U.S. NAVAL RESEARCH LABORATORY

The Efficacy and Practicability of Combining Ballast Water Exchange with Treatment: Results of Shipboard Trials

Lisa A. Drake[1], Cameron S. Moser[1], Matthew R. First[2], Scott C. Riley[3], Stephanie H. Robbins-Wamsley[3], Vanessa Molina[3], Jonathan F. Grant[4], Gregory C. Kepler[4], and Tim P. Wier[3]

[1]Code 6137, Naval Research Laboratory, Key West, FL 33040
[2]Code 6137, Naval Research Laboratory, Washington, DC 20375
[3]Excet, Inc., Springfield, VA 22150
[4]Battenkill Technologies, Inc., Manchester Center, VT 05255

ICAIS • 22-26 OCT 2017 • Ft. Lauderdale

U.S. NAVAL RESEARCH LABORATORY

Overview

In the US, both the USCG and EPA are responsible for regulating ballast water discharges

The EPA Vessel General Permit (**VGP**) includes additional requirements for vessels entering the Great Lakes through the St. Lawrence Seawater System, if:

(1) operated outside the Exclusive Economic Zone (EEZ, nominally 200 nm offshore) and >200 nm from any shore

(2) taken on ballast water with a salinity of <18 ppt within the previous 30 days

If both of these qualifications are met, once a vessel is required to meet the numeric discharge standard, it must also conduct **“ballast water exchange”** or **“saltwater flushing”**

U.S. NAVAL RESEARCH LABORATORY

Experimental Design

- Ideally, compare

  2 tanks with ballast water **treatment**

  vs.

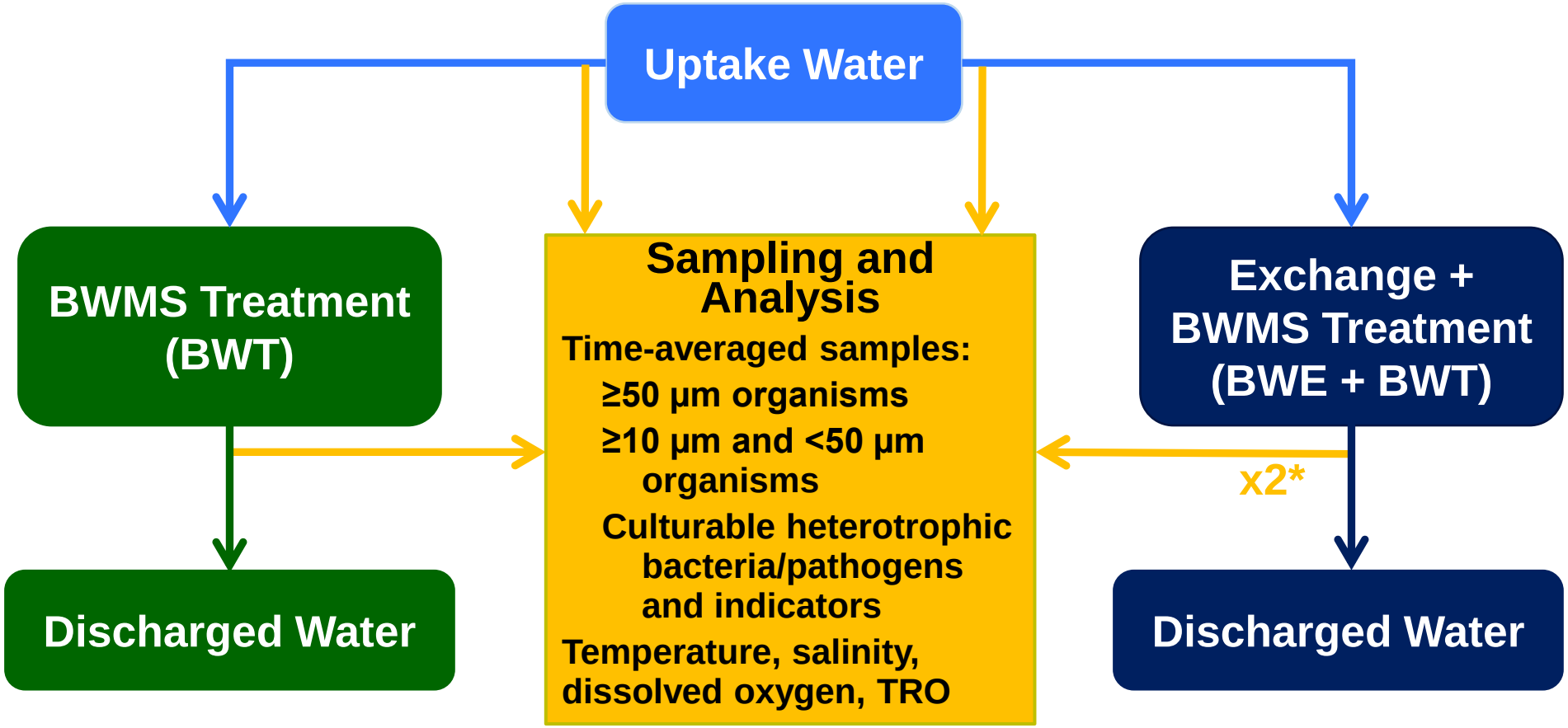
  2 tanks with **exchange*** + BWMS **treatment**

- Multiple vessels, multiple trials per vessel
  → Meta-analysis with other studies

***at least **50 nm** (and ideally **200 nm**) from shore

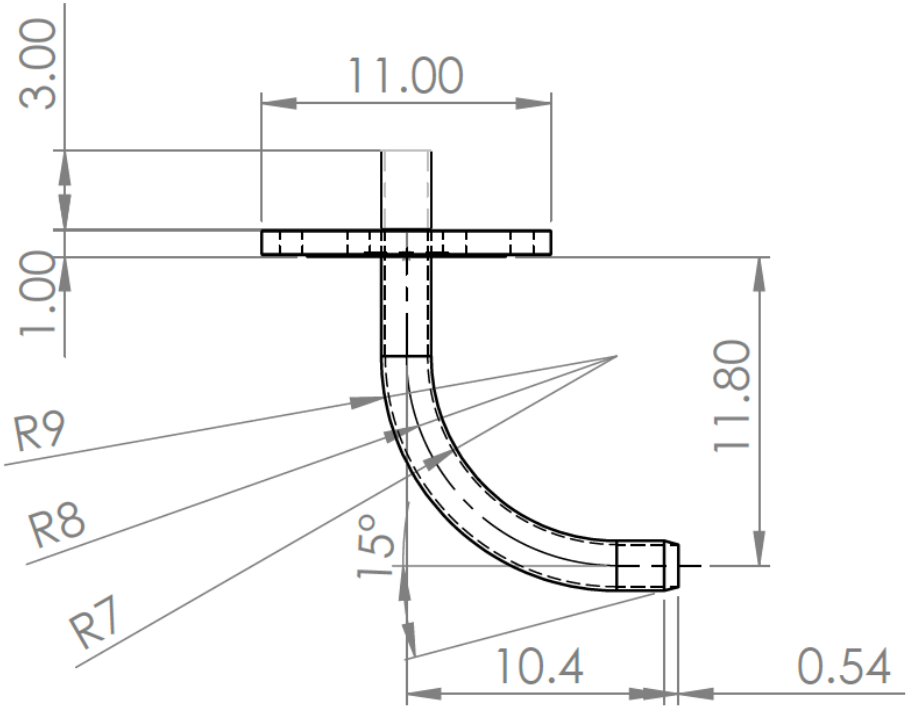
U.S. NAVAL RESEARCH LABORATORY

Experimental Design



*In the BWE + BWT tanks, ideally, samples will also be collected as the tanks are emptied and filled for exchange

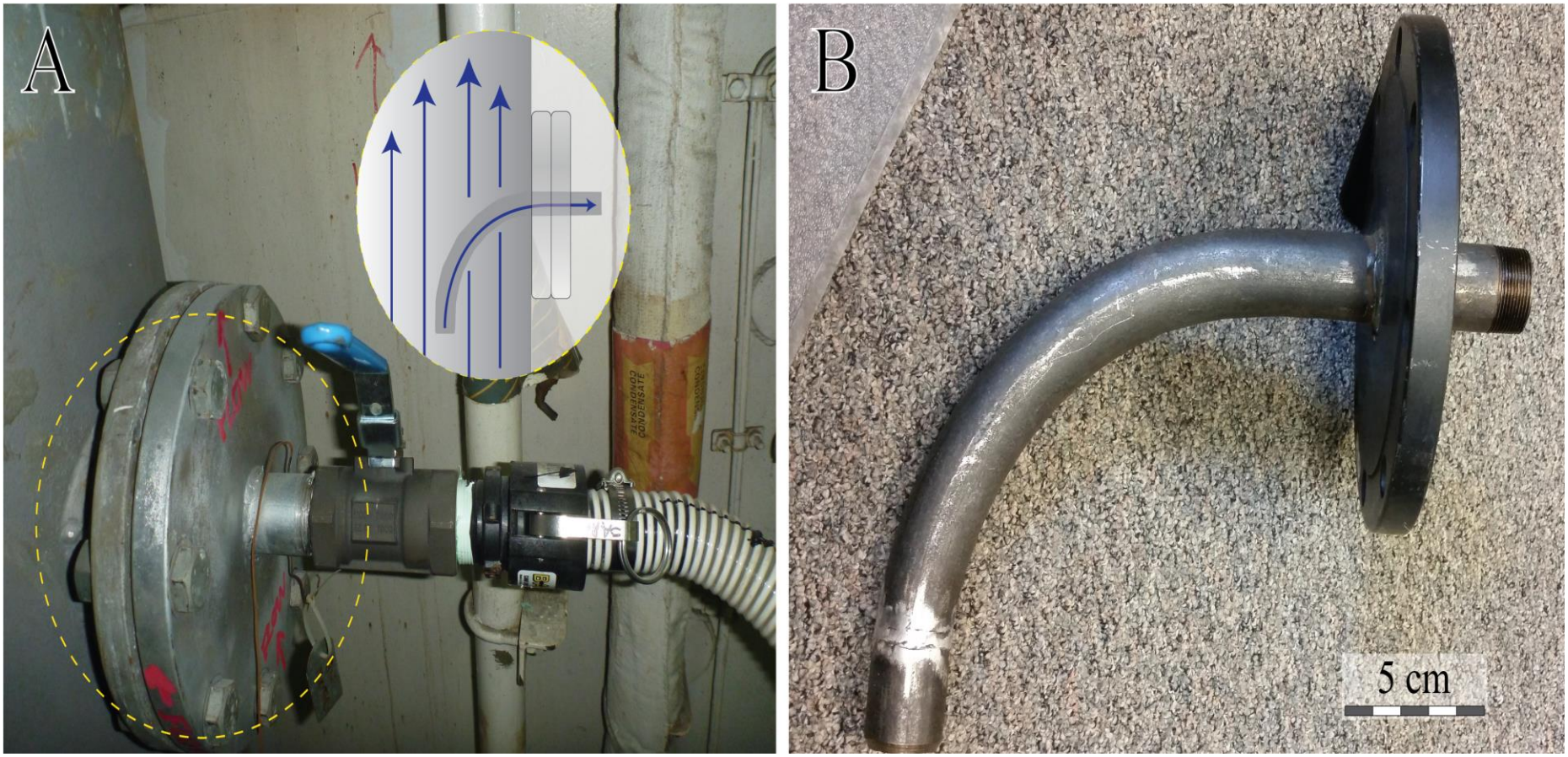
Methods—Sample Collection



Sample probe designed for the vessel and per International Organization for Standardization (ISO) Standard 11711-1: 2013

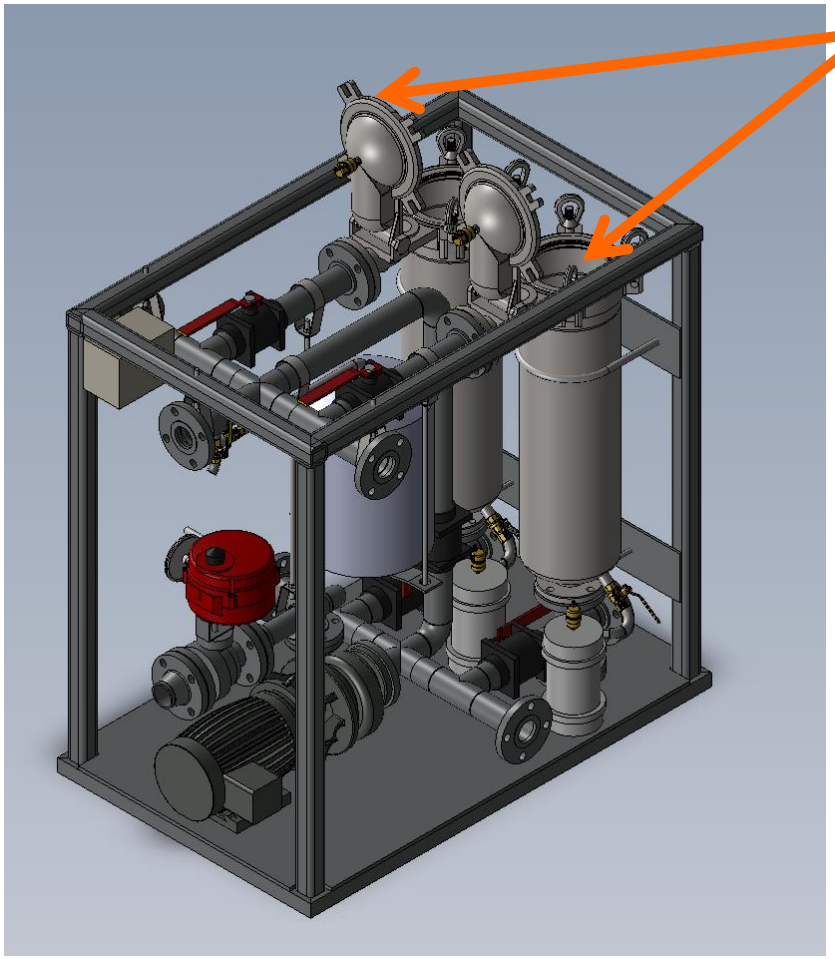
U.S. NAVAL RESEARCH LABORATORY

Methods—Sample Collection



Sample probe as installed on vessel

Methods—Shipboard Filter Skid

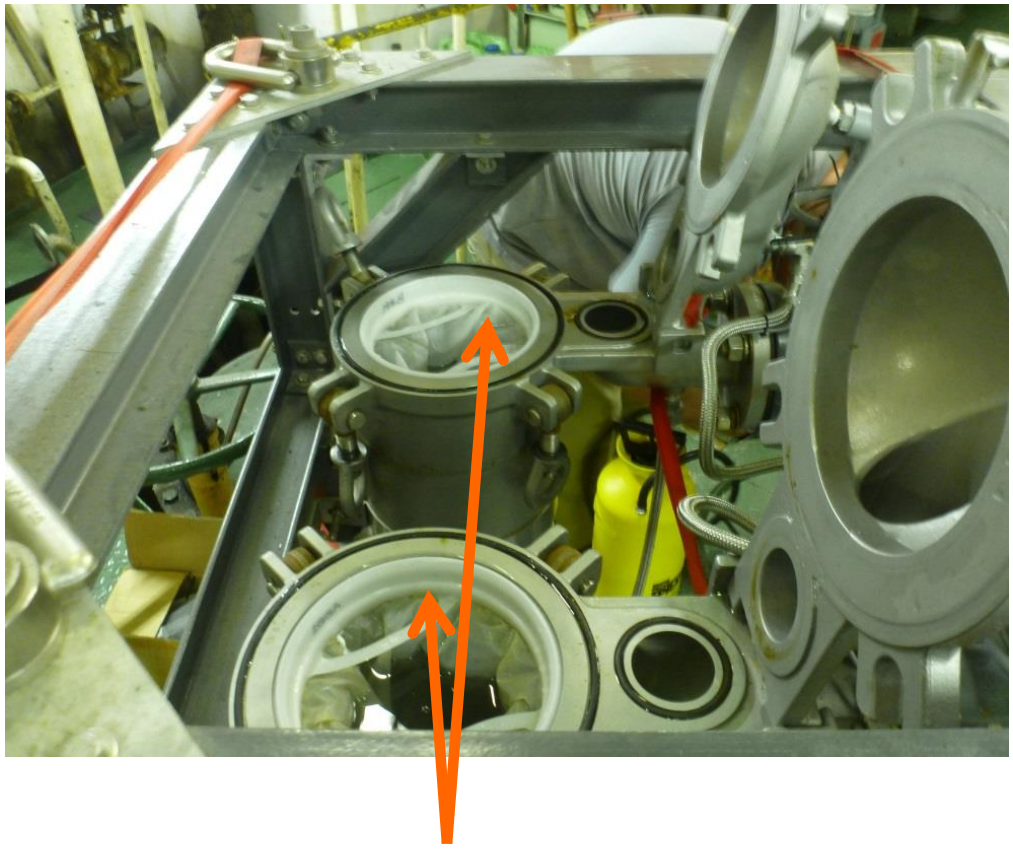


- 35-µm nylon monofilament filter bags in housings
- Obtains time-averaged samples of organisms
  - Flow-through sampling
  - ≥50 µm (filter bags)
  - ≥10 µm and <50 µm as well as <10 µm (drip sampler)

U.S. NAVAL RESEARCH LABORATORY

Methods—Shipboard Filter Skid

Methods—Shipboard Filter Skid



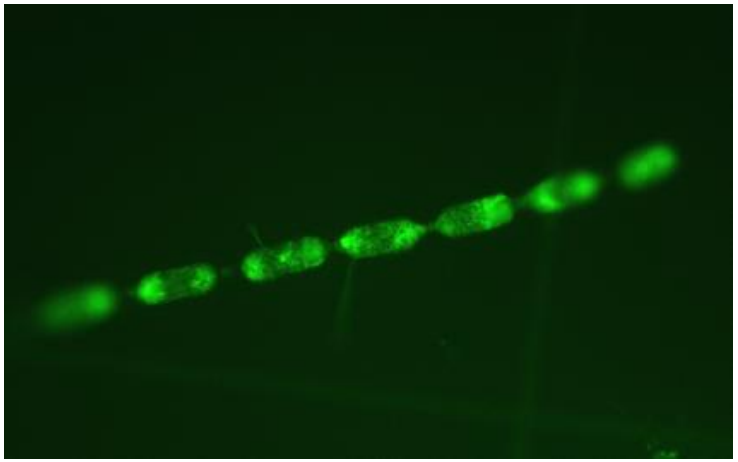
Filter bags before removal

Rinsing of filter bags after trial

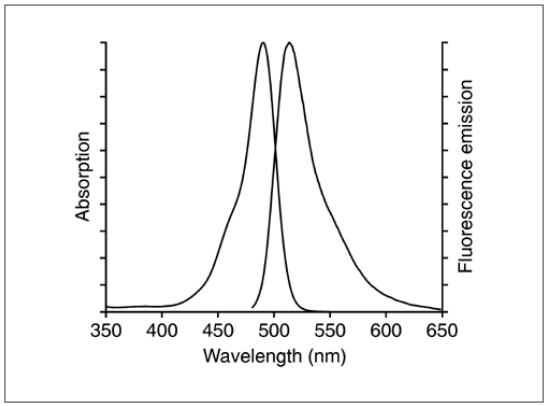
Methods—≥10 and <50 µm (ETV*)

Probes + Movement + Direct Counts = # of Living Organisms

Fluorescein Diacetate (FDA) +
Cell Tracker Green (CMFDA)
+ movement



www.microscopy.uk.com



www.invitrogen.com

*Environmental Technology Verification Program Protocol

U.S. NAVAL RESEARCH LABORATORY

Methods—≥50 µm; ≥10 and <50 µm

U.S. NAVAL RESEARCH LABORATORY

Ballast Water Management System

- Filter (40 µm) + electrolytic chlorine generator (ECG)
  - Vessel was retrofitted with BWMS
  - BWMS used for all ballasting events
  - BWMS includes a flow meter, salinity sensor, and total residual oxidant sensor (TRO) to monitor and control TRO production
  - BWMS requires 24-hour hold time

U.S. NAVAL RESEARCH LABORATORY

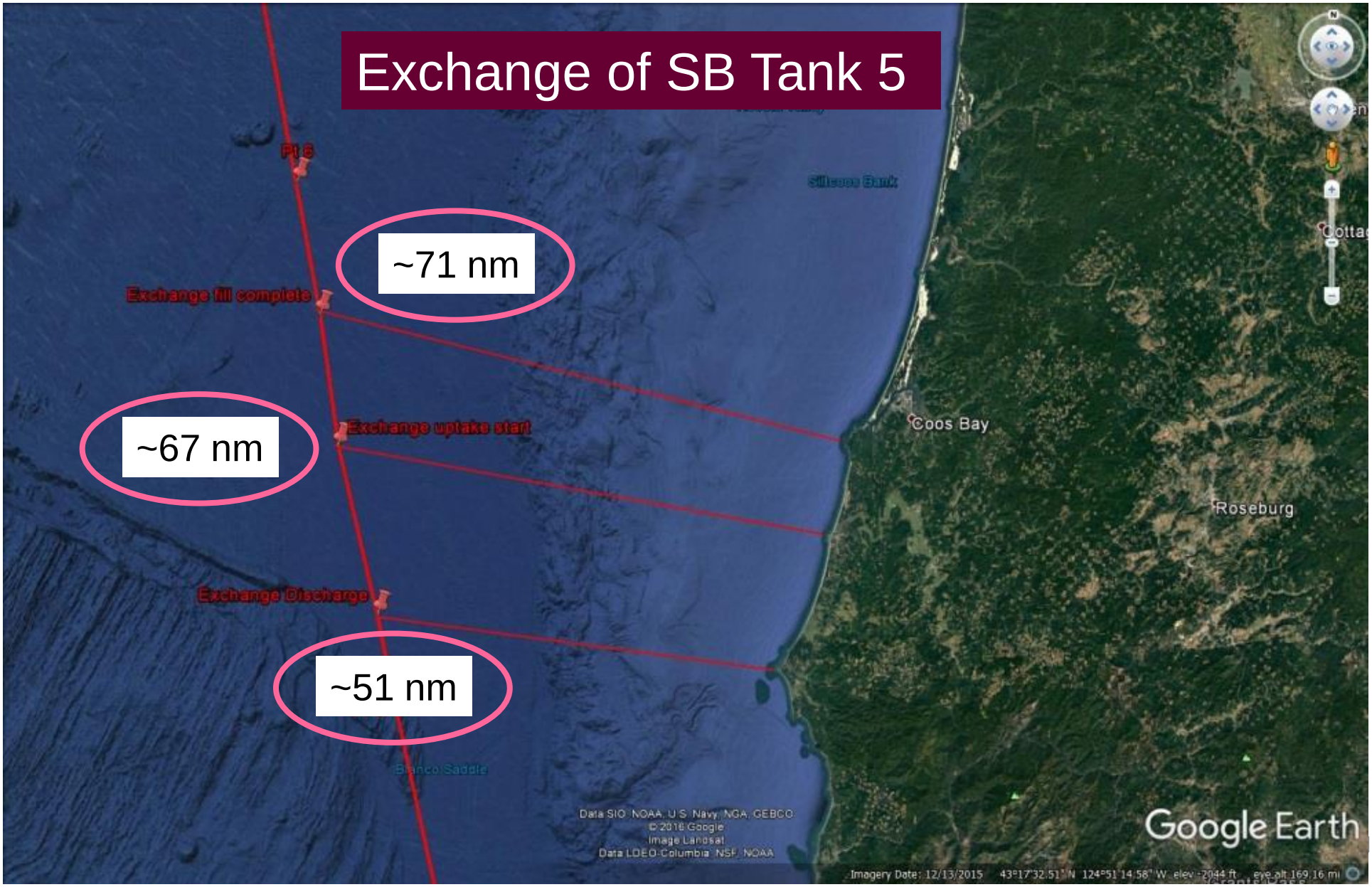
Ballast Water Management System

- During discharge, the oxidant level of the water is measured with a TRO sensor and neutralized as needed

- BWMS automatically logs all ballasting operations

U.S. NAVAL RESEARCH LABORATORY

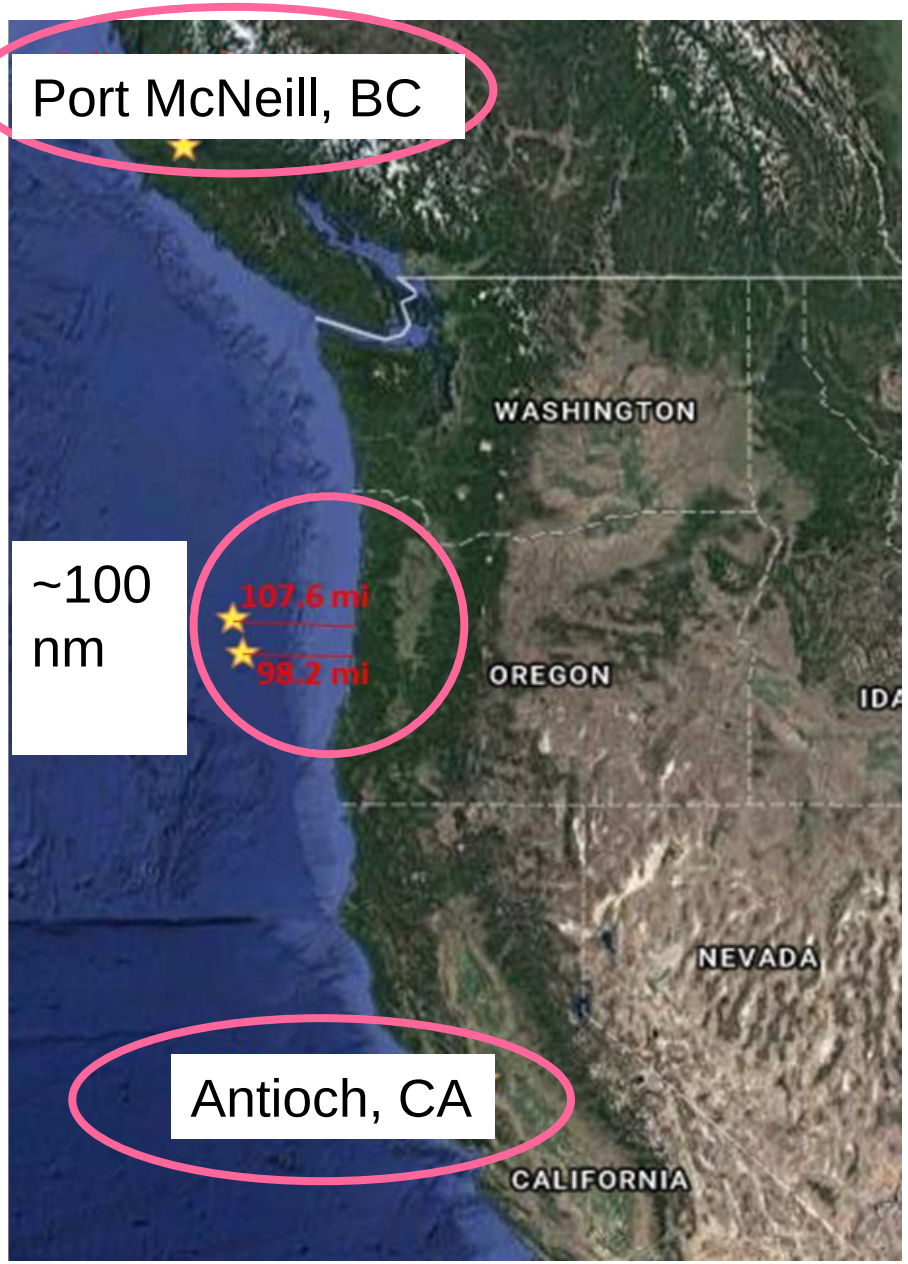
Voyage 1—16-23 OCT 2016



U.S. NAVAL RESEARCH LABORATORY

Voyage 2—01-05 FEB 2017

Exchange of SB Tank 2



U.S. NAVAL RESEARCH LABORATORY

Results—≥50 µm

Voyage Number	Sample	Total (m^{-3})
1	Uptake SB Tank 6 (UP-6)	31,680
	Uptake SB Tank 5 (UP-5)	38,640
	Discharge BWE SB Tank 5 (EX-DIS-5)	27
	Uptake BWE SB Tank 5 (EX-UP-5)	13
	Discharge SB Tank 6 (DIS-6)	0
	Discharge SB Tank 5 (DIS-5 [EX])	0
2	Uptake SB Tank 6 (UP-6)	2,912
	Uptake SB Tank 2 (UP-2)	2,752
	Discharge SB Tank 6 (DIS-6)	20
	Discharge SB Tank 2 (DIS-2 [EX])	0

- Voyage 1: Concentrations >discharge standard in BWE + BWT tank
- Voyage 2: Concentrations >discharge standard in BWT tank

U.S. NAVAL RESEARCH LABORATORY

Results—≥10 and <50 µm (ETV)

Voyage Number	Sample	Total (mL^{-1})
1	Uptake SB Tank 6 (UP-6)	0
	Uptake SB Tank 5 (UP-5)	10
	Discharge SB Tank 5 (EX-DIS-5)	0
	Uptake BWE SB Tank 5 (EX-UP-5)	0
	Discharge SB Tank 6 (DIS-6)	0
	Discharge SB Tank 5 (DIS-5 [EX])	0
2	Uptake SB Tank 6 (UP-6)	6
	Uptake SB Tank 2 (UP-2)	2
	Discharge SB Tank 6 (DIS-6)	0
	Discharge SB Tank 2 (DIS-2 [EX])	0

- Voyage 1: Almost all concentrations <discharge standard
- Voyage 2: ***All*** concentrations <discharge standard

U.S. NAVAL RESEARCH LABORATORY

Results—≥10 and <50 µm (MPN)

Voyage Number	Sample	MPN (cells mL^{-1})	Upper CI	Lower CI	SE
1	Uptake SB Tank 6 (UP-6)	0.619	4.38	0.089	0.999
	Uptake SB Tank 5 (UP-5)	0.619	4.38	0.089	0.999
	Discharge BWE SB Tank 5 (EX-DIS-5)	0.619	4.38	0.089	0.999
	Uptake BWE SB Tank 5 (EX-UP-5)	1.87	5.99	0.586	0.592
	Discharge SB Tank 6 (DIS-6)	<0.619*	N/A	N/A	N/A
	Discharge SB Tank 5 (DIS-5 [EX])	<0.620*	N/A	N/A	N/A
2	Uptake SB Tank 6 (UP-6)	1.446	2.616	0.799	0.303
	Uptake SB Tank 2 (UP-2)	1.383	2.518	0.760	0.306
	Discharge SB Tank 6 (DIS-6)	<0.08*	N/A	N/A	N/A
	Discharge SB Tank 2 (DIS-2 [EX])	<0.08*	N/A	N/A	N/A

*below level of detection

U.S. NAVAL RESEARCH LABORATORY

Results—≥10 and <50 µm (MPN)

Voyage Number	Sample	MPN (cells mL^{-1})	Upper CI	Lower CI	SE
1	Uptake SB Tank 6 (UP-6)	0.619	4.38	0.089	0.999
	Uptake SB Tank 5 (UP-5)	0.619	4.38	0.089	0.999
	Discharge BWE SB Tank 5 (EX-DIS-5)	0.619	4.38	0.089	0.999
	Uptake BWE SB Tank 5 (EX-UP-5)	1.87	5.99	0.586	0.592
	Discharge SB Tank 6 (DIS-6)	<0.619*	N/A	N/A	N/A
	Discharge SB Tank 5 (DIS-5 [EX])	<0.620*	N/A	N/A	N/A
2	Uptake SB Tank 6 (UP-6)	1.446	2.616	0.799	0.303
	Uptake SB Tank 2 (UP-2)	1.383	2.518	0.760	0.306
	Discharge SB Tank 6	<0.08*	N/A	N/A	N/A

*below level of detecti

- Voyage 1: ***All*** concentrations <discharge standard
- Voyage 2: ***All*** concentrations <discharge standard

U.S. NAVAL RESEARCH LABORATORY

Results—*E. coli* and Enterococci

Voyage Number	Sample	Sub-sample	*E. coli* (per 100 mL)			Enterococci (per 100 mL)		
			MPN	95% Confidence Limit		MPN	95% Confidence Limit	
				Lower	Upper		Lower	Upper
1	Uptake (UP-6)	A	<10	0.0	37	<10	0.0	37
		B	<10	0.0	37	82	3.6	153
		C	10	10	55	93	45	169
	Uptake (UP-5)	A	<10	0.0	37	<10	0.0	37
		B	<10	0.0	37	<10	0.0	37
		C	10	10	55	<10	0.0	37
	Discharge (EX-DIS-5)	A	<10	0.0	37	41	17	95
		B	<10	0.0	37	52	18	108
		C	<10	0.0	37	10	0.0	37
	Uptake (EX-UP-5)	A	<10	0.0	37	10	10	55
		B	<10	0.0	37	10	10	55
		C	<10	0.0	37	<10	0.0	37
	Discharge (DIS-6)	A	<10	0.0	37	<10	0.0	37
		B	<10	0.0	37	<10	0.0	37
		C	<10	0.0	37	<10	0.0	37
	Discharge (DIS-5 [EX])	A	<10	0.0	37	<10	0.0	37
		B	<10	0.0	37	<10	0.0	37
		C	<10	0.0	37	<10	0.0	37

U.S. NAVAL RESEARCH LABORATORY

Results—E. coli and Enterococci

Voyage Number	Sample	Sub-sample	*E. coli* (per 100 mL)			Enterococci (per 100 mL)		
			MPN	95% Confidence Limit		MPN	95% Confidence Limit	
				Lower	Upper		Lower	Upper
2	Uptake (UP-6)	A	7.1	3.0	13.7	2	0.3	5.9
		B	5.2	1.8	10.8	6.2	2.3	12.1
		C	3.1	0.7	8.9	2	0.3	7.1
	Uptake (UP-2)	A	3.1	0.7	8.9	2	0.3	7.1
		B	2	0.3	7.1	3	0.6	7.3
		C	1	0.1	5.5	1	0.0	3.7
	Discharge (DIS-6)	A	<1	0	3.7	<1	0.0	3.7
		B	<1	0	3.7	<1	0.0	3.7
		C	<1	0	3.7	<1	0.0	3.7
	Discharge (DIS-2 [EX])	A	<10	0.0	37	<1	0.0	3.7
		B	<10	0.0	37	<1	0.0	3.7
		C	<10	0.0	37	<1	0.0	3.7

- Voyage 1: ***All*** concentrations <discharge standard
- Voyage 2: ***All c***oncentrations <discharge standard

U.S. NAVAL RESEARCH LABORATORY

Results—*Vibrio cholerae*

Voyage Number	Sample	Sub-sample	Positive for *Vibrio cholerae* O1	Positive for *Vibrio cholerae* O139
1	Uptake (UP-6)	A	no	no
		B	yes	yes
		C	no	no
	Uptake (UP-5)	A	no	no
		B	no	no
		C	no	no
	Discharge (EX-DIS-5)	A	no	yes
		B	no	no
		C	no	no
	Uptake (EX-UP-5)	A	no	no
		B	no	no
		C	no	no
	Discharge (DIS-6)	A	no	no
		B	no	no
		C	no	no
	Discharge (DIS-5 [EX])	A	no	no
		B	no	no
		C	no	no

U.S. NAVAL RESEARCH LABORATORY

Results—*Vibrio cholerae*

Voyage Number	Sample	Sub-sample	Positive for *Vibrio cholerae* O1	Positive for *Vibrio cholerae* O139
2	Uptake (UP-6)	A	yes	no
		B	yes	no
		C	yes	yes
	Uptake (UP-2)	A	yes	yes
		B	no	no
		C	no	no
	Discharge (DIS-6)	A	no	no
		B	no	no
		C	no	no
	Discharge (DIS-2 [EX])	A	no	no
		B	no	no
		C	no	no

- Voyage 1: Concentrations >discharge standard in BWE + BWT tank
- Voyage 2: Concentrations <discharge standard

U.S. NAVAL RESEARCH LABORATORY

Summary

- ≥50 µm: discharge standard exceeded (~2x) in both BWT and BWE + BWT samples
- ≥10 and < 50 µm: Low uptake concentrations in both trials
  - ETV and MPN results agreed
- *E. coli* and enterococci: Low uptake concentrations in both trials
- *V. cholerae*: Uptake concentrations exceeded standard, and one discharge sample (BWE + BWT) exceeded the standard

U.S. NAVAL RESEARCH LABORATORY

Environmental Match

- Samples were collected to determine diversity
- Analyses are underway (at EPA) to conduct metagenomic sequencing and taxonomic classification to determine community profiles
  - Prokaryotes (16S) and eukaryotes (18S) for the whole water samples and some of the MPN tubes
- Computational and statistical analysis will be performed on the classified DNA sequences to assess the effects of ballast treatment strategies

Acknowledgements

This work was funded by the Environmental Protection Agency, agreement # DW-17-92399701

We greatly appreciate:

the advice and programmatic support of
Robin Danesi and **Jack Faulk** (EPA)

the kind cooperation of
the Master and Crew of the ship and the ship management company

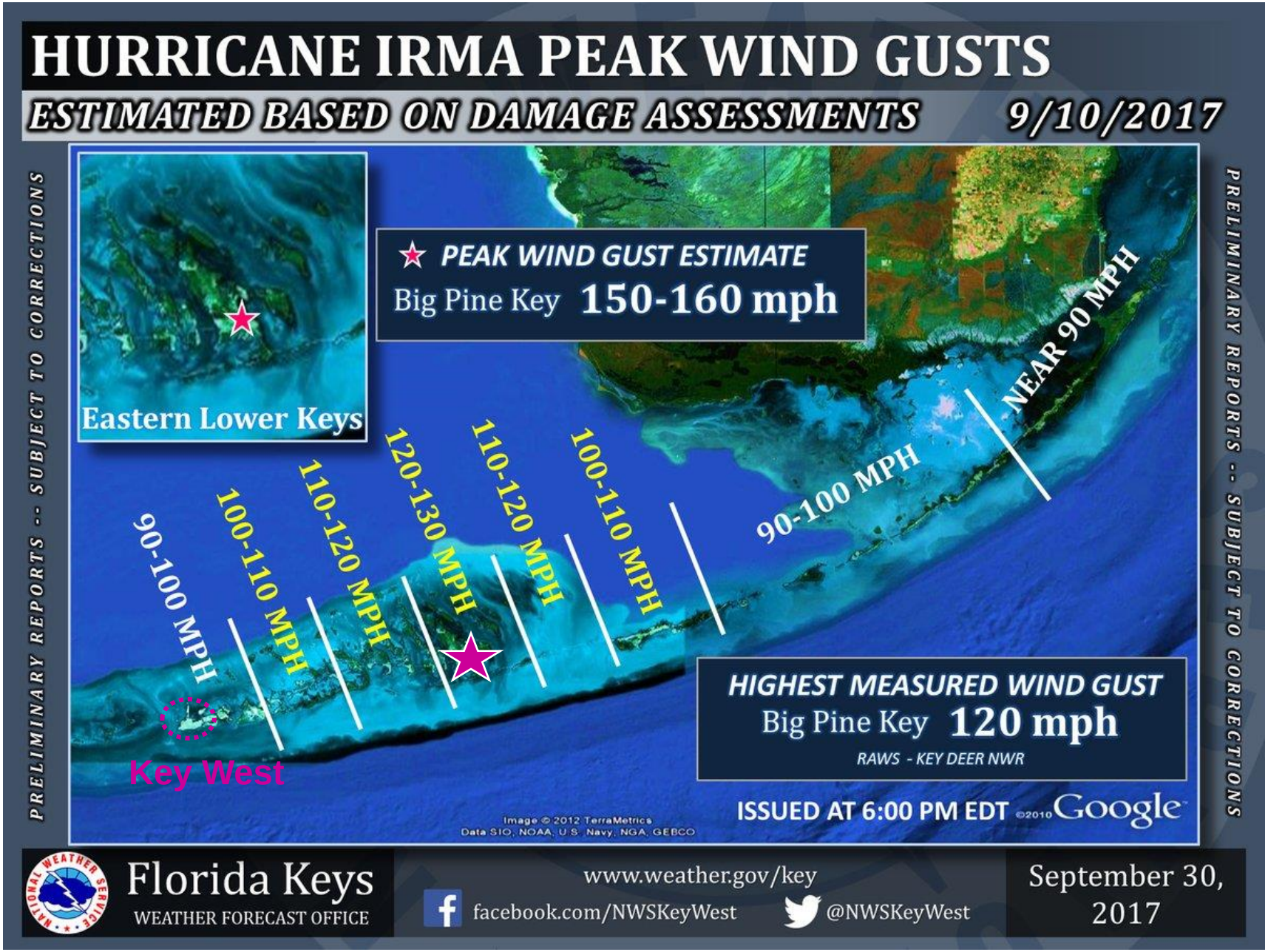
U.S. NAVAL RESEARCH LABORATORY

Related Efforts

- Practicability of conducting exchange + treatment
  - Analyses of USCG data (National Ballast Information Clearinghouse [NBIC] and Automatic Identification System [AIS] reports)
    - Two research papers; one published, the other in preparation
  - Survey of shipowners
    - Results are being analyzed

U.S. NAVAL RESEARCH LABORATORY

Hurricane Irma

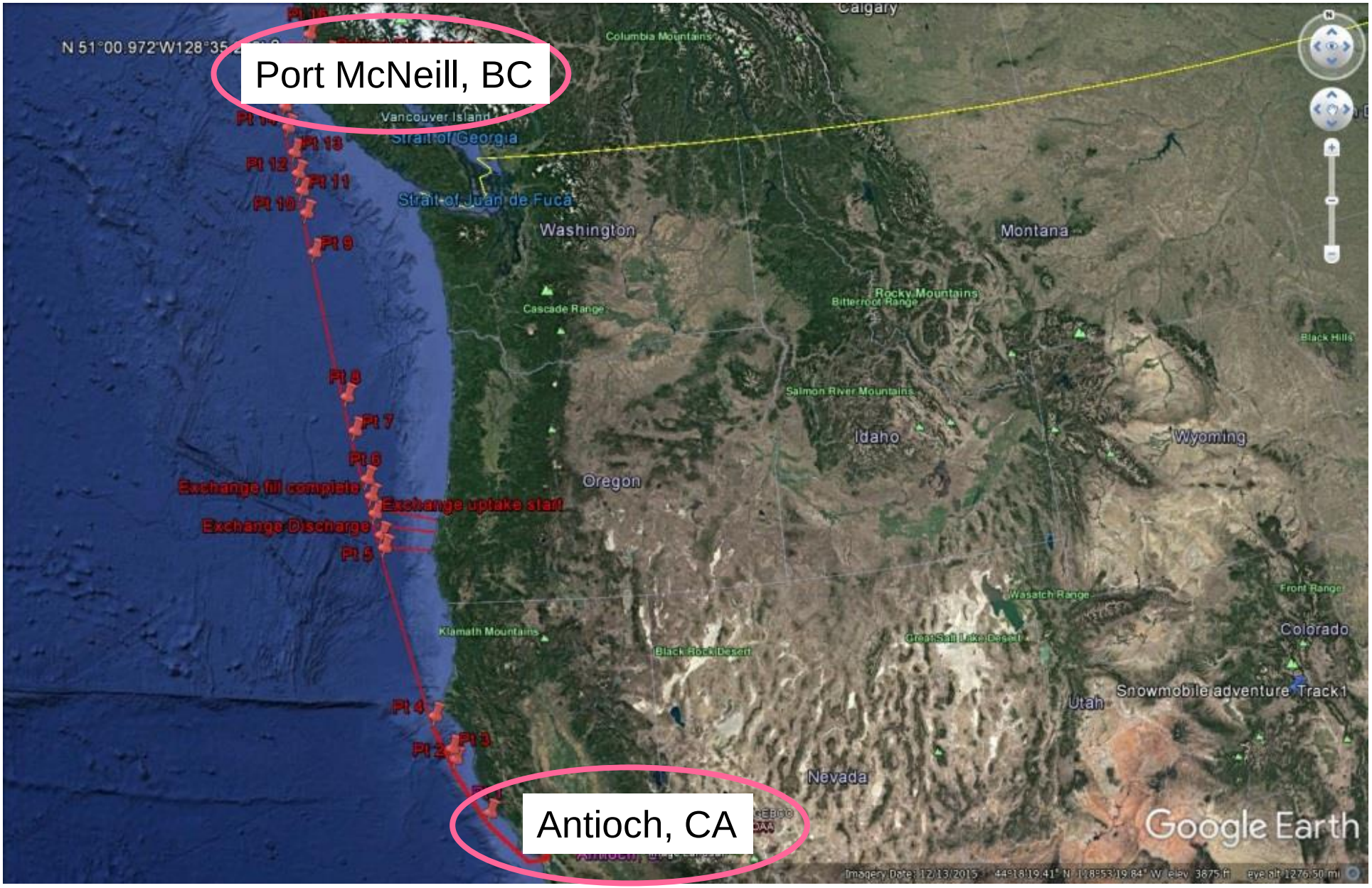


U.S. NAVAL RESEARCH LABORATORY

Hurricane Irma

U.S. NAVAL RESEARCH LABORATORY

Voyage 1—16-23 OCT 2016



Ballast Water Exchange

Ballast water exchange

- Exchange of ballast water in mid ocean
- Conducted either by emptying and refilling tanks or by overflowing tanks with a volume of water equivalent to three times the volume of the tanks

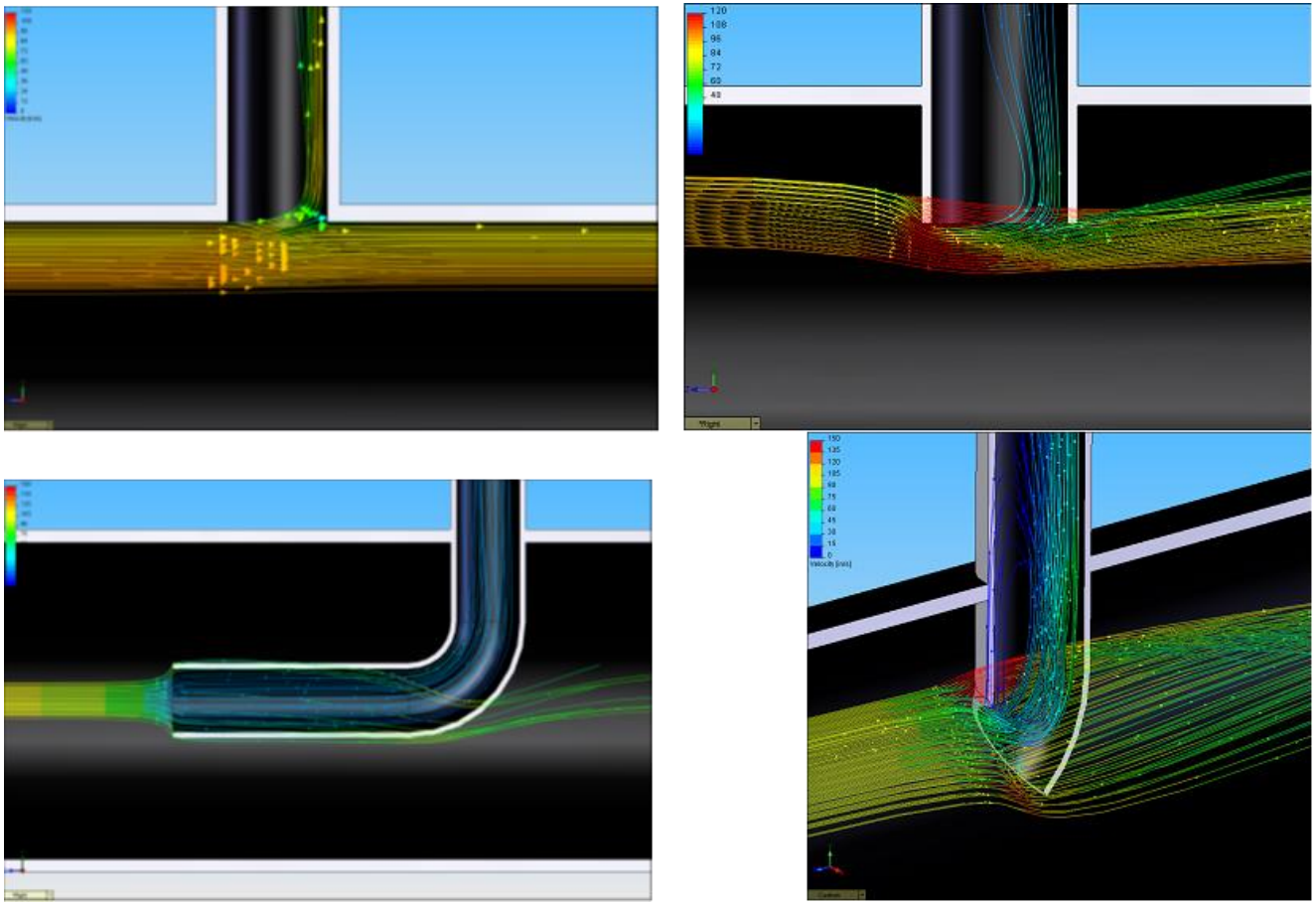
Ballast Water Exchange

Saltwater flushing

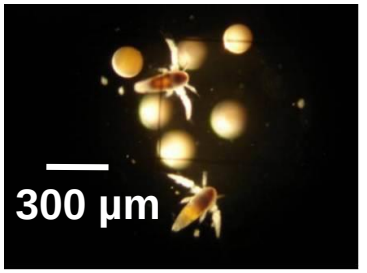
- Addition of off-shore water to empty ballast tanks; the mixing of the water with residual ballast water and sediment through the motion of the vessel; and the discharge of the mixed water until loss of suction
- Residual water remaining in the tank has either a salinity ≥ 30 parts per thousand or a salinity concentration equal to the ambient salinity of the location where the uptake of the added water took place.” (EPA 2013)

U.S. NAVAL RESEARCH LABORATORY

Methods—Sample Collection



Modeling studies
Empirical studies



Sample probe to collect representative samples (IMO Guidelines (G2), Wier et al. 2015)

U.S. NAVAL RESEARCH LABORATORY

Schedule

Voyage	Operation (Tank)	Location and Distance from Shore	Date/Time
1	Uptake	Antioch, CA N38°00.951’ W121°47.175’	17OCT Tank 6 Starboard 10:21 fill start—12:40 fill stop; 18OCT Tank 5 Starboard 12:35 fill start 14:41 fill stop
	Discharge as BWE	Open ocean N 42°54.024’ W 125°42.065’	21OCT Tank 5 Starboard 8:46 discharge start 10:06 discharge stop
	Uptake as BWE	Open ocean N43°14.491’ W125°50.633’	21OCT Tank 5 Starboard 10:33 uptake start 11:42 uptake stop
	Discharge	Port McNeill, British Columbia N 50°36'57.35" W 127°10'42.81"	23 OCT Tank 5 Starboard 13:00 discharge start; stop time not recorded Tank 6 Starboard 20:00 discharge start; stop time not recorded

U.S. NAVAL RESEARCH LABORATORY

Schedule

Voyage	Operation (Tank)	Location and Distance from Shore	Date and Time
2	Uptake	Antioch, CA N38°00.951' W121°47.175'	01 FEB 2017 Tank 6 SB 2:52 uptake start 4:15 uptake stop 01 FEB 2017 Tank 2 SB 6:03 uptake start 6:32 uptake sampling stop; Tank 2 uptake stop time not recorded
	BWE started	Open ocean N 44°06.2' W 126°06.7'	03 FEB 2017 Tank 2 SB No sampling occurred; researchers did not ride vessel. Exchange started at 8:30
	BWE completed	Open ocean N44°33.7 W126°17.2'	03 FEB 2017 Tank 2 SB No sampling occurred. Exchange completed on 3 FEB at 10:50
	Discharge	Port McNeill, British Columbia N 50°36'57.35" W 127°10'42.81"	05 FEB 2017 Tank 6 SB 12:10 discharge start 13:15 discharge stop 05 FEB 2017 Tank 2 SB 16:21 discharge start 17:00 discharge stop

U.S. NAVAL RESEARCH LABORATORY

Sample Flow Rates

Voyage Number	Operation Type	Average Ballast Flow Velocity (ft s^{-1})	Average p4SFS Flow Velocity (ft s^{-1})	Average Isokinetic Ratio
1	Uptake SB Tank 6 (UP-6)	7.3	3.1	1.5
	Uptake SB Tank 5 (UP-5)	7.9	2.5	1.8
	Uptake BWE Tank 5 (EX-UP 5)	8.0	3.3	1.6
2	Uptake SB Tank 6 (UP-6)	7.9	4.5	1.3
	Uptake SB Tank 5 (UP-2)	7.7	4.5	1.3

Flow rates observed on the ship's flow meter during uptake operations in Voyage 1 varied between 1222 and 1637 $m^3 h^{-1}$ (5380 and 7207 gpm, respectively

U.S. NAVAL RESEARCH LABORATORY

Sample Volumes

Sample Type	Sample Volume
Shipboard analysis of living organisms	
≥50 µm	3 m^3 (concentrated to 500 – 900 mL)
≥10 µm and <50 µm	5 – 10 L (concentrated to 50 mL)
Laboratory analysis of whole water	
Dissolved and suspended materials	1 L (whole water)
Algal MPN	250 mL (whole water)
Metagenomics of microplankton	500 mL (whole water)

U.S. NAVAL RESEARCH LABORATORY

Most Probable Number (MPN)

Volume (mL)	Number of Tubes
0.78	15
0.078	15
0.0078	15
0.00078	15

U.S. NAVAL RESEARCH LABORATORY

Water Quality Parameters

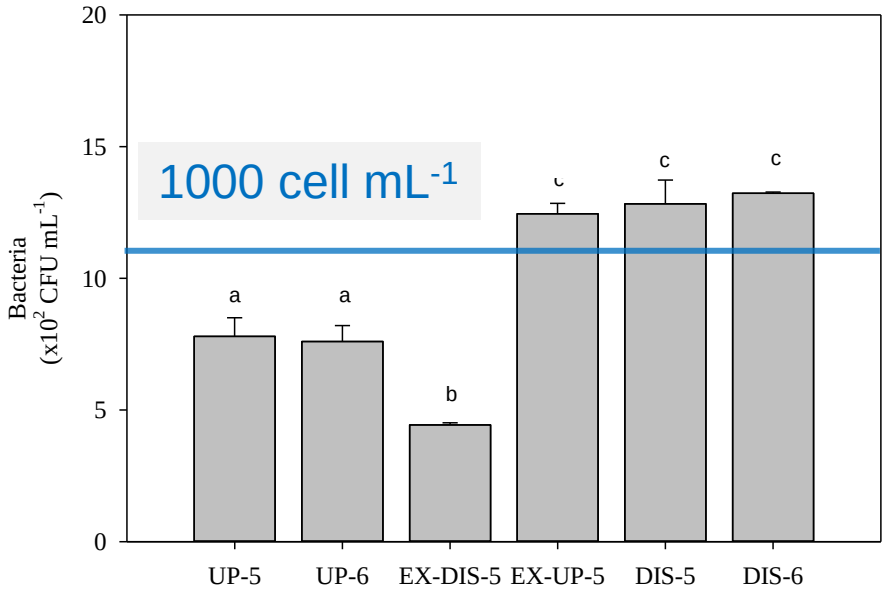
Voyage Number	Sample Type	TSS (SD) (mg L^{-1})	MM (SD) (mg L^{-1})	POM (SD) (mg L^{-1})	DOC (SD) (mg L^{-1})	*In Vivo* Chl *a* (µg L^{-1})
1	Uptake (UP-6)	14.26 (1.92)	10.78 (1.94)	3.48 (0.99)	2.14 (0.03)	0.601
	Uptake (UP-5)	10.85 (0.58)	5.67 (0.33)	5.19 (0.77)	2.13 (0.01)	0.836
	Exchange (EX-DIS-5)	18.93 (0.21)	15.89 (1.37)	3.04 (1.38)	2.04 (0.01)	0.045
	Exchange (EX-UP-5)	4.70 (0.98)	-0.22 (1.37)	3.89 (1.04)	0.94 (0.02)	0.088
	Discharge (DIS-6)	13.19 (3.83)	8.11 (3.47)	5.07 (0.49)	1.59 (0.004)*	0.051
	Discharge (DIS-5)	7.67 (2.27)	4.44 (1.97)	3.22 (0.44)	1.87 (0.06)*	0.030

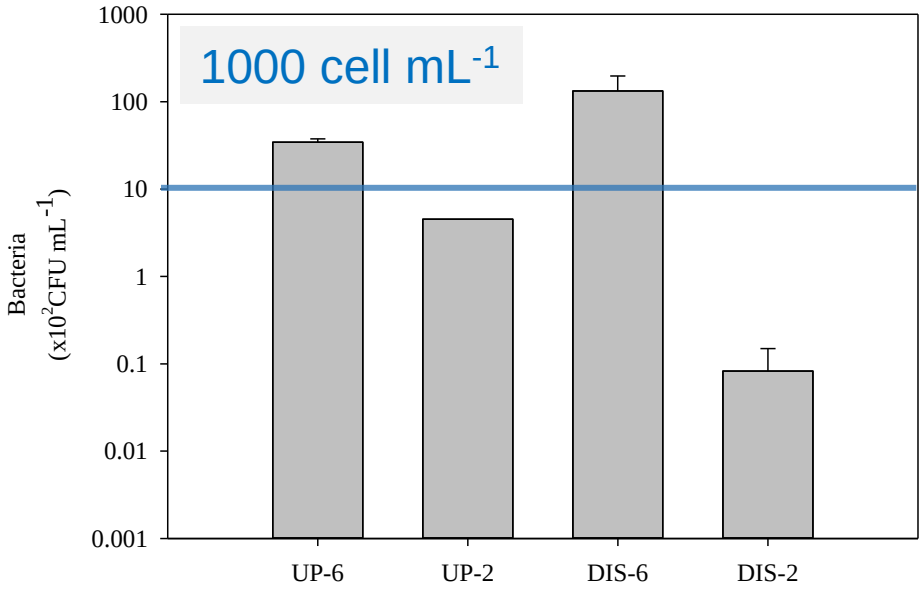
U.S. NAVAL RESEARCH LABORATORY

Water Quality Parameters

Voyage Number	Sample Type	TSS (SD) (mg L^{-1})	MM (SD) (mg L^{-1})	POM (SD) (mg L^{-1})	DOC (SD) (mg L^{-1})	*In Vivo* Chl *a* (µg L^{-1})
2	Uptake (UP-6)	18.67 (0.0)	12.67 (1.45)	6.00 (1.45)	4.34 (0.05)	0.924 (0.150)
	Uptake (UP-2)	23.33 (0.88)	18.67 (1.45)	4.67 (0.58)	4.10 (0.10)	0.906 (0.025)
	Discharge (DIS-6)	16.78 (1.17)	10.67 (0.33)	6.11 (0.84)	4.45 (0.25)	0**
	Discharge (DIS-2)	7.57 (2.91)	1.00 (2.03)	6.67 (0.88)	3.51 (0.03)	0**

Results—Bacteria





n = 3 subsamples

BWMS Use and Feedback

- The crew was well aware of how to use the BWMS; they use it every time they ballast

- During the first voyage, both the port and starboard BWMS were observed and functioning

BWMS Use and Feedback

- Voyage 1
  - Seawater supply pump to Starboard Tank 5 did not prime on 18 OCT (salinity was 1.8 psu), likely because the inlet was above the waterline—when the trim was adjusted, the pump was primed
  - A note was included on the BWMS control screen to ensure the chemicals used in the TRO monitors are changed every 3 months

U.S. NAVAL RESEARCH LABORATORY

BWMS Use and Feedback

- During Voyage 1, a technician from the BWMS manufacturer was aboard:
  - Repaired a controller interface panel in the engine control room (damaged due to water dripping on it); the BWMS was functional, but this operator interface terminal was not visible
  - Tried to fix a leak on the SB side BWMS filter housing (where the cleaning nozzle mechanism is located) that did not affect the operation of the BWMS; he did not have the proper part

BWMS Use and Feedback

- During Voyage 1, a technician from the BWMS manufacturer was aboard:
  - Fixed minor alarms that included a valve indicating an incorrect position: the First Officer determined that the valve was open, but the position indication was not communicating with the operator interface terminal; the BWMS technician repaired it

U.S. NAVAL RESEARCH LABORATORY

Accomplishments and Next Steps

- Signed memorandum of agreement (11 MAY 2015)
- Completed first ship visit (19 JUL 2015)
- Constructed filter skid (16 DEC 2016)
- Installed filter skid (15-17 AUG 2016)
- Conducted two shipboard trials (OCT 2016, MAY 2017)
  - Results of Trials 1 and 2 showed inconsistent results in BWT vs. BWE + BWT
  - NRL Letter Report issued to EPA on 01 MAR 2017
- Conduct one more shipboard trial
  - Summarize results of all three trials in a manuscript for publication in a peer-reviewed journal
- Complete other research efforts