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Evaluation of the Jotun Hull Skating Solution: A Proactive Ship Biofouling In-Water Cleaning System

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Table of Contents

Foreword 1
Executive Summary 2
Acronyms 4
1. Introduction and Background 6
2. Description of the Jotun Hull Skating Solution 7
3. Experimental Design 7
  3.1 Dive Survey for Biofouling Quantification 7
    3.1.1 Dive Survey Conditions 7
    3.1.2. Dive Survey Methods 8
  3.2 Water Quality Assessment 9
    3.2.1 Ambient Conditions 9
    3.2.2 Water Quality Sampling 9
    3.2.3 Water Quality Sample Analysis 10
4. Results – Data Summaries 11
  4.1 Dive Survey for Biofouling Quantification 11
    4.1.1 Dive Survey Results 11
  4.2 Water Quality Measures 15
    4.2.1 Ambient Water Conditions 15
    4.2.2 Total Suspended Solids 16
    4.2.3 Particulate and Dissolved Organic Carbon 17
    4.2.4 Biocides - Copper and Zinc 17
    4.2.5. Particle Size Distribution 20
    4.3. Attempted Water Quality Tests 22
5. Quality Assurance and Quality Control 22
  5.1. Blanks and Duplicate Sample Analysis 22
  5.2 Data Quality Review: Water Samples 23
7. Contributors and Approvals 25
Appendix A. Agreed to Test Plan 26

Foreword

This report presents the results of an independent evaluation of the Jotun Hull Skating Solution (HSS), a proactive ship in-water cleaning (IWC) system designed to prevent macrofouling growth on submerged ship surfaces, as part of an ongoing biofouling management program. The HSS was deployed on the two ships, M/V *Talisman* and M/V *Tysla*, for testing and was evaluated in two locations: the Port of Long Beach (Pier F205, 415 W. Ocean Blvd., Long Beach, CA) and the Port of Baltimore (Dundalk Marine Terminal, 2700 Broening Hwy, Baltimore, MD). The Jotun HSS system was independently tested by the Alliance for Coastal Technologies (ACT) and Maritime Environmental Resource Center (MERC), in collaboration with the US Naval Research Laboratory (NRL), Smithsonian Environmental Research Center (SERC), and California State Lands Commission (CSLC). Support for this evaluation is provided by the U.S. Maritime Administration (MARAD), the Maryland Port Administration (MPA), and the California State Lands Commission (CSLC).

There were three fundamental goals for this ACT/MERC evaluation of a proactive IWC system:

- Develop and demonstrate test methods for assessing efficacy and environmental safety of proactive IWC systems;
- Provide comprehensive, robust, and independent data on the performance of the Jotun HSS system; and
- Assess broadly the state of technology and maturity of commercially available proactive IWC approaches.

This report is submitted by Dr. Mario Tamburri, ACT and MERC's Principal Investigator and Director, at the University of Maryland Center for Environmental Science (UMCES) Chesapeake Biological Laboratory (CBL). Full descriptions of the tests, subcontractors, and personnel (and their responsibilities) can be found in the IWC Test Plan (Appendix A) and the ACT and MERC Quality Assurance Project Plans (QAPPs, available upon request).

It is important to note that ACT and MERC do not certify technologies or guarantee that an IWC system will always, or under circumstances other than those used in testing, operate at the levels tested. This evaluation does not seek to determine regulatory compliance; does not rank technologies or compare their performance; does not label or list technologies as acceptable or unacceptable; and does not seek to determine "best available technology" in any form.

Executive Summary

Proactive IWC is used to: (a) remove, prevent, or reduce the attachment and growth of biofilms (i.e., microfouling or slime layer) on ship's submerged surfaces; (b) remove newly settled or attached stages (i.e., microscopic) of macrofouling organisms; and (c) ultimately minimize or prevent macrofouling growth (individual, or colonies of, organisms visible to the human eye). While proactive IWC has gained attention in recent years as a promising solution to both ship operational needs (i.e., reduced biofouling and the resulting reductions in fuel use and exhaust emissions) and environmental protection (i.e., reduced biosecurity risks through ship transport of non-indigenous species), there has yet to be comprehensive, science-based, independent testing of any specific system.

The HSS IWC system, developed and operated by Jotun, was designed to work with a specific proprietary high-performance hull antifouling coating (SeaQuantum Skate) to proactively remove biofilms from hull surfaces and to prevent or limit macrofouling growth. This ACT/MERC evaluation was carried out to provide comprehensive independent, empirical data on the HSS system performance, including: (a) biofilm cleaning and macrofouling prevention efficacy through dive surveys over time and (b) environmental impacts through water quality measures (including total suspended solids [TSS], particulate carbon [PC], dissolved organic carbon [DOC], particle size distribution [PSD], and metals [Cu, Zn]) during cleaning activities. Qualitative observation of potential impacts to hull coatings were also recorded when possible. The evaluation was designed to include assessments of performance on different types of hull surfaces and under different types of environmental conditions. Given that the HSS system is fundamentally designed to minimize macrofouling growth over time, the biofouling and water quality measures were to be collected at three to four sampling events, per test ship, over nine to twelve month test periods (roughly at the beginning, middle, and end).

While testing of the HSS system was attempted on the M/V *Talisman* (over approximately one year), a variety of logistical constraints and technology limitations did not allow for the collection of any targeted biofouling or water quality data on this first test ship. However, in September 2021, the copper- and zinc-based SeaQuantum Skate antifouling coating was applied, and a Hull Skater cleaning unit installed, on the M/V *Tysla* (second test ship) during drydocking. ACT/MERC testing was initiated during the M/V *Tysla*'s first visit to the Port of Long Beach after new coating applications (October 2021), approximately six weeks after leaving drydock. No biofouling was recorded on untreated (control, not to be cleaned) or treated (to be cleaned) test locations on the M/V *Tysla*. A second dive survey in Long Beach was conducted approximately six months later (March 2022). Some light biofouling was observed (biofilms, fouling rating [FR] < 20) and treated surfaces qualitatively appeared to have less biofilm accumulation than untreated surfaces. However, little can be concluded on the prevention of macrofouling growth with only two surveys over six months, and with no clear measurable differences in biofouling found in control and treated test locations.

Several attempts were made to assess possible environmental impacts of the HSS cleaning operations but because of IWC technology limitations and malfunctions, only one water quality sampling trial was successfully completed. In November 2021, a test trial was conducted during M/V *Tysla* cargo operations in the Port of Baltimore. While it would be expected that TSS levels are elevated around the cleaning unit as biofilms are removed from the ship surface, and perhaps that new antifouling coatings might have higher copper and zinc leach rates, we are unable to draw any definitive conclusions on possible environmental impacts with data from only one trial. However, it must be noted that the single successful water quality trial did find measurably higher levels of coating biocides around the cleaning unit (both during cleaning and when stationary on the side of the test ship), which could suggest possible HSS environmental, and coating performance, impacts.

The ACT/MERC evaluation of the HSS system was terminated in June 2022, after repeated delays, mechanical failures, and because the system could not be operated as designed for an appropriate test of performance. Novel technologies are often prone to unpredicted operational limitations and mechanical problems. This is particularly true for complex systems working under very challenging and highly variable conditions. While a complete test was not possible, this effort was able to: (a) successfully develop and carryout robust and feasible test protocols for the assessment of proactive IWC systems; (b) provide some initial, but limited, data on the performance of the Jotun HSS IWC system; and (c) offer some insight into the maturity of commercially-available IWC technologies, which show promise but currently may still be in the early stages of development.

Acronyms

ACT	Alliance for Coastal Technologies
ADQ	Audit of Data Quality
BDL	Below Detection Limit
BRL	Below Reporting Limit
CBL	Chesapeake Biological Laboratory
CRMS	New Zealand Craft Management Risk Standard for vessel biofouling
CSLC	California State Lands Commission
CTT	Core Test Team
Cu	Copper
DI	Deionized (water)
DM	Data Manager
DOC	Dissolved Organic Carbon
DQA	Data Quality Assessment
FR	Fouling Rating (US Navy)
HSS	Hull Skating Solution
IC	Integrated Continuous
ISO	International Organization for Standardization
IWC	In-Water Cleaning
KW	Kruskal-Wallis
LPSA	Laser Particle Size Analysis
MARAD	U.S. DOT Maritime Administration
MERC	Maritime Environmental Resources Center
MPA	Maryland Port Administration
NASL	Nutrient Analytical Services Laboratory
NRL	U.S. Naval Research Laboratory
POC	Particulate Organic Carbon
PSD	Particle Size Distribution
QAPP	Quality Assurance Project Plan
QA	Quality Assurance
QC	Quality Control
QAQC	Quality Assurance/Quality Control
QMP	Quality Management Plan
QMS	Quality Management System
SD	Standard Deviation
SERC	Smithsonian Environmental Research Center
SM	Standard Methods

SOP	Standard Operating Procedure
TAC	Technical Advisory Committee
TSA	Technical Systems Audit
TSS	Total Suspended Solids
UMCES	University of Maryland Center for Environmental Science
USEPA	United States Environmental Protection Agency
Zn	Zinc

1. Introduction and Background

The Alliance for Coastal Technologies (ACT) and Maritime Environmental Resource Center (MERC), in collaboration with the U.S. Naval Research Laboratory (NRL), Smithsonian Environmental Research Center (SERC), and the California State Lands Commission (CSLC), comprise the Core Testing Team (CTT), which conducted an independent evaluation of the Jotun HSS system designed to proactively remove ship biofouling. Biofouling—or the colonization of wetted surfaces by aquatic organisms—presents significant problems for the maritime industry. The biofouling of vessels can interfere with operations and may result in increased corrosion, drag, fuel consumption, and greenhouse gas emissions. Ship biofouling is also a significant, if not the most dominant, vector for the global-scale transfer and introduction of non-indigenous marine species, which can have enormous ecological and economic impacts in coastal environments. A number of IWC technologies and approaches have been developed over the past 10 years and have typically focused on hull husbandry to reduce drag and fuel consumption in support of the maritime industry.

This evaluation of the Jotun HSS was focused on a proactive IWC system that conducts periodic biofilm assessments and removal to prevent, inhibit, or limit macrofouling growth. The evaluation followed the ACT (www.act-us.info) and MERC (www.maritime-enviro.org) approaches for independent testing. This included the establishment of a Technical Advisory Committee (TAC) and field testing on the M/V *Talisman* and M/V *Tysla* in 2020 through 2022. Test Protocols were developed with the aid of Jotun and the TAC. Although scientific advice to underpin the development of performance standards for the removal of biofouling exist, there are currently no accepted U.S. or international in-water biofouling cleaning protocols or standards. Therefore, this evaluation provides data on IWC system performance, and treatment efficacy, in the form of percent removal and macrofouling prevention. This evaluation also measured the potential release of chemical contaminants, associated with antifouling coatings, into the water column as IWC systems are used. The impacts of IWC systems on the coatings themselves was only evaluated in a cursory manner.

2. Description of the Jotun Hull Skating Solution

The Jotun Hull Skating Solution (HSS) has been developed by Jotun in collaboration with a number of industry, technology, and shipping partners, including Kongsberg Maritime, Semcon, DNV GL, Telenor, and Wallenius Wilhelmsen Ocean. HSS is designed for ships in challenging operations, to ensure underwater hull areas (excluding niche areas) can remain free of significant macrofouling. The solution combines a specific hull coating, real-time fouling alerts based on a fusion of operational and environmental data and inspections, and proactive cleaning with an underwater cleaning vehicle (i.e., cleaning unit).

The SeaQuantum Skate is defined by Jotun as a high-performance, self-polishing biocidal (dicopper oxide, zinc oxide, and other ingredients) coating designed specifically for proactive cleaning with the underwater cleaning unit. The Hull Skater (i.e., cleaning unit) is a magnetic crawler, with 4 high-definition cameras for navigation and inspection and a 90 cm wide rotating brush, designed for proactive cleaning of the specific high-performance coating without causing damage or erosion. It is normally operated at a speed of around 0.5 m/s. Inspection and proactive cleaning of all hull areas will normally take around 2 to 8 hours depending on vessel size and fouling condition. The cleaning unit is kept onboard the ship and launched via a launch and recovery ramp on the deck. An umbilical connects the vehicle with an onboard communications interface from which a secure network allows operation from a control center onshore. Surveys and alerts are configured to ensure any biofouling is identified and removed at an early stage (Fouling Rating [FR] 10 to 20), before it significantly affects ship performance or biosecurity risk.

3. Experimental Design

The following is a brief summary of the test protocols employed. Additional details can be found in the agreed to and signed Test Plan (Appendix A) and required protocol amendments (available upon request).

3.1 Dive Survey for Biofouling Quantification

3.1.1 Dive Survey Conditions

The dive surveys to quantify the biofouling present on hull areas of the M/V *Tysla* were conducted on 17 October 2021 and 25 March 2022 at Pier F205 at the Port of Long Beach during daylight hours. Water column visibility was estimated at 3-4 meters. A small boat was used as a dive platform and all lockout/tagout and other dive requirements were in place.

The IWC treated (cleaned) and control (not cleaned/untreated) areas were delineated prior to the dive surveys in consultation with Jotun. The dive survey test location was approximately 40 m in length near midships on the port side, extending from approximately two meters below the water line to one meter above the bilge keel. This location was the non-dock (outboard) side of the vessel and had a depth of approximately 8 m. Only vertical and slightly curved vertical sides of the ship were considered.

3.1.2. Dive Survey Methods

Both low-visibility survey method and photo-survey methods were used during the two biofouling surveys in Long Beach. A 1 m^2 magnetic quadrat with a grid of 50 points was placed on hull surfaces, and the point count method was used to record biofouling or hull surface under all 50 points (Figure 1). An additional record of percent cover of each fouling rating present in the four quadrants (bands) of the quadrat was taken to ensure the entire 1 m^2 area was accounted for (Figure 1). Within each 1 m^2 quadrat, 24 still images were taken. Details regarding the dive survey techniques can be found in the *ACT-MERC/SOP/IWC/DS 1.0 – Dive Surveys.*

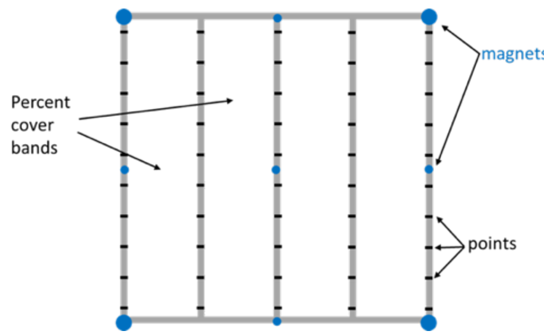

Figure 1. Quadrats were used to determine biofouling cover in two ways: using a point count method of 50 points on the 1 m^2 area, then, using percent cover visual estimates within the four bands of space within the quadrat.

Stratified sampling was completed among four different categories:

1. inside the treated flat surface area (n=6),
2. inside the treated curved surface area (n=6),
3. inside the untreated flat surface area (n=6),
4. inside the untreated curved surface area (n=6).

The dive survey included measuring percent coverage and type of fouling organisms based on the U.S. Navy FR (fouling rating) scale to define the type of biofouling (Naval Ships' Technical Manual 2006), and Floerl *et al.* (2005) to define percentage cover (see Test Protocol). The surveyed areas included designated cleaned (treated) and not cleaned (untreated/control) locations.

The four categories of biofouling type are (Naval Ships' Technical Manual 2006):

- Slime (FR 20 or less) (in-water removal or treatment of slime is considered to be of low biosecurity risk),
- Moderate (soft) biofouling (FR 30),
- Moderate (hard) biofouling (FR 40–80), and
- Heavy (hard) biofouling (FR 90 or greater).

Percent cover categories (Floerl *et al.*, 2005):

- Absent (0%);
- Light (1–5% of the available surface);
- Considerable (6–15%);
- Extensive (16–40%); and
- Very heavy (41–100%).

Differences in biofouling percent cover were tested among areas sampled using non-parametric Kruskal-Wallis (KW) tests. During the surveys, divers recorded whether the following coating conditions were visible within the quadrats: scratches, brush marks, paint flakes, pitted, bare metal/polish through, dock block, or no blemishes.

3.2 Water Quality Assessment

3.2.1 Ambient Conditions

Background or ambient water quality samples were collected at the Dundalk Marine Terminal at the ship's docking location on 3 days: the day prior (November 4, 2021), the day of (November 5, 2021), and the day after (November 6, 2021) the IWC event. Water quality conditions were recorded using a multiparameter instrument and a Secchi disc, and included the collection of water samples for chemical laboratory analyses, discussed in section 3.2.2 below. Weather was observed and recorded. Tides were recorded according to tide charts and observation. Other pertinent observations such as recent storm events or plankton blooms were noted.

3.2.2 Water Quality Sampling

The impacts on water quality during Jotun HSS cleaning operations were measured during only one test cleaning event, at three sampling stations (U, B1, and B2). Stations U and B1 were continuous, time-integrated water samples occurring during operation of the Jotun HSS unit. Station B2 involved discrete sampling to provide ambient water quality information, occurring the day prior, day of, and day after the cleaning event (Table 1). All samples were collected according to ACT-MERC/SOP/IWC/SC 1.0 – *In-Water Cleaning Sample Collection*. Station details follow:

Water quality sampling station included:

Station U - Sampling intake located on the HSS. One sampling hose was attached to the HSS vehicle to sample the exhaust water from the cleaning unit. A pump pulled water from this sample point to the surface to fill a 20L sample carboy over a 30-minute period using time-integrated continuous sampling techniques. Two separate samples were collected using this method, U1 and U2. During the U1 sampling period, the Jotun HSS was attached to the hull with brushes disengaged, and *not moving*. According to the test plan, the HSS was supposed to be moving along the hull during the U1 sampling period; however, *movement did not occur*. During the U2 sampling period, the Jotun HSS conducted normal proactive cleaning operations with the cleaning brushes engaged. The U1 20L carboy was subsampled for TSS and biocides (e.g., copper (Cu), zinc (Zn)). The U2 20L carboy was subsampled for TSS, POC, DOC, particle size distribution, and biocides.

Station B1 - Background sample >50 m away from the test area. This station was sampled simultaneously with the U2 sample. A hose was deployed and attached with magnets closely to the hull of the ship. The sample point was greater than 50 m away and on the opposite side of the ship from the area being cleaned. Using time-integrated continuous sampling techniques, a peristaltic pump was used to draw water from the sample location up and into a shoreside-located 20L sample carboy. The B1

20L carboy was immediately subsampled for TSS, POC, DOC, particle size distribution, and biocides.

Station B2 - Discrete background (ambient) samples pre- and post- cleaning. Station B2 was located on the pier near the ship's berthing location. Discrete samples were collected at eight time points using a four-liter Van Dorn sampler: On the day before and the day after the cleaning event, three samples were taken at 3 distinct time points. On the day of the cleaning event, one sample was collected approximately two hours before and another sample collected two hours after the cleaning event. These eight B2 discrete samples were immediately subsampled for TSS and biocides.

The collection and subsampling of samples U1, U2, and B1 were conducted in a similar manner. The sample flow rates were set to collect between 15 to 20 L of water during a sample period using manifolds equipped with flow meters and a bypass valve. The exact volumes of the carboys were determined after the sampling period. During the subsampling, a 20 L carboy sample was uniformly mixed immediately prior to collecting subsamples for the analyses listed above for each station.

3.2.3 Water Quality Sample Analysis

Samples were analyzed by certified laboratories for total suspended solids (TSS), particulate carbon (PC), dissolved organic carbon (DOC), particulate, dissolved and extractable metals (copper and zinc), and particle size distributions. TSS, PC, and DOC were analyzed in triplicate by the Nutrient Analytical Services Laboratory at the UMCES Chesapeake Biological Laboratory, following the procedures outlined in the following:

NASL/SOP - *Determination of Total Suspended Solids and Total Volatile Solids in Fresh/Estuarine/ Coastal Waters* (2019); NASL/SOP – *Determination of Carbon and Nitrogen in Particulates and Sediments of Fresh/Estuarine/Coastal Waters, Plant and Animal Tissue, and Soils Using Elemental Analysis* (2019);

NASL/SOP - *Determination of Dissolved Organic Carbon/Non-Purgeable Organic Carbon (DOC/NPOC), and Total Organic Carbon (TOC) in Fresh/Estuarine/Coastal Waters using High Temperature Combustion and Infrared Detection* (2019) (Nutrient Analytical Services Laboratory, UMCES-CBL);

Copper and zinc analyses (in triplicate) were conducted by Dr. Andrew Heyes (UMCES-CBL) using EPA methods 200.8 and 6020A. Particle size distribution analyses were conducted by Particle Technology Labs (555 Rogers St., Downers Grove, IL 60515);

One sample each from stations U2 and B1 was analyzed once using ISO 13322-1: *Particle Size Analysis - Image Analysis Methods, Part 1. Static Image Analysis,* then analyzed three times using Single Particle Optical Sensing (SPOS), ISO 21501-2:2007. *Determination of particle size distribution--Single particle light interaction methods--Part 2: Light scattering liquid-borne particle counter*, and ISO 21501-

3:2007. *Determination of particle size distribution--Single particle light interaction methods--Part 3: Light extinction liquid-borne particle counter.*

4. Results – Data Summaries

4.1 Dive Survey for Biofouling Quantification

4.1.1 Dive Survey Results

The M/V *Tysla* was drydocked in August 2021 and was coated with SeaQuantum Skate. The dive inspection occurred from roughly midship extending towards the aft of the vessel (Figure 2). During the October 2021 dive survey, no biofouling was recorded, either through the point counts, or through the photo survey (Figure 3). The only markings present on the hull were likely scuff marks from dockside or tug fenders. During the March 2022 dive survey, there were areas with no biofouling present, and areas with up to FR < 20 biofouling, in both the treated and untreated areas (measured using the point counts and photo survey; Figure 4). Point count data for the March dive survey indicate a significant difference between treated and untreated areas on flat surfaces (KW test, df = 1, chi-squared = 5.444, p = 0.0196). KW tests were not conducted on the other areas. A summary of percent cover and FR for both biofouling dive surveys is provided in Figure 5, but the limited data did not allow for a meaningful assessment of proactive macrofouling prevention.

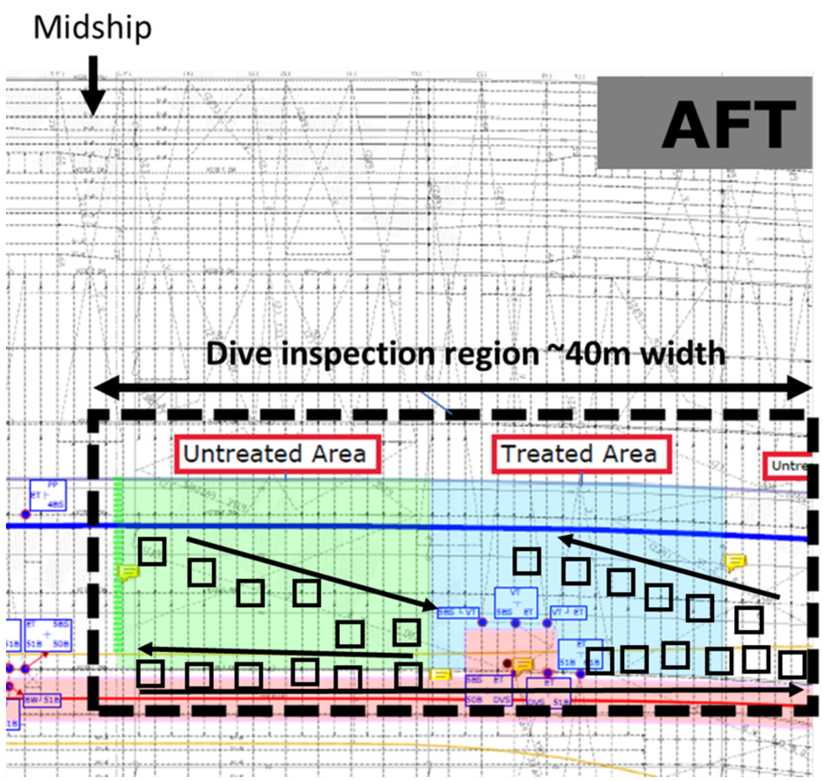

Figure 2. Hull survey areas with approximate position of quadrats (□) and dive profile (→)

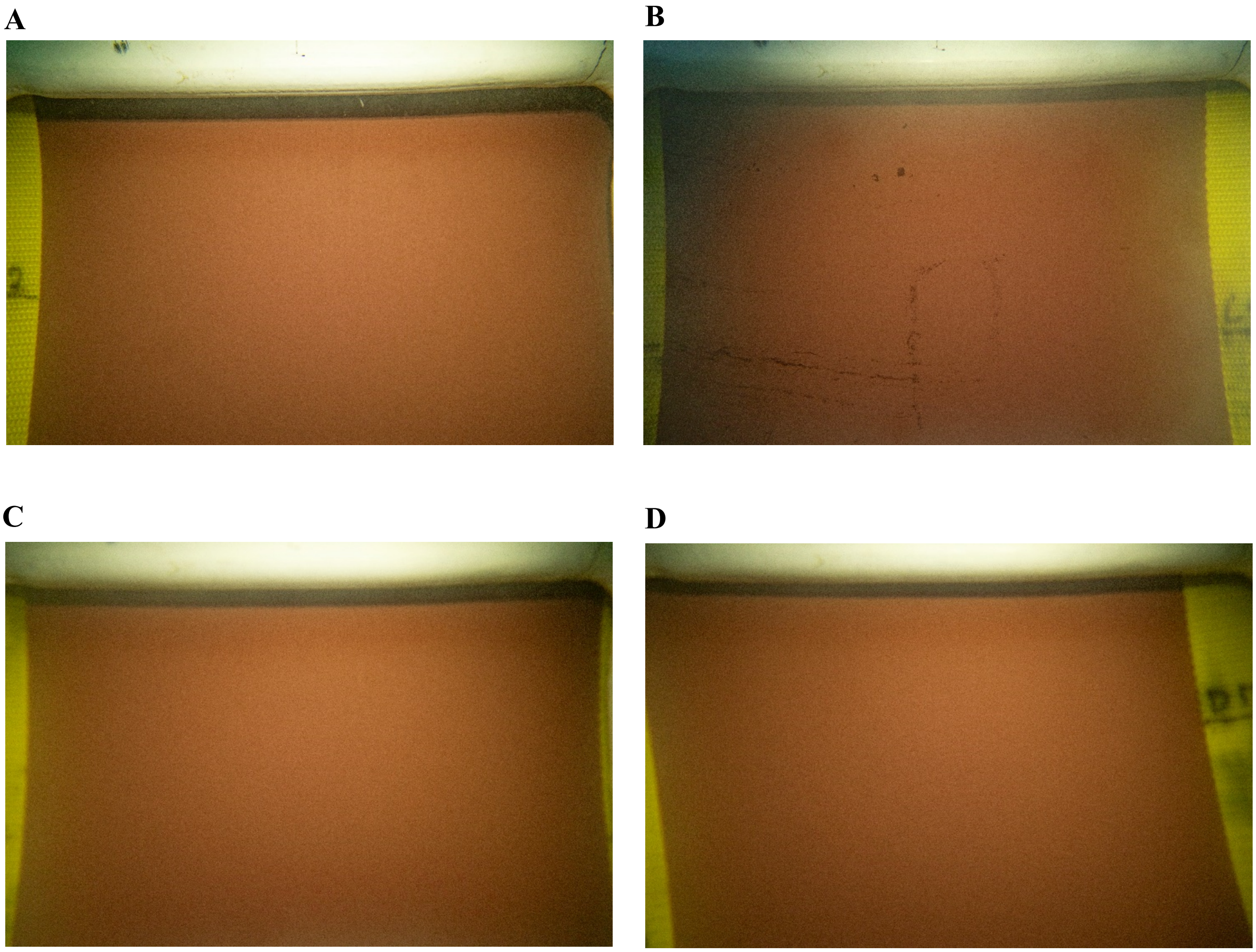

Figure 3. Pictures from the initial photo survey in October 2021. A) flat untreated, B) flat treated, C) curved untreated, and D) curved treated, FR 10 or less.

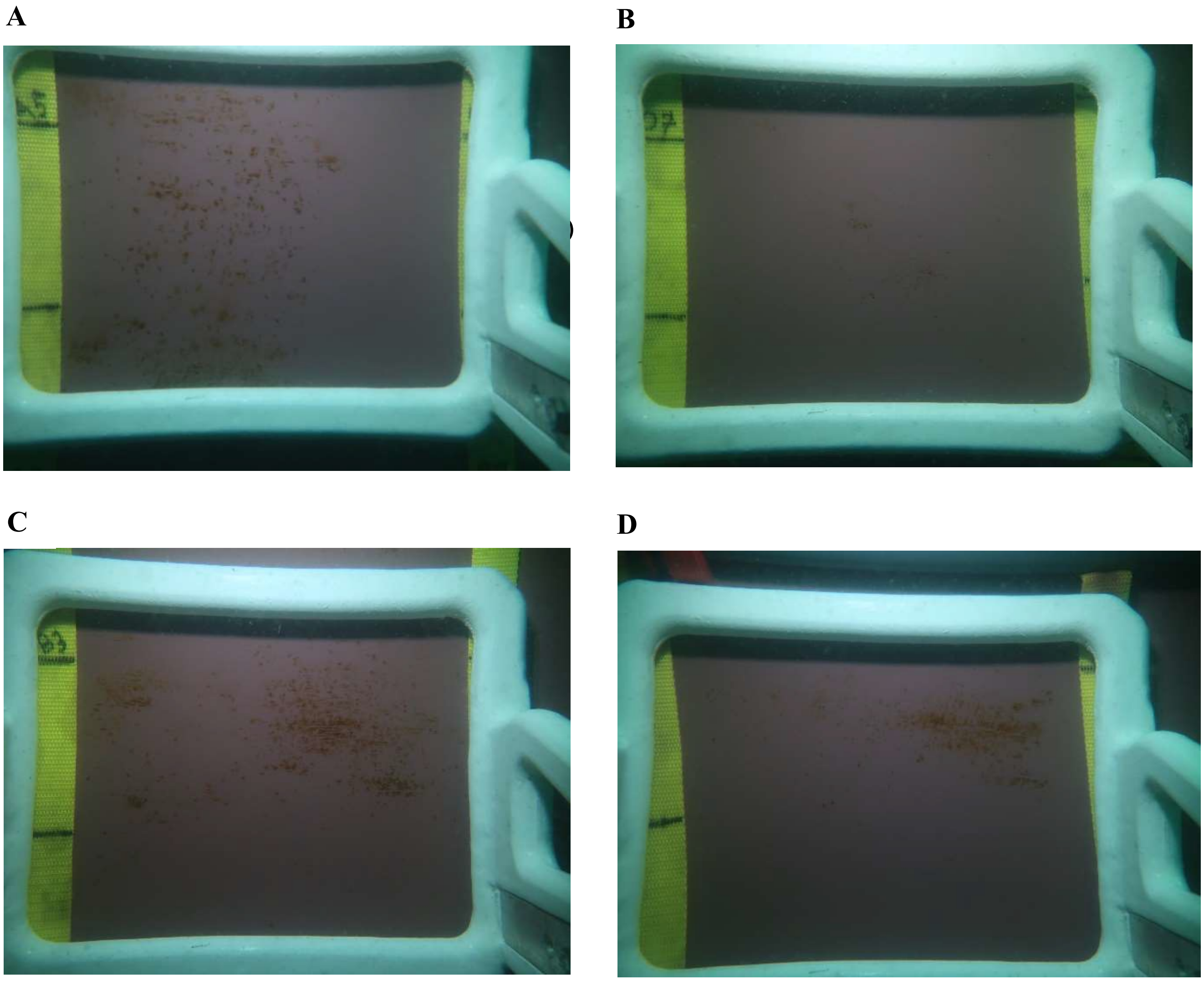

Figure 4. Pictures from the second photo survey in March 2022. A) flat untreated, B) flat treated, C) Curved untreated, and D) curved treated. The brown coloration is biofilm present on the hull, FR 20 or less.

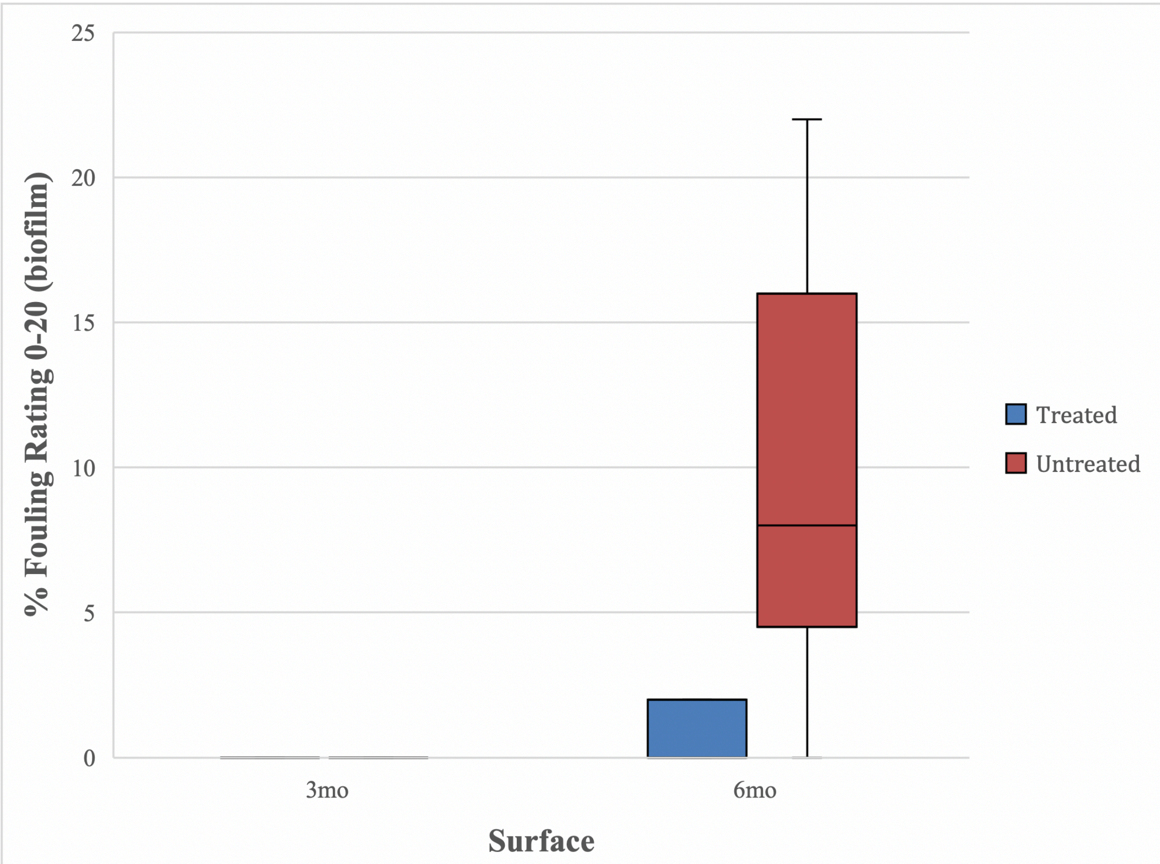

Figure 5. Frequency of fouling rating 0-20 (biofilm) observed on the vessel hull during the initial (3 mo) and second (6 mo) survey. No heavier fouling (e.g. macrofouling) was observed in either treated or untreated samples and at either time point. Error bars show the lowest and highest data points (n=6); median value is also indicated.

4.2 Water Quality Measures

Once, during November 4-6, 2021, water quality conditions were measured before, during and after HSS cleaning event. These limited data did not allow for a meaningful assessment of possible environmental impact from HSS cleaning operations.

4.2.1 Ambient Water Conditions

Table 2. Mean (SD) water conditions observed at 4 m depth, during testing in Baltimore.

Sample Time	Temp (°C)	Salinity (psu)	DO (mg/L)	Secchi depth (m)	Wind (mph)
24h pre-test^	16.4 (0.1)	9.7 (0.1)	6.4 (0.2)	1.6 (0.1)	6.0 (1.0)
2 h pre-test*	16.2	9.4	6.5	1.1	10.0
2 h post-test*	16.4	9.7	7.2	0.7	9.0
24h post-test^	15.2 (0.2)	8.6 (0.2)	8.6 (0.1)	0.4 (0.2)	8.7 (3.8)

^Average of three discrete sample time-points.
*One discrete sample time-point

Table 3. Tide data during November testing period in Baltimore.

	Time	**H/L**
	EST	
Nov 4th	06:20 am	H
	12:44 pm	L
Nov 5th	07:07 am	H
	01:21 pm	L
Nov 6th	07:56 am	H
	02:03 pm	L

4.2.2 Total Suspended Solids

Table 4. Mean (SD) background/ambient (B1, B2) and HSS intake (U1- HSS system stationary, U2- HSS system cleaning) total suspended solids (TSS) concentrations.

Sample Time	TSS (mg/L)			
	B1	B2	U1	U2
24h pre-test*	N/A	5.0 (0.8)	N/A	N/A
2 h pre-test**	N/A	15.4 (1.3)	N/A	N/A
During testing^	7.6 (0.7)	N/A	49.0 (5.2)	77.2 (2.4)
2 h post-test**	N/A	16.8 (1.5)	N/A	N/A
24h post-test*	N/A	19.2 (15.2)+	N/A	N/A

*Three discrete sample time points
**One discrete sample time point
^One integrated sample
+A plankton bloom was observed (visually from the surface) and appeared to increase in algal densities over the 3 sampling times, which may account for the increasing TSS concentrations over the total sampling time period, causing the high SD.

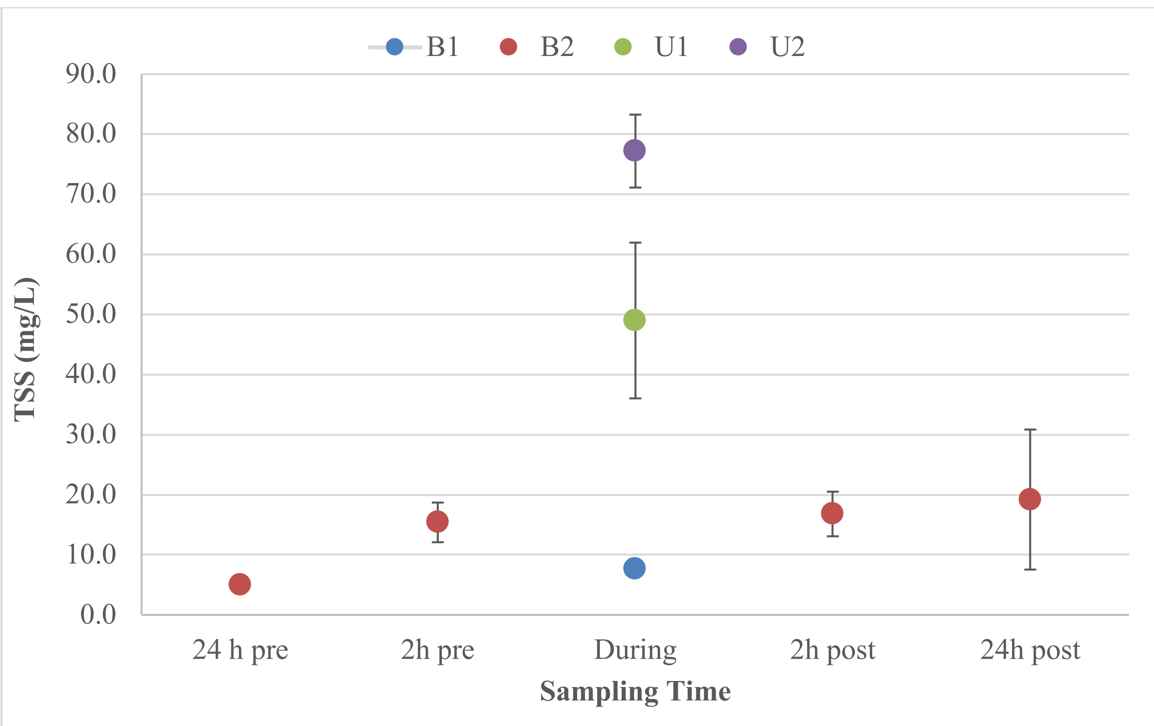

Figure 6. Time series of total suspended solids data. The 95% confidence (CI) intervals are shown in the error bars. The 95% CI for some stations were too low to display on the graph.

4.2.3 Particulate and Dissolved Organic Carbon

Table 5. Mean (SD) particulate and dissolved organic carbon concentrations from samples collected during testing in in Baltimore at Stations B1 and U2.

Station	POC (mg/L)	DOC (mg/L)
B1	0.6 (0.0)	3.3 (0.1)
U2	15.8 (0.2)	5.0 (0.1)

4.2.4 Biocides - Copper and Zinc

Elevated levels of coating associated biocides were measured around the HSS cleaning unit, both during cleaning and when stationary on the side of the test ship, during the one water quality test trial.

Table 6. Toxic substances criteria for dissolved inorganic substances in Maryland ambient surface waters (Code of Maryland Regulations Sec. 25.08.02.03-2, last updated April 2021).

	Freshwater		Estuarine Water		Salt Water	
	Acute (µg/L)	Chronic (µg/L)	Acute (µg/L)	Chronic (µg/L)	Acute (µg/L)	Chronic (µg/L)
Copper	13.0	9.0	6.1	N/A	4.8	3.1
Zinc	120.0	120.0	N/A	N/A	90.0	81.0

Table 7. Mean (SD) concentration of copper in dissolved, particulate, and extractable form (samples collected during testing in Baltimore).

	Copper	Dissolved Mean (SD) (µg/L)	Particulate Mean (SD) (µg/L)	Extractable Mean (SD) (µg/L)
24h pre-test	**B2-T0**	0.70 (0.24)	0.72 (0.32)	1.82 (0.21)
	B2-T1	0.75 (0.10)	0.65 (0.31)	1.67 (0.21)
	B2-T2	0.73 (0.13)	BQL	1.29 (0.18)
2h pre-test	**B2-T3**	BQL	BQL	1.27 (0.31)
During	**B1**	2.66 (0.05)	0.78 (0.08)	3.70 (0.31)
	U1	9.72 (0.46)	6.95 (1.27)	13.13 (0.95)
	U2	10.93 (0.19)	19.80 (1.94)	30.04 (0.39)
2h post-test	**B2-T4**	0.66 (0.13)	BQL	0.98 (0.06)
24h post-test	**B2-T5**	0.51 (0.06)	BQL	0.91 (0.11)
	B2-T6	0.52 (0.05)	0.69 (0.26)	0.67 (0.23)
	B2-T7	BQL	BQL	1.28 (0.13)

BQL = below quality limit, see Table 9.

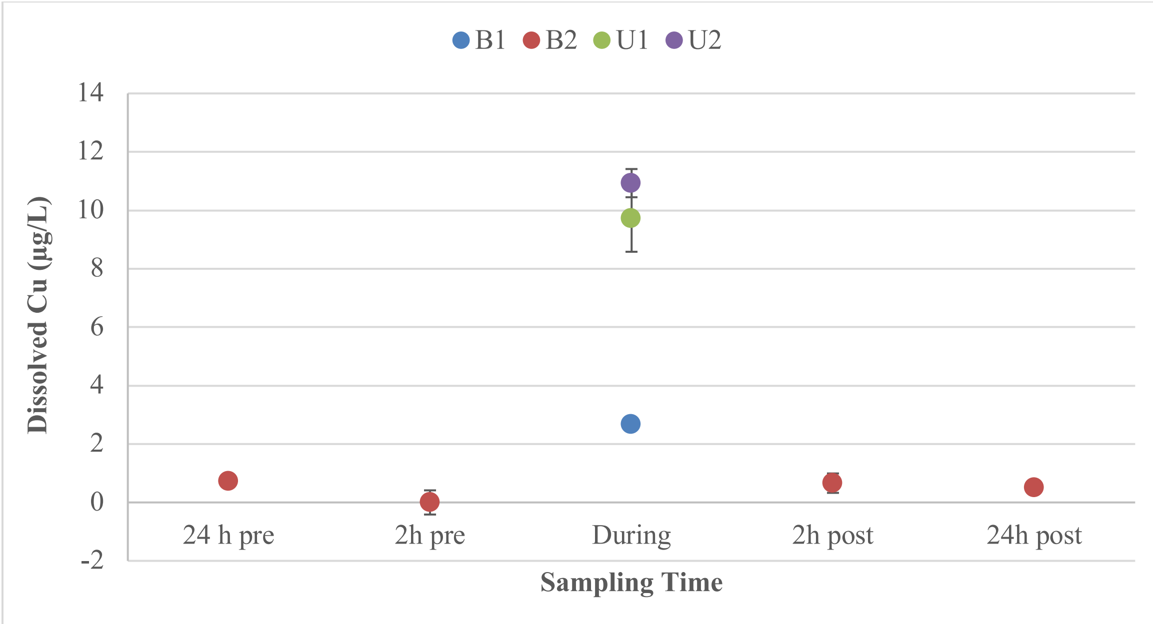

Figure 7. Time series of dissolved copper data. The 95% confidence (CI) intervals are shown in the error bars. The 95% CI for some stations were too low to display on the graph. Stations shown at or below 0 are BQL. The detection limits are shown in Table 9.

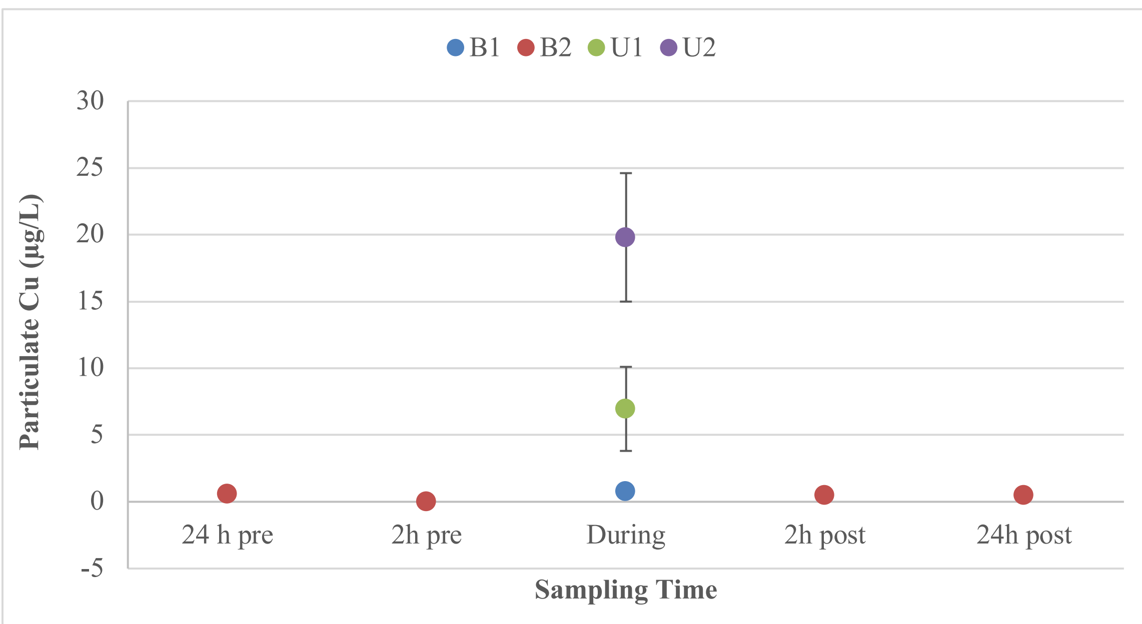

Figure 8. Time series of particulate copper data. The 95% confidence (CI) intervals are shown in the error bars. The 95% CI for some stations were too low to display on the graph. Stations shown at or below 0 are BQL. The detection limits are shown in Table 9.

Table 8. Mean (SD) concentration of zinc in dissolved, particulate, and extractable form (samples collected during testing in Baltimore).

	Zinc	**Dissolved Mean (SD) (µg/L)**	**Particulate Mean (SD) (µg/L)**	**Extractable Mean (SD) (µg/L)**
24h pre-test	**B2-T0**	5.10 (0.80)	2.30 (1.22)	10.65 (1.02)
	B2-T1	1.28 (0.26)	1.99 (0.24)	6.36 (1.20)
	B2-T2	1.75 (0.72)	1.82 (0.57)	5.59 (1.15)
2h pre-test	**B2-T3**	2.53 (0.65)	2.29 (0.57)	7.88 (3.16)
During	**B1**	5.13 (0.22)	2.53 (0.70)	9.63 (1.57)
	U1	6.08 (1.22)	8.19 (0.55)	17.43 (0.50)
	U2	5.17 (0.33)	10.44 (2.69)	15.00 (0.41)
2h post-test	**B2-T4**	2.95 (0.44)	2.99 (1.43)	4.37 (0.44)
24h post-test	**B2-T5**	1.77 (0.25)	3.26 (1.47)	3.74 (0.05)
	B2-T6	1.97 (0.23)	6.94 (2.61)	*7.45 (4.38)
	B2-T7	2.10 (1.96)	2.56 (0.80)	5.83 (0.12)

BQL = below quality limit, see Table 9.
*Average of 4.06, 5.88 and 12.40 µg/L

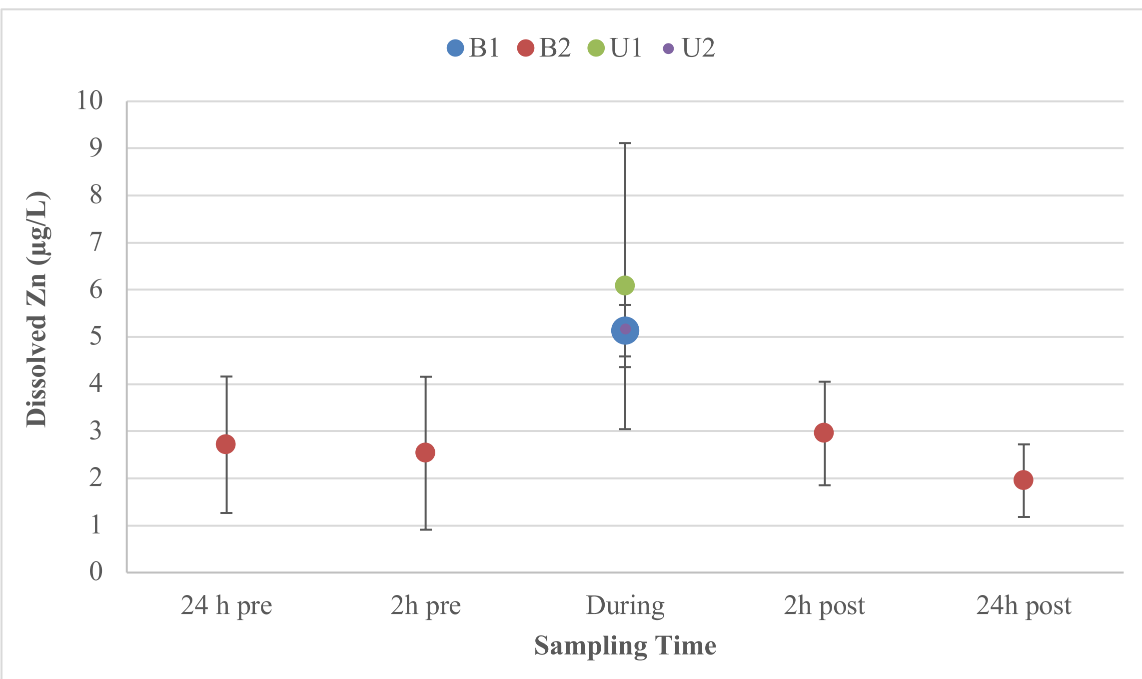

Figure 9. Time series of dissolved zinc data. The 95% confidence (CI) intervals are shown in the error bars. The detection limits are shown in Table 9.
*Data points for B1 (5.13 µg/L) and U2 (5.17 µg/L) are close together and shown as one larger circle.

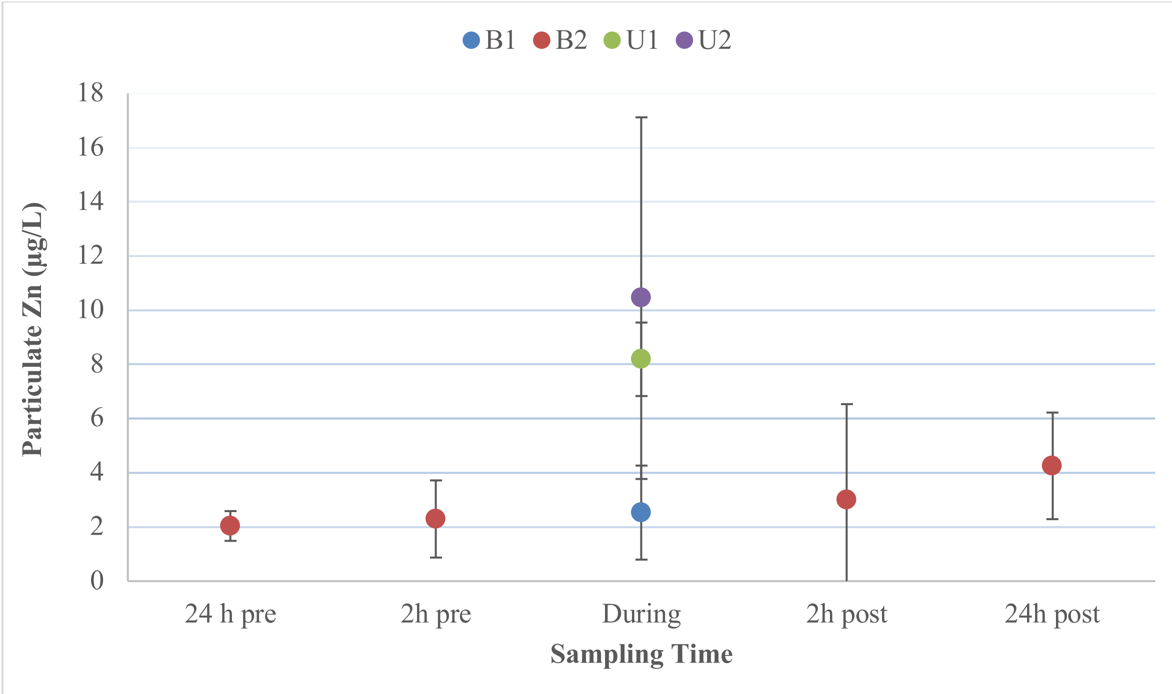

Figure 10. Time series of particulate zinc data. The 95% confidence (CI) intervals are shown in the error bars. The 95% CI for some stations were too low to display on the graph. The detection limits are shown in Table 9.

Table 9. Quality limits for copper and zinc samples in Baltimore.

		Quality Limit (QL) (µg/L)	Detection Limit (DL) (µg/L)
Copper	Dissolved	0.5	0.1
	Particulate	0.5	0.1
	Extractable	0.5	0.1
Zinc	Dissolved	1.0	0.5
	Particulate	1.0	0.1
	Extractable	1.0	0.5

4.2.5. Particle Size Distribution

One sample each was collected from stations B1 and U2. These samples were shipped to PTL where they were each subsampled one time for the Static Image Analysis and three times for Single Particle Optical Sensing (SPOS) analyses. Tables 10, 11, and 12 show the results of the static image analysis for the particle size distribution samples. The samples were extremely difficult to dilute for image analysis; therefore, only one replicate was analyzed using this technique. Tables 13, 14, and 15 show the results using SPOS. Blank results are located in the QAQC description (Section 5).

Table 10. Particle size analysis data summary for samples collected during testing in Baltimore. The table shows the circular equivalent diameter.

Station	Cumulative number % less than indicated size			Number Mean (µm)	Cumulative volume % less than indicated size			Volume Mean (µm)
	D[n, 0.10]	D[n, 0.50]	D[n, 0.90]		D[v, 0.10]	D[v, 0.50]	D[v, 0.90]	
B1	1.10	1.66	4.43	2.54	10.89	69.90	73.70	51.36
U2	1.07	1.50	4.53	2.57	26.41	67.54	125.7	78.08

Table 11. Particle shape data summary for samples collected during testing in Baltimore. The table shows the aspect ratio.

Station	Cumulative number % less than indicated size			Number Mean (µm)	Cumulative volume % less than indicated size		
	D[n, 0.10]	D[n, 0.50]	D[v, 0.10]		D[v, 0.10]	D[n, 0.50]	D[n, 0.90]
B1	0.558	0.791	0.929	0.770	0.331	0.722	0.828
U2	0.562	0.787	0.922	0.770	0.281	0.669	0.859

Table 12. Particle shape data summary for samples collected during testing in Baltimore. The table shows circularity.

Station	Cumulative number % less than indicated size			Number Mean (µm)	Cumulative volume % less than indicated size		
	D[n, 0.10]	D[n, 0.50]	D[v, 0.10]		D[v, 0.10]	D[n, 0.50]	D[n, 0.90]
B1	0.557	0.898	0.974	0.830	0.399	0.642	0.738
U2	0.560	0.896	0.973	0.829	0.155	0.500	0.635

Table 13. Particle size data summary using SPOS techniques. This table shows the cumulative *number* % less than indicated size (µm).

Station	Cumulative number % less than indicated size (µm)			Number Weighted Mean (µm)
	10th percentile	50th percentile	90th percentile	
B1	0.54 (0.00)	0.75 (0.01)	2.83 (0.05)	1.50 (0.02)
U2	0.52 (0.00)	0.66 (0.01)	1.41 (0.03)	1.00 (0.01)

Table 14. Particle size data summary using SPOS techniques. This table shows the cumulative *volume* % less than indicated size (µm).

Station	Cumulative volume % less than indicated size (µm)			Volume Weighted Mean (µm)
	10th percentile	50th percentile	90th percentile	
B1	11.19 (1.47)	54.86 (16.97)	118.89 (17.49)	59.79 (12.58)
U2	23.53 (0.47)	36.71 (1.15)	76.93 (17.67)	45.02 (5.97)

Table 15. Particle concentration summary using SPOS techniques. This table shows mean (SD) of the stock concentration number of particles per milliliter.

Station	Stock Concentration # of Particles/ml
B1	3.97×10^4 (5.20×10^2)
U2	5.73×10^5 (1.15×10^3)

4.3. Attempted Water Quality Tests

Below (Table 16) is a summary of attempted testing of the HSS system for possible water quality impacts, on both the M/V *Talisman* and the M/V *Tysla*, and the reasons for canceled trials. The table also includes the one successful test trial (November 2021).

Table 16. Attempted water quality trial test dates on the M/V *Talisman* and the M/V *Tysla* in Baltimore, MD.

Date	Test Ship	Reason for Cancelation
9/26/2020	*Talisman*	HSS system inoperable due to problems with a magnetic wheel
4/25/2021	*Talisman*	Winds exceeding the 11 mph (5 m/s) threshold for safe deployment of the HSS cleaning unit
5/25/2021	*Talisman*	HSS system not operational due to electrical problems
11/5/2021	*Tysla*	Successful water quality test *
4/15/2022	*Tysla*	HSS system inoperable due to prior system damage
6/29/2002	*Tysla*	HSS system remained inoperable (needed repairs not completed)

* Results provided above

5. Quality Assurance and Quality Control

All testing activities conducted by ACT and MERC comply with their respective Quality Management Systems (QMS), which include the policies, objectives, procedures, authority, and accountability needed to ensure quality in work processes, products, and services.

5.1. Blanks and Duplicate Sample Analysis

Trip DI blanks were collected for metals on all three sample days (Table 17). Tables 18 and 19 show the results of the particle size distribution analysis for blank samples from Baltimore.

Table 17. Results of trip (DI) blank for analysis of metal concentrations in Baltimore.

	Sample Day	Trip Blank	
		Dissolved Mean (SD) (µg/L)	**Particulate Mean (SD) (µg/L)**
Copper	Day 1	BQL	BDL
	Day 2	BDL	BQL
	Day 3	BDL	BDL
Zinc	Day 1	BDL	BDL
	Day 2	BDL	1.01
	Day 3	BDL	BDL

Table 18. Results of particle size determination SPOS analysis using deionized water blanks. This table shows the cumulative number % less than indicated size (µm).

Station	Cumulative number % less than indicated size (µm)			Number Weighted Mean (µm)
	10th percentile	**50th percentile**	**90th percentile**	
QAQC	0.52	0.58	0.85	0.70

Table 19. Particle size data summary using SPOS techniques. This table shows the cumulative volume % less than indicated size (µm).

Station	Cumulative volume % less than indicated size (µm)			Volume Weighted Mean (µm)
	10th percentile	**50th percentile**	**90th percentile**	
QAQC	18.29	49.56	50.67	37.27

5.2 Data Quality Review: Water Samples

ACT/MERC QA staff independently conducted a data quality review for the complete data sets for the tests.

The following quality control elements were reviewed for the Jotun HSS IWC test water quality data sets:

- Chain of custody and sample handling,
- Replicate samples, and
- Blank samples.

All field activities followed standard record keeping and chain-of-custody procedures. Sample handling procedures were followed as described in SOPs for the method or the Test Protocols. Field QC samples included field replicates and blanks. Analysis of the QC samples verified that data quality standards were met.

Data verification confirmed that the sampling procedures specified in the Test Protocols and SOPs were followed, and that the ACT/MERC measurement systems performed in accordance with approved methods.

The data validation also confirmed that the data were accumulated, transferred, summarized, and reported correctly. There is sufficient documentation of all procedures used in the data collection and analysis to validate that the data were collected in accordance with the evaluation's quality objectives.

An audit of data quality (ADQ) showed there is sufficient documentation of all procedures used in the data collection and analysis to verify that the data have been collected in accordance with ACT/MERC quality objectives defined in the ACT/MERC QMSs.

The DQA determined that the test's data quality objectives, described in the ACT QAPP (ACT 2015) and the MERC land-based QAPP (MERC, 2020) were achieved.

5.2.3. Dive Surveys

QC procedures relating to the acquisition and analysis of video and still image data from underwater video surveys have not been developed comparable to QC and data assessment procedures for water quality sampling and analyses. QC of the quantitative and qualitative data from underwater imagery primarily involves multiple analysts working independently but following the same protocol to minimize bias.

Data verification, using the diver survey log sheets, confirmed that the sampling procedures specified in the Test Protocols were followed. The raw data records were complete. Data validation of a subset of the data confirmed that the data were accumulated, transferred, and reported correctly. The overall quality of the point count and percent cover data was acceptable and suitable for use in the statistical analyses to evaluate the effect of the in-water cleaning on biofouling.

7. Contributors and Approvals

The Testing Team included: C. Arriola, G. Ashton, J. Barnes. M. First, A. Heyes, G. Ng, S. Robbins-Wamsley, B. Rubinoff, A. Saley, C. Scianni, A. Shick, T. Shick, D. Sparks, G. Ruiz, G. Smith and M. Tamburri.

We thank the crews of the M/V *Talisman* and M/V *Tysla* and Jotun HSS operations team.

Approved By:

5 September 2022
Date

Dr. Mario Tamburri
ACT and MERC Director

5 September 2022
Date

Katherine Davis
QA Manager

Appendix A. Agreed to Test Plan

Available for download at https://www.maritime-enviro.org/Downloads/Other_ Publications/ACT_MERC_Jotun_Proactive_IWC_Test_Plan_5Aug2020_signed.pdf