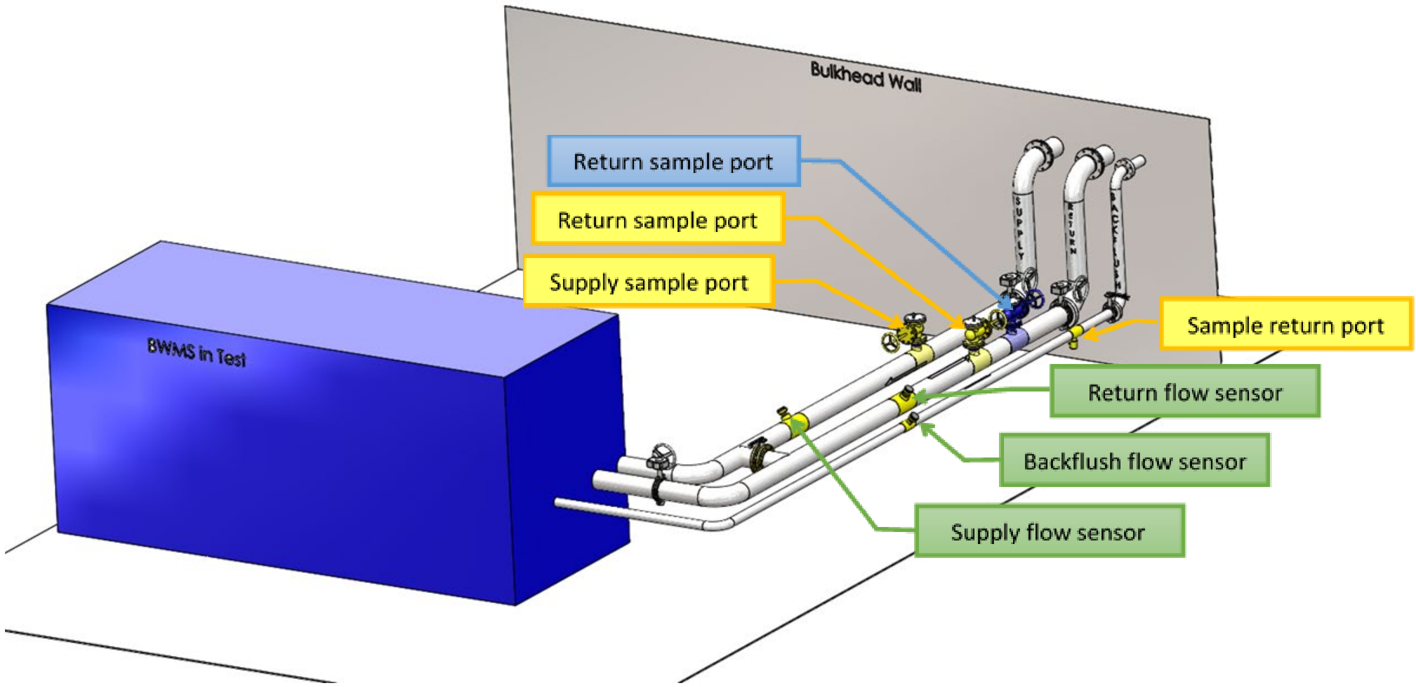


Figure 2. Typical BWMS installation on the No. 1 Cargo Deck looking aft. At the far (aft) end, vertical steel piping attaches to flanges on the forward bulkhead of the engine room. Horizontal PVC piping is used to supply and return ballast water to and from the BWMS in the cargo space; each ballast pipe has its own flow sensor. The ballast water supply line to the BWMS is the pipe on the left, the return line from the BWMS is the middle pipe, and the backflush line is the rightmost (smaller diameter) pipe. Filter backflush leads overboard through the backflush piping. The sample ports provide for collection and the sample return port allows for disposal of sample water during testing. Orientation of the BWMS may not be as shown, as routing of ballast piping is unique to each BWMS.

Execution of ship ballasting and all BWMS operations were performed by ship's crew in accordance with the NRL TQAP. Training for the test operations was conducted by NRL, while training for the BWMS operation was conducted by the manufacturer's technical representative. Science teams conducted sampling operations per the TQAP over the course of testing.

2.2 Experimental design

A formal TQAP was developed for testing of each BWMS, customized as necessary for the installation characteristics and requirements associated with a given treatment technology and system configuration. Each BWMS TQAP conforms to the NRL Code 6137's quality management system, and these shipboard tests are identified as CWOT. The experimental design for the project incorporated input from NSWC, and ballast sequences were based on common ballast evolutions for amphibious class ships. Testing was conducted using ambient harbor water while pierside at its normal berthing location in Baltimore Harbor; no testing was performed while the vessel was underway. The operators were allowed to vary times and sequences as well as the order of test sequences as needed to accommodate ship ballasting requirements, maintenance, or other concerns. The operators logged dates, ballasting operations, and BWMS run conditions and were assigned full time to conducting these tests.

Test conditions were defined in the TQAP by the Test Operations Matrix; this was a 20-day test schedule that was repeated once to achieve 40 days of testing. The matrix identifies the first set if tests as 1.01 through 1.20, and repeats the target test conditions in a second set identified as 2.01 through 2.20. The initial matrix was developed after discussions with Navy personnel to define the range of flow conditions of interest. The resulting matrix included daily test operations of ballast uptake, ballast discharge, or both. Discharge sequences mirrored the prior uptake sequence in terms of target flow rate, ballast tank, and run time. Duration of ballast sequences, flow rates, and tanks used for ballasting were adjusted to accommodate both the capabilities of the BWMS under test and the requirements of the ship while moored. The overall test operations matrix provided for total ballasting of approximately 20,000 m^3 of water (i.e., 20,000 m^3 ballasted with that same volume subsequently deballasted) and 220 hours of ballasting and deballasting treatment operations. For each of the BWMS tested, treatment occurred both on uptake (ballasting) and discharge (deballasting), where systems producing oxidants provided neutralization but no disinfection on discharge. While target flow rates were defined in the test operations matrix, flow rates achieved were varied due to changes in water quality (and resulting backflush activity) and conditions such as tank levels and head pressure within the ship’s ballast system.

Two replicate ballast / deballast evolutions were specifically designed to allow BE sample collection to assess biological treatment performance. BE tests provided target uptake and discharge flow to and from the number 5 centerline (5CL) ballast tank with target flow rates at 70% of TRC with a nominal run time of 2.5 hours. In all tests, the uptake (test cycles 1.17 and 2.17) was conducted on a Friday and the discharge (test cycles 1.18 and 2.18) on a Monday to provide a nominal three day hold time, and to allow sampling teams time to collect, process, and analyze samples consistent with ETV sampling protocols.

2.3 Data collection and analytical methods

2.3.1 Operational data

Data generated during the daily operational testing included both handwritten logs (by the operators) and electronically logged data (by the BWMS and science team sensors). While the electronic logs recorded specific quantitative test parameters, the operator-generated logs were intended to include both quantitative and qualitative data. The operator logs also served as test records in accordance with NRL’s quality management system. As the purview of this report is the BE Tests, the specifics of the operational data are not included here.

2.3.2 Water sample data

2.3.2.1 Biological efficacy (BE) data

Two ballast – deballast evolutions were dedicated to collection of water sampling of uptake and discharge water for BE assessments. No attempts were made to control the makeup of the uptake water, and the hold time was fixed at approximately three days, with uptake occurring on a Friday and discharge occurring on a Monday. The same ballast tank was used for the BE sampling in each of the tests, with target uptake and discharge flows at 70% of the BWMS TRC.

The number of living organisms in two regulated size classes (≥10 and <50 µm, and ≥50 µm) were quantified according to the methods found in the EPA *Generic protocol for the verification of ballast water treatment technology, version 5.1* (EPA 2010). The document was released under the EPA ETV Program and hereafter, it is referred to as the ETV Protocol. The ETV Protocol was incorporated by reference in USCG ballast water discharge regulations (46 CFR 162.060), and is utilized during U.S. TA testing. MARAD contracted the Maritime Environmental Resource Center (MERC) to perform all sample collection and analysis for each replicate uptake-discharge cycle during the BE tests. In these tests, no control tank was used, and only a subset of TA parameters were monitored (e.g., indicator bacteria were not analyzed).

Ballast water samples were collected using ETV compliant sample probes designed by NRL. Ambient concentrations of live organisms sent to the BWMS (i.e., challenge conditions) were measured in ballast uptake samples, and the post-treatment ballast discharge samples were analyzed to measure the BE of the treatment. For the ≥50 µm size class, volumes were filtered through a 35 µm plankton net with a minimum target volume of 1.6 m^3. Integrated sample volumes of at least 15 L were collected for analysis of both the ≥10 and <50 µm size class and for water chemistry analyses. The sample flow rates and sample collection times were consistent with ETV Protocol test guidance, and allowed sample collection to occur in the morning of the test. This left the afternoon for the samples to be processed and analyzed. The weekend hold time was consistent across all tests, and provided time to prepare the sampling equipment for the subsequent discharge sampling.

Ballast uptake water from Baltimore Harbor was sourced through the upper sea chest and samples were collected using the ETV probes in the supply line to the BWMS. Treated water was sent to tank 5CL and held in the tank over the weekend. Discharge samples were collected using the ETV probe in the return line from the BWMS. Each BE sampling event followed the same test cycle sequence from the test operations matrix, where sampling was conducted over the time it took to fill or drain tank 5CL; this was planned to be approximately 2.5 h. Tank 5CL is located approximately at the center bottom of the ship, and was expected to be a consistent test as it would have minimal effect on trim or list of the ship during ballast operations.

2.3.2.2 Filter efficacy data

Filter efficacy was qualitatively examined during the second and third CWOT. These assessments included photomicrography of concentrated samples, and particle size assessments of whole water samples in accordance with ISO 4406 by RTI Laboratories. Samples were typically collected before and after the BWMS (from supply and return sample ports). On a ballasting test cycle, this provides separate observations of source uptake (harbor) water and treated water to allow a qualitative assessment of the filter performance.

A sample volume of 20 L was collected over several test cycles using both the pre- and post-BWMS sample probes during ballast uptake. Each 20 L sample was screened through a 35 µm mesh to retain particles ≥50 µm in size. The collected filtrand was then rinsed from the mesh into a 50 mL Falcon® tube and resuspended to 50 mL by adding particle free water. Half this concentrated sample was poured into a 60 mL capacity syringe—equipped with a leur-lock tip—connected to a 25 mm diameter capacity filter housing. The filter housing was pre-loaded with a 25 mm diameter, 0.45 µm-membrane filter.

Once the 25 mL sample is loaded into the syringe, the plunger is inserted and depressed in a slow and steady motion forcing the sample water through the membrane filter. The water that passes through (filtrate) is captured in a waste container. Next, the syringe and filter housing apparatus are rinsed three times with 0.7 µm filtered water that is then passed through the membrane filter as described above. The filter is then removed and photographed with any ≥50 µm particles on it; standard 50 µm microbeads may be added as a size reference.

2.3.2.3 Total Residual Oxidant (TRO) data

Measurement of TRO was performed for BWMS C (using electrochlorination treatment) on several whole water grab samples obtained after stable running conditions had been established. Analysis was according to EPA-certified Standard Method 4500-CL G (2017), also known as the DPD method. The method uses N,N-diethyl-p-phenylenediamine (DPD) to generate a colorimetric intensity response that is directly related to the concentration of Total Chlorine in the water sample. Color intensity was measured using a DR300 Pocket Colorimeter (The HACH Company, Loveland, CO), and the results were reported as a concentration per volume of Total Chlorine (i.e., mg L^{-1}). The DR300 sample readings were made in triplicate (i.e., analytical replicates) per sample and recorded manually.

3 BWMS A

3.1 Executive summary

BWMS A provided filtration and ultraviolet (UV) disinfection of ballast water, and as tested it received International Maritime Organization (IMO) type approval and acceptance as a USCG AMS. The BWMS proved suitable for shipboard installation, although the BWMS flow sensor was not properly calibrated, and its readings were demonstrably low. The BWMS functioned with few operational or maintenance issues, which typically had a mean time to repair of an hour or less. The BWMS included self-cleaning wipers for the UV lamps. There were a number of alarms that occurred frequently. The majority of these were common during startup and shutdown and were typically attributed to the ship's test setup or operator error. Neither alarms nor maintenance issues impacted the crew's ability to operate the BWMS. With regard to the test environment, target ballast flows were difficult to maintain; this was both due to the lack of flow sensor calibration and the configuration of the test setup (discussed below). Based on tank soundings and fill times, flow rates were typically higher during ballasting than deballasting. Deballast flow rates were often lower than the target flow.

The two biological efficacy tests according to the ETV Protocol examined living organisms in both the ≥10 and <50 µm and the ≥50 µm size classes. In one test, the results for the smaller size class were below the discharge standard, but in the other they exceeded the discharge standard. In both tests, the larger size class showed roughly a 1-log reduction between uptake and discharge, and both exceeded the discharge standard by at least three orders of magnitude. The possibility of contamination was assessed as unlikely.

3.2 Any exceptional test conditions

Test execution was generally in accordance with the TQAP, including BE sampling operations. Of note, prior to the installation of the BWMS, M/V Cape Washington was in dry dock, and the ballast tanks had been cleaned and filled with fresh (municipal) water, so no contamination was expected from pre-existing ballast water or sediment in the ballast tanks. Additionally, issues running the port ballast pump piping with the variable frequency drive prevented the use of variable flows via the ballast pump. Instead, the tests were run using the starboard pump which had two fixed speeds, and flows were regulated using valves instead of pump speed.

3.3 Any exceptional data collection methodology

Data collection was conducted largely in accordance with the TQAP, however some ballast and deballast sequences were modified to better balance operations to starboard and port ballast tanks. In addition to completing the test operations matrix, two additional operational test cycles were conducted, one to repeat an invalid test due to a ship issue with a valve in the ballast system, and the other to replicate conditions to see if an unusual behavior in the BWMS controlling output flow recurred (it did not). These did not affect the BE test cycles.

3.4 Summary of BE results

Sampling for BE analyses occurred over approximately 3 h for both the uptake and discharge of tank 5CL. For the first trial, ballasting occurred on 8 DEC 2017 (test cycle 1.17) with deballasting (discharge) on 11 DEC 2017 (test cycle 1.18). For the second trial, ballasting occurred on 9 FEB 2018 (test cycle 2.17) with deballasting on 12 FEB 2018 (test cycle 2.18). Uptake ballast water was sampled from the supply line prior to treatment, and deballast water was sampled from the return line after treatment and prior to overboard discharge. During ballasting and deballasting, samples were collected for the ≥50 µm and the ≥10 µm and <50µm size classes. Hold times for both BE tests was between 65 and 70 h; the IMO type approval certificate for BWMS A did not specify a hold time.

Data extracted from the report submitted by MERC are presented below and summarize the test data on water chemistry (Table 4), live organism concentrations (Table 5), and sample volumes (Table 6). Ambient water was brackish and the ETV biological challenge water conditions were met during uptake; the treated discharge limits exceeded the USCG and IMO discharge standards (Table 5). Centric diatoms and eggs were found in the uptake and discharge samples during both tests. As per the ETV Protocol, non-swimming diatoms and eggs are **not** included in the live counts below but MERC documented those additional counts in their report for completeness. No obvious signs of contamination were observed in the samples.

Table 4. Average (standard deviation) water quality and chemistry challenge conditions observed during uptake events for BWMS A. The ETV challenge conditions for temperature are 4 – 35 °C, with brackish salinity ranging between 10 – 20 ppt. (Note: units of ppt are approximately equal to Practical Salinity Units (PSU), which are a measure of conductivity at a constant pressure and temperature.) There are no challenge requirements for DO or Chl.

Test Cycle	Temp (°C)	Salinity (ppt)	DO (mg L^{-1})	Chl (µg L^{-1})
1.17	10.6 (±0.4)	12.4 (±0.2)	9.6 (±0.4)	11.0 (±1.5)
1.18	10.9 (±0.0)	11.9 (±0.3)	9.0 (±0.1)	1.1 (±0.1)
2.17	2.1 (±0.1)	11.3 (±0.0)	12.9 (±0.2)	18.8 (±2.0)
2.18	3.3 (±0.9)	11.2 (±0.1)	10.7 (±0.1)	11.3 (±2.1)

Chl= chlorophyll, DO = dissolved oxygen.

Table 5. Mean (standard deviation) of live organism concentrations in ballast uptake and treated discharge for BWMS A. The ETV challenge water requirements are 10^5 organisms m^{-3} for the ≥50 µm size class, and 10^3 for the ≥10 and <50 µm size class. Corresponding discharge limits are 10 organisms m^{-3} and 10 organisms mL^{-1}, respectively.

Test Cycle	Ballast Uptake		Test Cycle	Treated Discharge	
	≥50 µm live org m^{-3}	≥10 and <50 µm live org mL^{-1}		≥50 µm live org m^{-3}	≥10 and <50 µm live org mL^{-1}
1.17	50,754 (±825)	3,437 (±191)	1.18	8,605 (±2,608)	7 (±3)
2.17	144,433 (±3,769)	3,037 (±875)	2.18	12,570 (±879)	94 (±10)

Table 6. Sample volumes for BWMS A as collected for analysis of the ≥50 µm size class and the integrated whole water samples used for water chemistry and analysis of the ≥10 and <50 µm size class.

Test Cycle	Ballast Uptake		Test Cycle	Treated Discharge	
	≥50 µm analytical volume (m^3)	Integrated whole water sample volume (L)		≥50 µm analytical volume (m^3)	Integrated whole water sample volume (L)
1.17	3.2	35	1.18	2.9	40
2.17	3.4	38	2.18	4.2	48

3.5 Relevant discussion and/or conclusion (including potential for contamination)

Both ETV sampling events showed live ≥50 µm organism counts that exceeded the discharge standard, so the likelihood of contamination affecting the measurements was evaluated. For contamination to occur, harbor water with living organisms would need to be added to the tanks without going through the treatment system, or the sample collection process would need to sample untreated water from another source in the ship's ballast system. The first scenario could be caused by valve leakage, and in one test cycle, this did actually occur (test cycle 2.05). Here the cause for the valve leakage was identified (all ballasting valves were tested over a weekend by the Chief Mate, and the leaking valve failed to close properly). In that case, the amount of water was significant and apparent to the test operator, so the test was considered invalid and repeated (in test cycles 3.05 and 3.06). The second scenario would require either ballasting from the wrong tank (which did not occur and would be apparent to the crew), having untreated water in the tank, or the sampling of remnant harbor waters in the ballast pipes. Both scenarios were analyzed and found to be unlikely to have occurred. The first would have required a significant volume (>50 m^3) of harbor water to result in the observed organism concentrations. Procedures during testing would have flushed any untreated waters remaining in the piping prior to sample collection, thus eliminating the second scenario.

While there were no requisite challenge conditions required for these tests, harbor waters in the Port of Baltimore provided suitable numbers of organisms to nearly meet ETV Protocol challenge conditions for the first test, and did meet them for the second BE test. The water quality characteristics were approximately 25% of the minimum levels called out in the ETV Protocol for dissolved organic materials, particulate organic materials, and total suspended solids. While ultraviolet transmittance (UVT) is not specified by the ETV Protocol, historical UVT levels in the Port of Baltimore are above 80%; as such this was not expected to be overly challenging. The UVT measurements collected by NSWCCD over the course of testing were all above 80%. While there was no limit of UVT observed in the type approval documentation, the Operational Maintenance and Safety Manual (OMSM) indicates a minimum design UVT of 40%; the system reduces treatment flow to accommodate a decrease in UVT. Treatment system test logs indicate that the minimum dose of 50 mJ cm^{-2} was achieved during normal operations. This indicates that the manufacturer specified target treatment was achieved under the challenge conditions provided by these tests.

Uptake waters were relatively low in both turbidity and particulates (below ETV challenge levels), and the BWMS rarely initiated backflushing as a result of differential pressure across the filter; the backflushing during uptake treatment was typically initiated by timer. However, treated discharge data for both BE test cycles show a number much greater than the discharge standard for the larger size class of organisms, which are expected to be removed at uptake by the filter.

4 BWMS B

4.1 Executive summary

While BWMS B proved suitable for shipboard installation, it required additional post-commissioning support and troubleshooting to ensure operational readiness. Installation of the BWMS was straightforward, but getting the system operational required a factory engineer to supply replacement parts from overseas, and repairs following multiple failures subsequent to commissioning.

The failures that occurred were not detected by the factory-commissioning checklist. The system rarely demonstrated the UV dosage levels required by USCG type approval (TA), and then only after repeated maintenance through the manual cleaning of UV reactor components (this system did not provide any automated cleaning of UV lamp sleeves). The system was unable to meet discharge limits in the two biological efficacy evaluations, and samples assessing the filter efficacy suggest that the supplied filter is only marginally effective at removing larger microorganisms and particles.

Once initial operational failures were resolved, treatment operations proceeded with minimal issues through a 40-day test cycle matrix, except that the system operated with a continuous treatment alarm (indicating the UV dose did not meet TA requirements). This alarm was present from commissioning on, and the service engineer believed the low UV levels were due to heavy rain causing turbidity in the water and it would clear up. Following a continued decline in UV intensity with very low readings at the end of biological efficacy test cycles, the test team decided to clean the UV reactor components. This dramatically increased UV intensity, but following a single test cycle, the levels would again decline to below USCG TA required levels and trigger a treatment alarm. There were also two lamp failures during the test; these were easily replaced.

Results from BE tests showed BWMS B did not meet discharge requirement for the ≥50 µm size class, but did meet discharge requirements for the ≥10 and < 50 µm size class. Of note, the challenge provided by harbor waters for the smaller size class was well under that required for TA testing. The larger size class showed roughly a 1-log reduction between uptake and discharge, and the smaller size class had approximately a 2-log reduction. The larger size class exceeded the discharge standard by at least three orders of magnitude. The possibility of contamination was assessed as unlikely.

To assess the efficacy of the filtration system, samples were collected before and after the treatment system during several ballast uptakes. Sample analyses included photomicrography, size fractionation, and particle sizing analysis. Results showed some reduction but not elimination of particles in the larger size class. This was consistent with the biological analyses.

4.2 Any exceptional test conditions

Both ETV test cycles were performed in September while organism densities were still at a high level (according to MERC). These were conducted two weeks apart in order to provide similar uptake (challenge) conditions over the two assessments. The UV intensity (UVI) readings had dropped from an initial value on the order of 300 W m^{-2} to around 40 W m^{-2} during the final ETV test cycle. While the OMSM indicated the UV reactors require annual cleaning, the low UVI prompted the test team's decision to disassemble the reactors to determine if cleaning was required. The quartz tubes protecting the lamps did require cleaning and this resulted in a substantial improvement in UVI.

During test cycle operations, ballast uptakes often appeared to result in less volume than anticipated, while deballast operations often completed sooner than expected given starting tank volumes. This particularly affected the first of the ETV tests, where the ballast operation took longer to complete than expected, and the deballast operation for the 5CL tank completed so quickly that the sampling needed to continue during the deballast of the next tank in the test sequence in order to obtain sufficient sample volume. It was believed these issues are due to leaking valves in the ship's ballast system, and this was later confirmed for the ballast uptake. Some of the treated ballast water sent to the ballast tank was instead being recycled back into the treatment system through a leaky valve. This resulted in less flow entering the test ballast tank and hence a longer time to fill the tank than expected, as well as some water being treated multiple times. The result of a tank emptying faster than expected suggested the potential for some of the deballast water leaking to the starboard overboard discharge prior to entering the treatment system. This scenario was not able to be confirmed, but remains a likely explanation for water from the test tank not passing through the treatment system.

4.3 Any exceptional data collection methodology

The uptake samples collected prior to and after treatment by BWMS B were examined in multiple ways to see if differences were visible as a result of filtration. Pre- and post-treatment comparisons were made to determine which were most effective in gauging the effectiveness of the BWMS filtration process. These included photomicrography and analysis of particle size distribution. For the former, images of the filtrate were collected on glass fiber filters. Imagery were acquired using brightfield illumination and 20x magnification. Only a portion of the filter was visible at this magnification so all images were aligned to the center of each filter. Particle size distribution analysis was conducting by a contracted analytical laboratory (RTI Laboratories).

4.4 Summary of BE results

The first BE trial consisted of a ballast uptake on 7 SEP 2018 (test cycle 1.17) and a ballast discharge (test cycle 1.18) on 10 SEP 2018. The second BE trial performed a ballast uptake (test cycle 2.17) on 21 SEP 2018 and a ballast discharge (test cycle 2.18) on 24 SEP 2018. For the first trial, water was held in the ballast tank for just under 70 h, and about 72.5 h for the second trial. Of note, during the deballast test cycle 1.18 of the first trial, the 5CL tank emptied much faster than expected, and insufficient sample volume had been collected. Sampling continued as the discharge was switched to the 5SB tank. As this tank also began to empty faster than expected, the MERC sampling team increased the sample flow to increase the sample volume to achieve measurement requirements. For reference, the BWMS B TA certificate specifies a hold time of at least 3 days (>72 h).

Data extracted from the MERC test report are presented below and summarize the test data on water chemistry (Table 7), live organism concentrations (Table 8), and sample volumes (Table 9).

Table 7. Mean (standard deviation) for water quality and chemistry challenge conditions observed during BE test cycles for BWMS B. The ETV challenge conditions for temperature are 4 – 35 °C, with brackish salinity ranging between 10 – 20 ppt. There are no challenge requirements for DO, Chl, or UVT. The effect of higher than average rainfall during the BE test cycles can be seen on the lower than normal salinity.

Test Cycle	Temp (°C)	Salinity (ppt)	DO (mg L^{-1})	Chl (µg L^{-1})	UVT (%)
1.17	28.9 (±0.1)	2.6 (±0.1)	6.5 (±1.2)	4.5 (±2.2)	78.0 (±0.9)
1.18	25.3 (±0.2)	2.6 (±0.1)	6.0 (±0.6)	0.2 (±0.1)	81.5 (±0.3)
2.17	24.4 (±0.1)	3.2 (±0.1)	5.2 (±0.6)	4.1 (±1.1)	76.3 (±0.9)
2.18	24.2 (±0.6)	3.2 (±0.1)	4.1 (±0.5)	2.3 (±0.2)	76.5 (±0.4)

Chl= chlorophyll, DO = dissolved oxygen, UVT = ultraviolet transmission.

Table 8. Mean (standard deviation) of live organism concentrations in ballast uptake and treated discharge for BWMS B. The ETV challenge water requirements are 10^5 organisms m^{-3} for the ≥50 µm size class, and 10^3 for the ≥10 and <50 µm size class. Corresponding discharge limits are 10 organisms m^{-3} and 10 organisms mL^{-1}, respectively.

Test Cycle	Ballast Uptake		Test Cycle	Treated Discharge	
	≥50 µm live org m^{-3}	≥10 and <50 µm live org mL^{-1}		≥50 µm live org m^{-3}	≥10 and <50 µm live org mL^{-1}
1.17	99,865 (±4,575)	541 (±49)	1.18	4,871 (±584)	4 (±1)
2.17	49,315 (±7,100)	117 (±37)	2.18	7,224 (±502)	3 (±1)

Table 9. Sample volumes as collected for analysis of the ≥50 µm size class and the integrated whole water samples used for water chemistry and analysis of the ≥10 and <50 µm size class.

Test Cycle	Ballast Uptake		Test Cycle	Treated Discharge	
	≥50 µm analytical volume (m^3)	Integrated whole water sample volume (L)		≥50 µm analytical volume (m^3)	Integrated whole water sample volume (L)
1.17	2.2	17	1.18	2.3	15
2.17	2.9	18	2.18	4.3	23

Prior to and during the BE tests, precipitation levels were above normal in the Baltimore area which contributed to salinity levels less than the ETV brackish range of 10-20 ppt. The observed organism populations were also lower than the typical seasonal populations reported by MERC. Results of organism counts for both BE tests are shown in Table 8. Organisms in ambient water met the ETV challenge water conditions for the ≥50 µm size class (≥10^5 m^{-3}) but not the ≥10 and <50 µm size class (≥10^3 mL^{-1}). The treated discharge organism counts exceeded the USCG and IMO discharge standards for the ≥50 µm size class, and met the discharge standard for the ≥10 and <50 µm size class. Centric diatoms and eggs were found in the uptake and discharge samples during both tests. As per the ETV Protocol, non-swimming diatoms and eggs are **not** included in the live counts but MERC documented those additional counts in their report for completeness.

4.5 Filter efficacy assessments

The uptake samples collected prior to and after treatment by BWMS B were examined in multiple ways to see if differences were visible as a result of filtration. Pre- and post-treatment comparisons using photomicrographs and particle size analysis were found most effective in gauging the effectiveness of the filtration process.

Photomicrography: Images of the filtrate collected on glass fiber filters (GF/F) are shown in Figure 3; these were acquired using brightfield illumination and 20x magnification. Only a portion of the GF/F was visible at this magnification so all images were aligned to the center of each filter. Of note, the first time this GF/F collection process was performed (17 OCT 2018), there was a leak in the apparatus, which resulted in some sample loss. A Quality Assurance and Quality Control step was subsequently put into place for all consecutive GF/F processing to test for potential leaks prior to sample processing. Additionally, a size reference was added to later GF/F images in the form of standardized, 50 µm diameter, red, microspheres (Figure 3). This allows a visual comparison of particles in both the uptake water and water that passed through the BWMS. The purpose of the filter treatment within the BWMS was to remove particles of size equal to and larger than the microspheres.

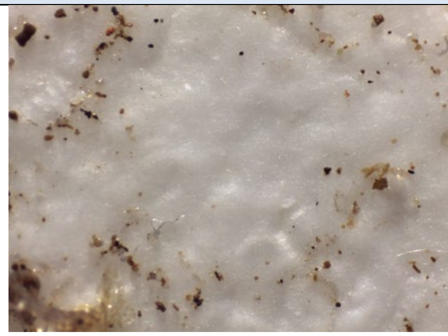
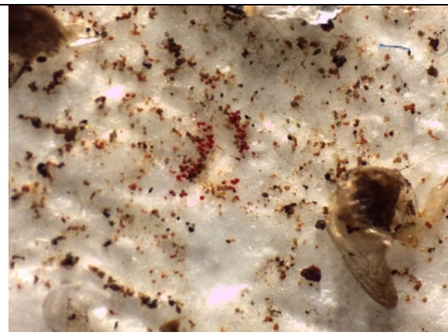
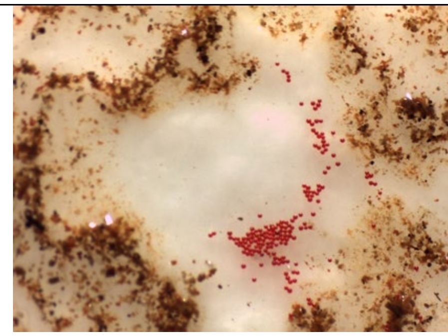
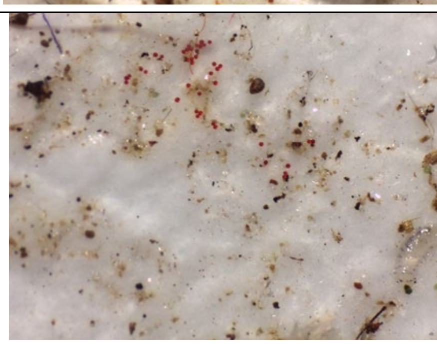
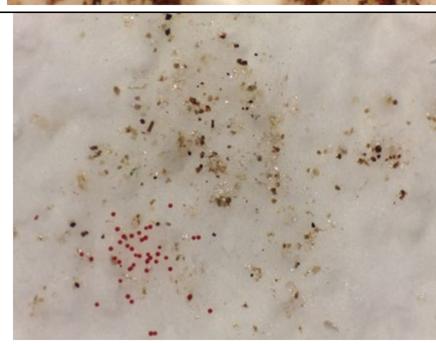
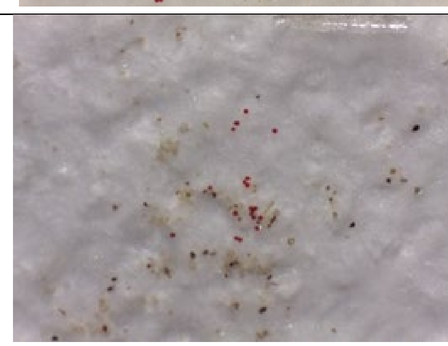
Test Cycle Date	**Supply (pre-treatment)**	**Return (post-treatment)**
Test Cycle 2.08 22 OCT 2019		
Test Cycle 2.09 23 OCT 2019		
Test Cycle 2.19 6 NOV 2019		
Test Cycle 2.10 13 NOV 2019		

Figure 3. Photomicrography images of glass-fiber filter (GF/F, 0.7 µm) showing filtrand (≥50 um particles) retained by a 35 µm sieve from BWMS B ballast uptake supply samples (left) and post-treatment return samples (right). Each row of images represents a test cycle in chronological order starting from top to bottom (2.08, 2.09, 2.19, and 2.10). Images are the central portion of a 25 mm diameter GF/F, with 50 µm diameter red microspheres added for scale (2.09 and later), acquired using a Leica EZ 4HD field microscope at 20x magnification under brightfield illumination.

Particle size distribution: The 10 mL subsamples for particle sizing analysis were shipped to RTI Laboratories where they were analyzed using laser diffraction under the specification of ISO 4406. A HIAC Royco Model 8000 laser liquid particle counter (HACH®) was used with a detector sensitivity of 2 µm to 400 µm. Particles that were >2 µm but ≤400 µm in size were binned into one of seven possible size categories with units of counts mL^{-1}. This method does not distinguish organisms from other particles.

Note that the BWMS filter was rated for 40 µm and was not expected to remove particles in the 2 µm - 10 µm and 10 µm - 25 µm categories. Through the 15 test cycles with particle sizing data, 99% of the particles were <50 µm, and 1% were ≥50 µm. In only one test cycle were any particles ≥200 µm detected (this was a deballast return of test cycle 2.18). A size category of >400 was listed by RTI with results reporting counts of 0. It is unclear if this represents zero particles or the machines inability to detect this size (based on its sensitivity parameters). However, with a filter rated at 40 µm, it is unlikely that particles ten times this dimension were present in the return samples.

The particle size data for supply and return counts are summarized in Table 10. Consistent with discharge standards, the particle counts are listed per m^3 for the ≥50 µm size class and per mL for the <50 µm size class. The data show that there is wide variability in the particle counts even among supply-only or return-only counts, irrespective of the size class and flow rate. To examine particle removal by the filter, percentage removal is calculated for the two size classes. Given the filter rating, a significant removal would be expected in the ≥50 µm size class, and minimal (if any) filtration effect for the <50 µm size class. Both positive removal (indicating *reduction* in counts) and negative removal (indicating *increase* in counts) were observed in both size classes in these samples. The average removal between supply and return over all test cycles was -18% for the ≥50 µm size class, and -60% for the <50 µm size class. Negative removal rates indicate higher average counts in the return samples than the supply samples. Given the high variability across all counts in the data, it is unclear if these results can be used to draw any conclusion on filter efficacy. It should be noted that land-based type approval testing requires at least a 4-log reduction (99.990%) for organisms ≥50 µm in the challenge water to achieve the regulatory discharge limit; this size class is removed from the uptake water primarily by filtration.

Table 10. Average of particle counts for samples obtained from the ballast supply (pre-treatment) and return (post-treatment) piping as binned into ≥50 µm and <50 µm size classes. Deballast return samples were also collected for the two BE tests and compared to the uptake supply particle counts. Percent removal indicates the decrease from Supply (pre-treatment uptake) to Return (post-treatment and deballast) counts; a negative value shows an increase following treatment. Average flow is determined from operator log entries. Calculated particle removal percentages are tabulated for each size class.

Test Cycle	Flow (m^3 h^{-1})	Counts of particles ≥50 µm (m^{-3})	% Removal ≥50 µm	Counts of particles <50 µm (mL^{-1})	% Removal <50 µm
1.01 Ballast Supply	120	12900	-	3562	-
1.01 Ballast Return	114	1400	89%	1918	46%

Test Cycle	Flow (m^3 h^{-1})	Counts of particles ≥50 µm (m^{-3})	% Removal ≥50 µm	Counts of particles <50 µm (mL^{-1})	% Removal <50 µm
1.17 Ballast Supply	230	4200	-	2521	-
1.17 Ballast Return	230	3300	21%	6377	-153%
1.18 Deballast Return[1]	223	300	93%	1997	21%
1.18_5SB Deballast Return[1,2]	223	700	83%	2058	18%
2.17 Ballast Supply	242	3600	-	8283	-
2.17 Ballast Return[2]	246	4400	-22%	8962	-8%
2.18 Deballast Return[1]	278	1000	72%	3056	63%
2.09 Ballast Supply	277	187000	-	1943	-
2.09 Ballast Return	232	272000	-45%	13580	-599%
2.19 Ballast Supply	232	105000	-	1250	-
2.19 Ballast Return	202	83000	21%	2150	-72%
2.10 Ballast Supply	227	75000	-	14967	-
2.10 Ballast Return	230	93000	-24%	19086	-28%
Avg. Ballast Supply	221	64617	-	5421	-
Avg. Ballast Return	209	76183	-18%	8679	-60%

[1] ETV Deballast removal was calculated against ETV uptake supply counts
[2] Mislabeled by test lab, but would have been remaining sample in lot sent to lab; this was a second sample obtained from deballasting of tank 5SB

4.6 Relevant discussion and/or conclusion (including potential for contamination)

Organism counts in the harbor waters in the Port of Baltimore were close but did not fully meet ETV Protocol challenge conditions for the first test, and they were less than half the ETV challenge conditions in the second BE test. In the first BE test, organisms in the ≥10 and <50 µm range were about half the challenge requirement, and in the second test they were about 10% the requirement. While not called out by the ETV Protocol, historical levels of UVT in Baltimore Harbor are on the order of 80%, which was not expected to be overly challenging. Also of note, the salinity was closer to fresh water (ranging from 2.6-3.2 ppt) due to the significant rainfall around the BE testing dates. The low salinity conditions should not have had any impact the efficacy of the UV treatment as salinity is not a system design limitation for BWMS B.

The highest total suspended solids (TSS), mineral matter (MM) and particulate organic carbon (POC) levels were seen during the ETV tests (data not shown), but these were still below ETV challenge requirements for brackish water, although they exceeded requirements for fresh water.

Outside of the BE tests, MM was less than 5 mg L^{-1}, and POC was under 7 mg L^{-1}; the combined ETV challenge requirement for TSS (the sum of MM and particulate organic matter measured as POC) in brackish water is 24 mg L^{-1}. Values of TSS were <20 mg L^{-1} for both BE tests. Flow data showed the filter backflushes at regular intervals as initiated by a timer, consistent with low filter loads in the uptake waters. However, treated discharge data from both BE test cycles show ≥50 µm organisms well above the discharge standard; those are expected to be removed at uptake by the filter. Non-BE tests also showed samples with ≥50 µm particulate matter passing through the filter, so it appears the harbor waters provided a challenge for the filter system.

Results from BE tests showed BWMS B did not meet discharge requirement for the ≥50 µm size class, but did meet discharge requirements for the ≥10 and < 50 µm size class. Of note, the challenge provided by harbor waters for the smaller size class was well under that required for TA testing. The larger size class showed roughly a one-log reduction between uptake and discharge, and smaller approximately a two-log reduction. The larger size class exceeded the discharge standard by at least three orders of magnitude. The possibility of contamination was assessed as unlikely.

To assess the efficacy of the filtration system, samples were collected before and after the treatment system during several ballast uptakes. Sample analyses included photomicrography and particle sizing analysis. Results showed some reduction but not elimination of particles in the larger size class. This is consistent with the biological analyses. Refer to Section 4.5 for filter efficacy assessment results.

5 BWMS C

5.1 Executive summary

Treatment technologies for BWMS C were filtration and full stream oxidant generation through electrolysis. The system operated with few issues during testing; most alarms from the system occurred at startup or shutdown of ballast operations and were linked to operating condition changes in ship systems. Power demand was less than anticipated from the system specifications. The highest power consumption occurred during uptake treatment when the filter is engaged and the electrolyzer generates oxidant; here power required is largely proportional to ballast flow rate. During discharge, the filter and the electrolyzer were not engaged. Total residual oxidant (TRO) in the discharge was neutralized using chemical injection of sodium bisulfate. Independent monitoring of TRO levels in ballast water samples was conducted on several occasions during stable operations (i.e., not at startup or shutdown) and measured values were within expected ranges. Here the target dose of 6 mg L^{-1} resulted in TRO readings above 3 mg L^{-1} following treatment (and initial oxidant demand), TRO levels at deballast from tanks were less than 2 mg L^{-1}, and TRO at discharge was near zero.

The BWMS showed reasonably good performance in treatment assessments. A qualitative assessment of filtration was performed by looking at particulate collection on filtered water samples from before and after the filtration system. The samples observed during BWMS testing indicated the filtration system was successful in removing the larger particles and organisms observed in the uptake samples. Biological efficacy measurements also confirmed this assessment. Two BE tests were analyzed according the protocols used for United States Coast Guard type approval testing. These showed the presence of organisms in both the ≥10 and <50 µm and the ≥50 µm size classes during uptake, with organism concentrations mostly above the thresholds needed for type approval testing. Measurements of treated discharge were below the detection limit for both BE tests in the lower size class and one test in the larger size class. In one test the ≥50 µm size class slightly exceeded the ballast water discharge standard of 10 organisms m^{-3} with a measurement of 11.9 organisms m^{-3}.

5.2 Any exceptional test conditions

Test execution was generally in accordance with the TQAP, although, the average recorded flow rates were less than the target set point. The standard deviations about the mean indicate the flow rate fluctuated over all target flow rates. The variation in flow can be also be observed due to filter loading between individual backflush cycles. Also of note, the variable frequency drive for the ship's main ballast pump was not fully functional as it would trip its breaker at higher flows. The crew accommodated for this by using one of two fixed pump speeds and manually adjusting a discharge valve to control flow to the desired settings. This may have contributed to variability in setting the target flow rate.

5.3 Any exceptional data collection methodology

Measurement of TRO was performed on subsamples of the integrated whole water samples collected at uptake, after treatment on uptake, prior to neutralization on discharge, and after neutralization on discharge. Measurements employed a Hach DR300 Pocket Colorimeter (see 2.3.2.3).

5.4 Summary of BE results

The first BE trial consisted of a ballast uptake on 20 NOV 2020 (test cycle 1.17) and a ballast discharge (test cycle 1.18) on 23 NOV 2020. The second BE trial performed a ballast uptake (test cycle 2.17) on 4 DEC 2020 and a ballast discharge (test cycle 2.18) on 7 DEC 2020. Treated water was held in the ballast tank for just under 72 h for both test cycles. The TA certificate for BWMS C does not specify a required hold time.

Data extracted from the MERC report are presented below to summarize the test data on water chemistry (Table 11), live organism concentrations (Table 12), and sample volumes (Table 13). TRO was not measured by MERC on uptake, however, they indicated that typical values for Port Covington range between .02 and .08 mg L^{-1} during spring through fall; no measurements were available for winter months.

Table 11. Mean (standard deviation) for water quality and chemistry challenge (uptake) conditions observed during BWMS C ETV BE test cycles. The ETV challenge conditions for temperature are 4 – 35 °C, with brackish salinity ranging between 10 – 20 ppt. There are no challenge requirements for DO or Chl.

Test Cycle	Temp (°C)	Salinity (ppt)	DO (mg L^{-1})	Chl (µg L^{-1})	TRO (mg L^{-1})
1.17	13.02 (±0.05)	12.6 (±0.01)	8.37 (±0.31)	7.20 (±1.21)	-
1.18	13.38 (±0.03)	12.59 (±0.04)	7.97 (±0.25)	0.391 (±0.05)	BDL
2.17	10.93 (±0.14)	11.82 (±0.02)	9.52 (±0.18)	13.5 (±0.32)	-
2.18	11.11 (±0.02)	11.82 (±0.01)	8.95 (±0.36)	0.490 (±0.03)	0.06 (±0.05)

BDL = below detection limit, Chl = chlorophyll, DO = dissolved oxygen, TRO = total residual oxidant.

Table 12. Mean (standard deviation) of live organism concentrations in ballast uptake and treated discharge during the ETV BE test cycles for BWMS C. The ETV challenge water requirements are 10^5 organisms m^{-3} for the ≥50 µm size class, and 10^3 organisms mL^{-1} for the ≥10 and <50 µm size class. Corresponding discharge limits are 10 organisms m^{-3} and 10 organisms mL^{-1}, respectively.

Test Cycle	Ballast Uptake		Test Cycle	Treated Discharge	
	≥50 µm live org m^{-3}	≥10 and <50 µm live org mL^{-1}		≥50 µm live org m^{-3}	≥10 and <50 µm live org mL^{-1}
1.17	57,157 (± 4562)	1,170 (± 125)	1.18	BDL	BDL
2.17	341,342 (± 14,465)	3,483 (± 496)	2.18	11.9	BDL

BDL = below detection limit

Table 13. Sample volumes as collected during the BWMS C ETV BE test cycles for analysis of the ≥50 µm size class and the integrated whole water samples used for water chemistry and analysis of the ≥10 and <50 µm size class.

Test Cycle	Ballast Uptake		Test Cycle	Treated Discharge	
	≥50 µm analytical volume (m^3)	Integrated whole water sample volume (L)		≥50 µm analytical volume (m^3)	Integrated whole water sample volume (L)
1.17	2.2	40	1.18	2.6	40
2.17	2.7	40	2.18	3.1	42

Salinity levels were in the brackish range of 10-20 ppt, and the observed organism populations in the ambient ballast uptake met ETV challenge conditions for all but the ≥50 µm size class in test cycle 1.17. Total organism counts at uptake and discharge for both BE tests are shown above in Table 12. Treated discharge organism counts slightly exceeded the USCG and IMO discharge standards for the ≥50 µm size class during the second BE test, and met the discharge standard for the ≥10 and <50 µm size class in both tests. MERC noted centric diatoms and eggs were found in the uptake samples from both tests, and centric diatoms and non-swimming bivalves were found in the discharge of test cycle one. As per ETV Protocols, non-swimming bivalves, diatoms and eggs were **not** included in the live counts, but MERC documented those additional counts in their report for completeness. No obvious signs of contamination were observed in the samples.

Additionally, TRO measurements were conducted by the NRL science team at various locations in the treatment path: at uptake, after treatment on uptake, prior to neutralization on discharge, and after neutralization on discharge. Each measurement consisted of 3 readings for each of 3 subsamples for a given test. The TRO readings were less than 0.1 mg/L at uptake, between 3 and 4 mg/L after treatment, above zero but less than 2 mg/L prior to neutralization, and less than 0.1 mg/L at discharge.

5.5 Filter efficacy assessments

Water samples collected from the supply and return lines to the BWMS were examined during ballast uptake operations to examine filter efficacy. Here, a larger volume (typically 20 L) was subsampled, concentrated on a 35 µm filter, and resuspended in a 50 mL volume of water. This concentrate of the ≥50 µm particles was then subsampled and collected on a 0.45 µm membrane filter to allow examination of particulates remaining after treatment. Particle size assessments were not conducted.

In some cases, microscopic observations of particles on the filter showed microorganisms such as copepods in the ballast uptake. In all cases, there were no microorganisms observed in samples from downstream of the filter, and qualitatively there were fewer large particles and less particles overall (Figure 4). This implies that the BWMS filter was effective in removing the larger particles (and organisms) from the uptake water, and is consistent with the BE results that showed a four-log reduction of organisms in the ≥50 µm size class.

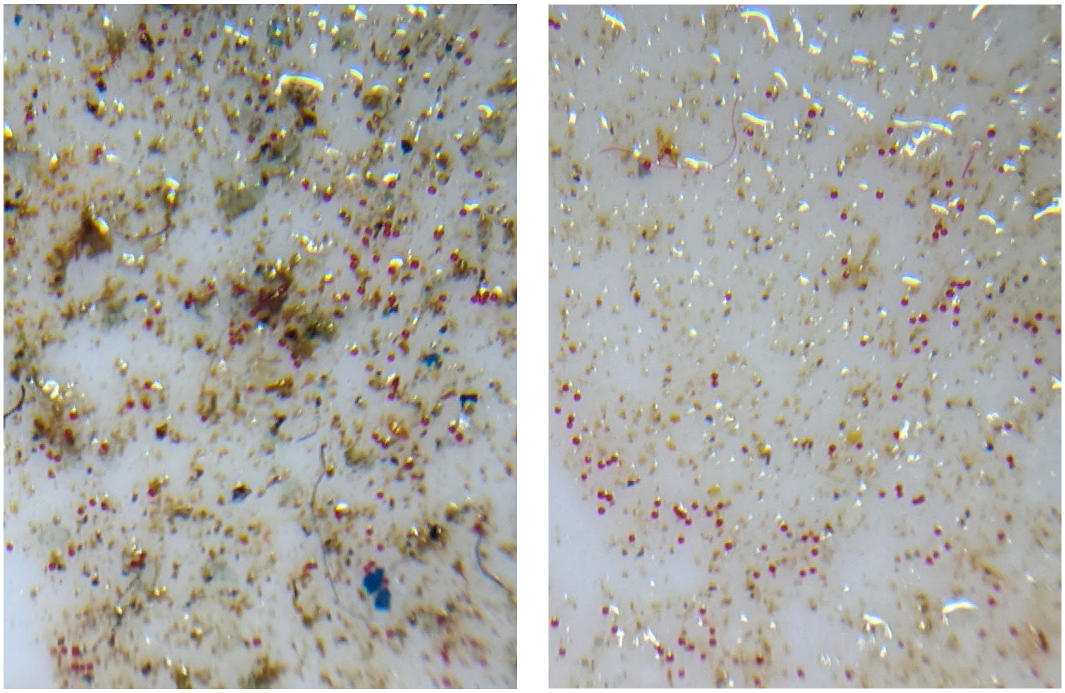


Figure 4. (left) Photomicrograph of supply (uptake) water filtered to extract and deposit particles ≥50 µm on a membrane filter. (right) Return (BWMS treated) water showing particles remaining after treatment. Red particles are 50 µm colored microbeads added as a size reference; images captured at magnification approximately x30.

5.6 Relevant discussion and/or conclusion (including potential for contamination)

Organism counts in the harbor waters in the Port of Baltimore were close but did not fully meet ETV Protocol challenge conditions in the largest size class on the first test, being approximately 57% of the 10^5 organisms required. In the second BE test both size classes achieved 3 times the minimum ETV challenge conditions. Salinity on all tests ranged between 11-13 ppt and temperatures were in the range of 11-13 °C. While not fully meeting ETV requirements on all tests, the organism concentrations were high enough to pose a challenge to the equipment.

Levels for TSS and total organic carbon (TOC) were not measured by MERC, but seasonal levels for Baltimore Harbor are well below ETV challenge water requirements, with TSS in the range of 6-12 mg L^{-1} and TOC < 7 mg L^{-1}. These levels were definitely high enough to trigger backflushing of the filter during uptakes, and the data show more frequent backflushing at higher main ballast flow rates as expected. There were no signs of filter clogging other than a lone circumstance where the operators noted a continuous backflush and stopped the test to inspect the filter. In that case no clogging or sign of filter impairment was detected. Observation of the filter efficacy samples showed a clear difference between the pre- and post-filtration samples, so the filter appeared to be operating effectively. The harbor waters provided a reasonable challenge to the system.

Treatment performance was nominal, where in one BE test the larger size class was measured at slightly over the discharge standard (~11 m^{-3}), and the other was not detectable. Both BE tests show no detection of organisms in discharges for the ≥10 and <50 µm size class. Based on BE evaluations of previous systems (both of which had similar or less difficult challenge conditions, and exceeded the larger size class discharge limits by more than 2 orders of magnitude), the filtration system used in this BWMS appears to be better than those seen in earlier tests; the filter is responsible for the elimination of organisms in the ≥50 µm size class.

There was some concern with the lag time in system response to excess TRO in deballast water. The delay is driven by the length of sample line between the TRO monitoring points in the pipe and the TRO analyzer, as well as by the algorithm which detects changes in TRO concentration. No adverse TRO readings were detected in the sampling performed by the NRL science team, but the samples were taken after a period of stable operation and the dynamics of TRO response were not examined.

6 OVERALL SUMMARY TABLE AND NOTES

The M/V Cape Washington proved a suitable platform for running the matrix of tests per the TQAP, and provided some of the expected variability in operating conditions found in ship ballast systems. The cargo deck location does impose certain constraints on the operation of the system, due to the extra lengths and smaller diameter piping added to the ballast system. While these constraints limit the upper flow rate and accentuate issues such as priming of pumps or control of flow associated when ballasting to tanks in different locations, testing with crew under shipboard conditions has provided more realistic testing than can be accomplished in a land-based test, and lend additional insight into ship deployment of commercial BWMS.

Overall, having ship's crew responsible for installation, operation, and maintenance of the BWMS under test provided an end user's perspective on system considerations. The ability of the operators to diagnose operating issues and their interaction with ship's systems generated usability data, and their ability to diagnose and repair equipment was extremely helpful during those tests where equipment had post-commissioning failures. The opportunity to additionally measure biological efficacy performance under shipboard operating conditions provided an indication of how well a system might perform when installed, although these tests were not designed to replicate a land-based Type Approval test. Here, the ambient ballasting conditions were in a brackish water environment while the ship was pierside and not underway. However, ballasting operations were entirely conducted using ship's pumps, piping, and ballast tanks which differ from the test environment in land-based type approval testing, and the tests provided experimental data not available to the Navy from shipboard type approval testing.

Over the course of the Cape Washington Operational Tests, three different commercial treatment systems were evaluated for biological efficacy performance, with two replicate BE tests conducted for each system. The BE tests were replicates across the different BWMS in that they ballasted to the same ballast tank and operated at a target flow rate of 70% of the specified treatment rated capacity for the BWMS. Two of the BWMS utilized filtration and UV disinfection treatments, while the third BWMS utilized filtration and full stream electrochlorination disinfection. In each system, the filter was engaged on uptake to remove organisms ≥50 µm in size. For UV treatments, both uptake and discharge waters were exposed to the disinfection treatment. For the EC treatments, the entire ballast was passed through an electrolyzer on uptake, and any residual oxidant during deballast was neutralized through chemical injection at discharge. All systems completed two sets of 20 operational test cycles defined in an operational test matrix where the matrix was both representative of Navy ballasting sequences and adapted to the ship constraints and the capabilities of the individual BWMS. This report documents only the results of the BE tests, and does not identify the identities of the systems under test. A summary of the BE performance is present below (Table 14).

Table 14. Results summary for living organism uptake and treated discharge counts from three BWMS tested on M/V Cape Washington over the period between October 2017 and January 2021.

BWMS and treatments	**BE Test Cycle**	**Ballast Uptake**		**Treated Discharge**	
		≥50 µm live org m^{-3}	**≥10-<50 µm live org mL^{-1}**	**≥50 µm live org m^{-3}**	**≥10-<50 µm live org mL^{-1}**
BWMS A Filtration + UV	1	50,754 (±825)	3,437 (±191)	8,605 (±2,608)	7 (±3)
	2	144,433 (±3,769)	3,037 (±875)	12,570 (±879)	94 (±10)
BWMS A Filtration + UV	1	99,865 (±4,575)	541 (±49)	4,871 (±584)	4 (±1)
	2	49,315 (±7,100)	117 (±37)	7,224 (±502)	3 (±1)
BWMS C Filtration + EC	1	57,157 (± 4562)	1,170 (± 125)	BDL	BDL
	2	341,342 (± 14,465)	3,483 (± 496)	11.9	BDL

BDL = below detection limit, EC = electrochlorination, UV = ultraviolet

Results from operational tests show varying performance of filter treatment subsystems used to remove organisms ≥50 µm in size. Both BWMS A and BWMS B were ineffective in removing sufficient quantities of organisms in this size class to meet the regulated discharge standard of 10 live org m^{-3}; these two BWMS generally achieved only a 1-log reduction for this size class of organisms. BWMS C did meet the discharge standard in one test, and nearly met it in the second, showing a much more effective filtration system with at least a 4-log reduction. In the latter two tests, these findings were corroborated via qualitative assessments of ballast water samples obtained before and after the filter where collected particulates were examined via photomicrography.

The UV disinfection process primarily targets the smaller ≥10 and <50 µm range of organism sizes. Here, variable results were observed for BWMS A in that one test met the discharge standard of 10 live org mL^{-1}, while the second did not. This system demonstrated a roughly 3-log reduction in live organisms as a result of treatment. BWMS B met the discharge standard for this smaller size class in both tests, however the ambient challenge was an order of magnitude lower than presented to the other BWMS. Here the reduction from ambient was approximate 2-log. Of note, the potential for reduced UV dosage to organisms in the ballast flow was observed in BWMS B. This system generated frequent treatment alarms and required frequent cleaning of the UV sleeves protecting the lamps to achieve the target UV dose.

The EC disinfection process targets any organisms that are present, although the removal of larger organisms by filtration also helps remove oxidant demand. This treatment was effective during both replicate BE tests in that the measurement results for this size class were below the detection limit for the method as used in type approval testing.

7 REFERENCES

U.S. Department of Defense (2019) ‘Regulations on Vessels Owned or Operated by the Department of Defense: Ballast Water, Change 2’. DoD Manual 4715.06, Volume 3, Office of the Under Secretary of Defense for Acquisition and Sustainment. https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodm/471506v3.pdf?ver=2019-08-26-075853-690

U.S. Environmental Protection Agency (2010) ‘Generic protocol for the verification of ballast water treatment technology’, version 5.1. Report number EPA/600/R-10/146, United States Environmental Protection Agency Environmental Technology Verification Program, Washington, DC http://www.uscg.mil/hq/cg5/cg522/cg5224/docs/600r10146.pdf