Ref No. [UMCES[CBL 11-020

Proof-of-Concept

Demonstration of Membrane Filters Efficacy on Ballast Water

October 2011

Maritime Environmental Resource Center
c/o Chesapeake Biological Laboratory
University of Maryland Center for Environmental Science
PO Box 38, Solomons, Maryland 20688, USA

Notice

This evaluation was conducted under specific, predetermined, agreed-upon protocols, criteria, and quality assurance procedures to assess the treatment system's performance.

MERC does not label or list technologies as acceptable or unacceptable but will present the results in an objective way.

MERC and the MERC Advisory Board do not provide certification for technologies, or certify that a technology will always operate as demonstrated. Additionally, no expressed or implied guarantee is provided as to the performance of the technology, or that a technology will always operate at the levels verified. MERC does guarantee the levels verified during the evaluation under the conditions, circumstances, and operations encountered as fully independent and credible.

This report has been reviewed by members of the MERC Advisory Board and provided to MERC funding agencies prior to public release. Mention of trade names or commercial products does not constitute endorsement or recommendation by MERC.

Questions and comments should be directed to Dr. Mario Tamburri, tamburri@umces.edu.

Table of Contents

1.0. MERC Background and Objectives

The Maritime Environmental Resource Center (MERC) is a State of Maryland initiative that provides test facilities, information, and decision tools to address key environmental issues facing the international maritime industry. The Center's primary focus is to evaluate the mechanical and biological efficacy, associated costs, and logistical aspects of ballast water treatment systems and the economic impacts of ballast water regulations and management approaches. A full description of MERC's structure, products, and services can be found at www.maritime-enviro.org.

To address the need for effective, safe, and reliable ballast water treatment systems to prevent the introduction of non-native species, MERC has developed as a partnership between the Maryland Port Administration (MPA), Chesapeake Biological Laboratory/ University of Maryland Center for Environmental Science (CBL/UMCES), U.S. Maritime Administration (MARAD), Smithsonian Environmental Research Center (SERC), and University of Maryland (UMD) to provide independent performance testing and to help facilitate the transition of new treatment technologies to shipboard implementation and operations.

This evaluation of filter performance was a proof-of-concept demonstration of the potential of microfiltration membranes to remove ballast water organisms. Detailed protocols and formal MERC Test Plan can be downloaded at www.maritime-enviro.org.

2.0. Introduction to Technology

This proof of concept focused on 0.1 µm, 20 inch, cartridge membrane filters that incorporate a proprietary high-flow hydrophilic PTFE (polytetrafluoroethylene) or asymmetric polysulfone filtration media. These membrane filters have been designed for filtration of aqueous and high-surface-tension liquids, especially where outgassing or bubbles are a concern. Current applications include high-throughput filling, packaging, and recirculation systems. For ballast water applications, these filters may be used as a final "polishing" step prior to discharging ballast water from a vessel that has already been treated by a conventional ballast water management system.

3.0 Test Protocol Summary

For all trials, the filter developer provided a test skid mounted with three different pre filters: 20-µm, 10- µm, and 5-µm) and two test filters: 20-inch 0.1 µm PTFE cartridge membrane filters, identified as Filter #1 and Filter #5. Each of the six trials included one of the test filters plus, zero to three pre filters (See trial composition table below).

All trials were conducted during January 2011. The water used for these six trials was continuously pumped sea-to-sea, from Baltimore Harbor (Patapsco River, MD, in the mesohaline region of the Chesapeake Bay) into the US Maritime Administration vessel *MV Cape Washington* via the sea chest.

To simulate water that would initially be pre-filtered by a commercially available ballast water filtration system, MERC provided the test filter skid with 35-µm filtered challenge water (labeled below as "challenge water" or "CW"). MERC collected both challenge water and post-filter samples at the beginning and end of each trial. When applicable, a midpoint sample was also collected. The timing of sampling and number of samples depended upon the filter system

pressure. Midpoint sampling occurred at about 15 psid and endpoint sample collection occurred just prior to 30 psid.

Water samples were analyzed for total suspended solids (TSS), particulate carbon (PC), dissolved organic carbon (DOC), particle size distribution (PSD), phytoplankton (10 - 50 µm and 5 - 10 µm), and total bacteria. The filter developer provided pre weighed and numbered 0.4 µm membrane filter pads for the TSS sample collection. Using a specialized filtration method, samples were collected and analyzed for TSS collected after the 0.1-µm test filters and after the 10 µm and 5 µm pre filters.

Using standard IMO G8 testing approaches for organisms > 50 µm, samples of unfiltered, ambient water were collected and analyzed for zooplankton communities (see Appendix A for results). This data provides insight on the zooplankton challenge conditions in ambient water.

General Test Parameters

1. Flow rate – consistent 10 gpm.
2. Trial duration – 5 hrs or until the pressure drop across the 0.1 µm filter reached 30 psid.
3. Trial volume – 3,000 gallons or total volume filtered before reaching 30 psid pressure drop at the 0.1 µm filter.
4. MERC delivered 35-µm filtered challenge water to the test filter system.

Test filter skid composition for each trial

	Trial 1	**Trial 2**	**Trial 3**	**Trial 4**	**Trial 5**	**Trial 6**
20 µm Pre Filter			X	X	X	X
10 µm Pre Filter					X	X
5 µm Pre Filter					X	X
0.1 µm Test Filter #1	X		X		X	
0.1 µm Test Filter #5		X		X		X

4.0. Trial Results

4.1. Water Quality - Physical Parameters

The parameters below were measured in the challenge water using a YSI 556 multi-parameter instrument.

For comments, see appendix A.

Trial Number	**Date**	**Avg. Temp (C°)**	**Avg. Salinity**	**Avg. DO (mg/l)**	**Avg. pH**
1	19-Jan-11	4.7	13.6	10.6	7.7
2	19-Jan-11	5.5	13.6	8.7	7.6
3	13-Jan-11	6.6	13.5	7.0	7.6
4	13-Jan-11	7.2	13.3	7.0	7.6
5	19-Jan-11	6.8	13.6	7.6	7.5
6	20-Jan-11	4.9	14.3	10.5	7.5

4.2. Water Quality - Total Suspended Solids
(CW = challenge Water)

Trial # 1 – Test Filter #1, 0.1 µm (no pre filters). 19 Jan 2011

			TSS (mg/L)		
Time point	**Sample ID**	**Sample Time**	**Avg**	**StDev**	**Notes**
T-0 Initial	CW	11:17	15.4	0.3	
T-1 Mid	No sample		N/A	N/A	
T-2 Final	CW	11:32	13.6	0.3	
Time-series	Post 0.1µm (#1)	11:20 - 11:57	0.17	N/A	Long term TSS test

Trial # 2 – Test Filter #5, 0.1 µm (no pre filters). 19 Jan 2011

			TSS (mg/L)		
Time point	**Sample ID**	**Sample Time**	**Avg**	**StDev**	**Notes**
T-0 Initial	CW	12:15	13.8	1.4	
T-1 Mid	No sample		N/A	N/A	
T-2 Final	CW	12:42	9.4	0.6	
Time-series	Post 0.1µm(#5)	ND	0.20	ND	Long term TSS test

Trial # 3 - Pre filter 20µm > Test Filter #1, 0.1µm. 13 Jan 2011

			TSS (mg/L)		
Time point	**Sample ID**	**Sample Time**	**Avg**	**StDev**	**Notes**
T-0 Initial	CW	10:30	22.2	0.8	
	Post 20 µm		3.7	0.6	
T-1 Mid	CW	11:05	25.9	1.6	0.1 filter pressure = 15 psid
	Post 20 µm		8.9	0.8	
T-2 Final	CW	12:00	15.5	0.4	0.1 filter pressure = approx. 30 psid
	Post 20 µm		6.6	1.2	
Time-series	Post 0.1µm (#1)	10:40 - 12:45	0.17	N/A	Long term TSS test

Trial # 4 - Pre filter 20µm > Test Filter #5, 0.1µm. 13 Jan 2011

			TSS (mg/L)		
Time point	**Sample ID**	**Sample Time**	**Avg**	**StDev**	**Notes**
T-0 Initial	CW	13:05	13.4	0.2	
	Post 20 µm		9.4	0.4	
T-1 Mid	CW	13:35	12.5	0.4	0.1 filter pressure = 15 psid
	Post 20 µm		11.1	1.2	
T-2 Final	CW	13:50	10.4	0.9	0.1 filter pressure = approx. 30 psid
	Post 20 µm		8.3	1.2	
Time-series	Post 0.1µm(#5)	13:17 - 14:14	0.10	N/A	Long term TSS test

Trial # 5 - Pre filter 20µm > pre filter 10µm > pre filter 5µm > Test Filter #1, 0.1µm.
19 Jan 2011

			TSS (mg/L)		
Time point	**Sample ID**	**Sample Time**	**Avg**	**StDev**	**Notes**
T-0 Initial	CW	9:05	25.5	1.8	
	Post 20 µm		6.6	0.0	
T-1 Mid	CW	9:35	23.3	0.4	0.1 filter pressure = 15 psid
	Post 20 µm		12.5	0.4	
T-2 Final	CW	9:52	22.1	1.0	0.1 filter pressure = approx. 30 psid
	Post 20 µm		12.5	1.0	
Time-series	Post 10 µm	9:16 - 9:45	2.90	N/A	
	Post 5µm	9:10 - 10:10	0.49	N/A	
	Post 0.1µm(#1)	9:13 - 10:10	0.19	N/A	Long term TSS test

Trial # 6 - Pre filter 20µm > pre filter 10µm > pre filter 5µm > Test Filter #5, 0.1µm.
20 Jan 2011

			TSS (mg/L)		
Time point	**Sample ID**	**Sample Time**	**Avg**	**StDev**	**Notes**
T-0 Initial	CW	9:08	13.7	0.1	
	Post 20 µm		5.8	0.8	
T-1 Mid	CW	9:54	13.2	1.4	0.1 filter pressure = 15 psid
	Post 20 µm		5.6	0.0	
T-2 Final	CW	10:34	9.2	0.8	0.1 filter pressure = approx. 30 psid
	Post 20 µm		6.3	0.7	
Time-series	Post 10 µm	9:10 - 9:45	4.89	N/A	
	Post 5 µm	9:10 - 10:50	0.23	N/A	Changed out 5 µm filter twice
	Post 0.1µm(#5)	9:13 - 10:50	0.16	N/A	Long term TSS test

4.3. Particle Size Distribution (PSD)

Water samples analyzed for particle size were drawn from challenge water and after each filter tested at each time point. Analysis was conducted at the Occoquan Watershed Monitoring Laboratory in Manassas, Virginia.

The EPA ASTM D4464 laser method was used to analyze these samples. While particles were detected and sized in the challenge water samples, particles were too dilute in the post 20-, 10- 5- or 0.1 µm samples (below detection limits) to be characterized.

For all samples analyzed after the 20 µm, 10 µm, 5 µm and 0.1 µm filters there was no detectable data due to low particle concentrations or counts. Thus, the data below list only the challenge conditions for the skid/filtration system. The average particle size in the challenge water ranged from 6.009 µm to 14.493 µm.

Trial # 1 – Test Filter #1, 0.1 µm (no pre filters). 19 Jan 2011

Challenge Water		**PSD (µm)**	
Time Point	**Sample Time**	**Avg**	**StDev**
LCS @ 1 µm – initial		1.003	
T-0 Initial	11:17	6.124	0.033
T-1 Mid – no sample		N/A	N/A
T-2 Final	11:32	6.141	0.062

Trial # 2 – Test Filter #5, 0.1 µm (no pre filters)**.** 19 Jan 2011

Challenge Water		**PSD (µm)**	
Time Point	**Sample Time**	**Avg**	**StDev**
T-0 Initial	12:15	6.204	0.018
T-1 Mid – no sample		N/A	N/A
T-2 Final	12:42	BDL	BDL
LCS @ 1 µm – final		1.003	

Trial # 3 - Pre filter 20 µm > Test Filter #1, 0.1 µm. 13 Jan 2011

Challenge Water		**PSD (µm)**	
Time Point	**Sample Time**	**Avg**	**StDev**
LCS @ 1 µm – initial		1.005	
T-0 Initial	10:30	12.893	1.060
T-1 Mid	11:05	14.493	0.884
T-2 Final	12:00	6.091	0.067
LCS @ 1 µm – final		1.002	

Trial # 4 - Pre filter 20 µm > Test Filter #5, 0.1 µm. 13 Jan 2011

Challenge Water		**PSD (µm)**	
Time Point	**Sample Time**	**Avg**	**StDev**
LCS @ 1 µm – initial		1.023	
T-0 Initial	13:05	6.060	0.045
T-1 Mid	13:40	6.009	0.030
T-2 Final	13:50	6.070	0.007
LCS @ 1 µm – final		1.025	

Trial # 5 - Pre filter 20µm > pre filter 10µm > pre filter 5µm > Test Filter #1, 0.1µm.
19 Jan 2011

Challenge Water		**PSD (µm)**	
Time Point	**Sample Time**	**Avg**	**StDev**
LCS @ 1 µm – initial		1.005	
T-0 Initial	9:05	13.417	0.145
T-1 Mid	9:35	12.863	0.225
T-2 Final	9:52	9.399	3.031
LCS @ 1 µm – final		0.996	

Trial # 6 - Pre filter 20 µm > pre filter 10 µm > pre filter 5 µm > Test Filter #5, 0.1 µm.
20 Jan 2011

Challenge Water		**PSD (µm)**	
Time Point	**Sample Time**	**Avg**	**StDev**
LCS @ 1 µm – initial		0.908	
T-0 Initial	9:08	6.021	0.065
T-1 Mid	9:54	6.134	0.062
T-2 Final	10:34	BDL	BDL
LCS @ 1 µm – final		0.996	

LCS = Laboratory control standard at 1.0 µm, from Duke Scientific
BDL = Below detection limit
T-0 samples were taken as soon as possible after the test filter system stabilized, T-1 samples were taken at about 15 psid, T-2 samples were taken at about 30 psid.

4.4. Total Organic Carbon (TOC)

In summary, particulate carbon (PC) concentrations ranged from 1.1 to 2.3 mg/l, dissolved organic carbon (DOC) concentrations ranged from 2.9 to 5.7 mg/l, and total organic carbon (TOC) challenge concentrations ranged from to 4.2 to 5.2 mg/l. Method detection limits for PC = 0.0633 mg/L and DOC = 0.24 mg/L.

Trial # 1 – Test Filter #1, 0.1 µm (no pre filters). 19 Jan 2011

			PC (mg/L)	DOC (mg/L)	TOC (mg/L)
Time Point	**Sample ID**	**Sample Time**	**Avg**	**Avg**	**(PC + DOC)**
T-0 Initial	CW	11:15	1.54	3.09	4.63
T-1 Mid	No sample		N/A	N/A	N/A
T-2 Final	CW	11:32	1.47	3.12	4.59

Trial # 2 – Test Filter #5, 0.1 µm (no pre filters). 19 Jan 2011

			PC (mg/L)	DOC (mg/L)	TOC (mg/L)
Time Point	**Sample ID**	**Sample Time**	**Avg**	**Avg**	**(PC + DOC)**
T-0 Initial	CW	12:15	1.58	3.15	4.73
T-1 Mid	No sample		N/A	N/A	N/A
T-2 Final	CW	12:42	1.12	3.18	4.30

Trial # 3 - Pre filter 20 µm > Test Filter #1, 0.1 µm. 13 Jan 2011

			PC (mg/L)	DOC (mg/L)	TOC (mg/L)
Time Point	**Sample ID**	**Sample Time**	**Avg**	**Avg**	**(PC + DOC)**
T-0 Initial	CW	10:30	2.26	3.04	5.30
T-1 Mid	CW	11:05	2.55	3.11	5.66
T-2 Final	CW	12:00	1.50	3.07	4.57

Trial # 4 - Pre filter 20 µm > Test Filter #5, 0.1 µm. 13 Jan 2011

			PC (mg/L)	DOC (mg/L)	TOC (mg/L)
Time Point	**Sample ID**	**Sample Time**	**Avg**	**Avg**	**(PC + DOC)**
T-0 Initial	CW	13:05	1.37	2.94	4.31
T-1 Mid	CW	13:40	1.38	2.97	4.35
T-2 Final	CW	13:50	1.14	2.95	4.09

Trial # 5 - Pre filter 20µm > pre filter 10µm > pre filter 5µm > Test Filter #1, 0.1µm.
19 Jan 2011

			PC (mg/L)	DOC (mg/L)	TOC (mg/L)
Time Point	**Sample ID**	**Sample Time**	**Avg**	**Avg**	**(PC + DOC)**
T-0 Initial	CW	9:05	2.36	3.23	5.59
T-1 Mid	CW	9:35	2.10	3.20	5.30
T-2 Final	CW	9:52	1.81	3.06	4.87

Trial # 6 - Pre filter 20µm > pre filter 10µm > pre filter 5µm > Filter #5, 0.1µm, 20 Jan 2011

			PC (mg/L)	DOC (mg/L)	TOC (mg/L)
Time Point	**Sample ID**	**Sample Time**	**Avg**	**Avg**	**(PC + DOC)**
T-0 Initial	CW	9:08	2.35	3.23	5.57
T-1 Mid	CW	9:54	2.07	3.25	5.32
T-2 Final	CW	10:34	1.79	3.07	4.86

4.5. Filter Life

In summary, both the membrane filters (PTFE and asymmetric polysulphone) were effective for extended periods when water was pre-filtered at 20 µm. However, pre-filtration below 20 µm had no detectable effect on filter life. In general, the asymmetric polysulphone filter membrane lasted longer than the PTFE filter membrane in all trials but changes in ambient water quality from trial to trial also influence filtration life.

4.6. Phytoplankton 10 - 50 µm and 5 - 10 µm

Overall phytoplankton conditions and densities were similar between trials. Cell density was very high and the tests occurred during a winter bloom of both *Skeletonema* and *Heterocapsa rotundatum*. Chains of *Skeletonema* were quite long, and some were noted to be in the reproductive phase by presence of auxospores. *H. rotundatum* was also experiencing a winter bloom noted by high density in the samples and distinctive color and odor of the sample water.

Dominant species	**Type**	**General Size**
Skeletonema costata	Diatom (chain forming)	Individual cells 9-10 µm but forms long chains 100+ µm in length
Heterocapsa rotundatum	Dinoflagellate	~5-6 µm
Other noted species		
Prorocentrum minimum	Dinoflagellate	22 x 15 µm
Heterocapsa triquetra	Dinoflagellate	24 x 16 µm
Ceratulina pelagica	Diatom (chain forming)	100 x 24 µm (can form larger chains)
Gyrodinium estruariale	Dinoflagellate	15 x 11 µm
Thalassiosira sp.	Diatom (chain forming)	Individual cells 8-12 µm
Amphora sp.	Diatom	8 x 30 µm
Leptocylindrus minimum	Diatom (chain forming)	2 x 30 µm (very long and thin)
Navicula sp.	Diatom	Varies 64 µm
Nitzschia sp.	Diatom (chain forming)	Varies 50 to 100+ µm
Chaetoceros sp.	Diatom (chain forming)	Individual cells 7-15 µm
Thalassionema sp.	Diatom (chain forming)	3 x 40 µm forms star patterns
Misc. Tinntinnids		
Polychaete larvae (Zooplankton)		

Trial # 1 – Test Filter #1, 0.1 µm (no pre filters). 19 Jan 2011
(CW = challenge water)

Time Point	Total Phyto 10-50 µm (#/ml)		Total Phyto 5-10 µm (#/ml)	
	CW	**Post 0.1 µm**	**CW**	**Post 0.1 µm**
T-0 Initial	12,832	0	19,121	0
T-1 Mid	No sample	N/A	N/A	N/A
T-2 Final	12,241	0	19,212	0

No cells detected at either time point after the 0.1 µm filter.

Trial # 2 – Test Filter #5, 0.1 µm (no pre filters). 19 Jan 2011

Time Point	Total Phyto 10-50 µm (#/ml)		Total Phyto 5-10 µm (#/ml)	
	CW	**Post 0.1 µm**	**CW**	**Post 0.1 µm**
T-0 Initial	15,839	0	22,762	2.5
T-1 Mid	No sample	N/A	N/A	N/A
T-2 Final	13,309	0	13,657	0.5

Cells after 0.1µm filtration were an unknown thin pennate diatom and some small chains of *S. costata*

Trial # 3 - Pre filter 20 µm > Test Filter #1, 0.1 µm. 13 Jan 2011

Time Point	Total Phyto 10-50 µm (#/ml)		Total Phyto 5-10 µm (#/ml)	
	CW	**Post 0.1 µm**	**CW**	**Post 0.1 µm**
T-0 Initial	8,454	0	12,990	24
T-1 Mid	11,332	0	12,292	0
T-2 Final	7,931	0	9,287	0

Cells after 0.1µm filtration included *L.minimum.*

Trial # 4 - Pre filter 20 µm > Test Filter #5, 0.1 µm. 13 Jan 2011

Time Point	Total Phyto 10-50 µm (#/ml)		Total Phyto 5-10 µm (#/ml)	
	CW	**Post 0.1 µm**	**CW**	**Post 0.1 µm**
T-0 Initial	8,507	0	11,745	50
T-1 Mid	8,507	0	8,832	49
T-2 Final	8,825	0	13,506	178

The majority of cells after 0.1µm filtration were *H. rotundatum, with* a few *S. costata* cells and unknown thin pennate diatoms.

19 Jan 2011

Time Point	Total Phyto 10-50 µm (#/ml) CW	Post 0.1 µm	Total Phyto 5-10 µm (#/ml) CW	Post 0.1 µm
T-0 Initial	11,840	0	14,871	4.5
T-1 Mid	13,006	0	16,753	0
T-2 Final	14,726	0	22,156	0

Cells after 0.1µm filtration included *H. rotundatum* and *S. costata.*

Trial # 6 - Pre filter 20µm > pre filter 10µm > pre filter 5µm > Test Filter #5, 0.1µm.
20 Jan 2011

Time Point	Total Phyto 10-50 µm (#/ml) CW	Post 0.1 µm	Total Phyto 5-10 µm (#/ml) CW	Post 0.1 µm
T-0 Initial	21,710	0	11,728	0
T-1 Mid	16,120	0	10,597	0
T-2 Final	21,414	0	13,903	0

No cells detected at either time point after the 0.1 µm filter.

4.7. Microbial Community

Samples for bacteria (*Vibrio, E. coli*, *Enterococci* and heterotrophic bacteria) were taken just before entering the filter system (after the 35-µm net) and after the last filter (0.1 µm) at the three time points.

Trial # 1 – Test Filter #1, 0.1 µm (no pre filters). 19 Jan 2011

Time Point	Heterotrophic Bacteria (CFU / 1 ml) CW	Post 0.1 µm	E. coli (MPN / 100 ml) CW	Post 0.1 µm
T-0 Initial	26,300	5	12.1	0
T-1 Mid	N/A	N/A	N/A	N/A
T-2 Final	20,400	0	11.1	0
Mean	23,350	2.5	11.6	0

After the 0.1 µm test filter, a 99.98% reduction (3.8 log) in heterotrophic bacteria and a 100% reduction in *E. coli* were found.

Trial # 2 – Test Filter #5, 0.1 µm (no pre filters). 19 Jan 2011

	Heterotrophic Bacteria (CFU / 1 ml)		E. coli (MPN / 100 ml)	
Time Point	**CW**	**Post 0.1 µm**	**CW**	**Post 0.1 µm**
T-0 Initial	15,300	0	14.3	0
T-1 Mid	N/A	N/A	N/A	N/A
T-2 Final	11,500	0	7	0
Mean	13,400	0	10.7	0

After the 0.1 µm test filter, a 100% reduction in heterotrophic bacteria and a100% reduction in *E. coli* were found.

Trial # 3 - Pre filter 20 µm > Test Filter #1, 0.1 µm. 13 Jan 2011

	Heterotrophic Bacteria (CFU / 1 ml)		E. coli (MPN / 100 ml)	
Time Point	**CW**	**Post 0.1 µm**	**CW**	**Post 0.1 µm**
T-0 Initial	16,500	30	62	0
T-1 Mid	55,500	15	66	0
T-2 Final	17,500	5	48	0
Mean	29,833	16.7	59	0

After the 0.1 µm test filter, a 99.89% reduction (3.3 log) in heterotrophic bacteria and 100% reduction in *E. coli* were found.

Trial # 4 - Pre filter 20 µm > Test Filter #5, 0.1 µm. 13 Jan 2011

	Heterotrophic Bacteria (CFU / 1 ml)		E. coli (MPN / 100 ml)	
Time Point	**CW**	**Post 0.1 µm**	**CW**	**Post 0.1 µm**
T-0 Initial	15,000	150	41	0
T-1 Mid	9,500	150	23	0
T-2 Final	18,000	120	19	0
Mean	14,167	140	28	0

After the 0.1 µm test filter, a 98.24% reduction (2 log) in heterotrophic bacteria and a 100% reduction in *E. coli* were found.

Trial # 5 - Pre filter 20µm > pre filter 10µm > pre filter 5µm > Test Filter #1, 0.1µm.
19 Jan 2011

	Heterotrophic Bacteria (CFU / 1 ml)		E. coli (MPN / 100 ml)	
Time Point	**CW**	**Post 0.1 µm**	**CW**	**Post 0.1 µm**
T-0 Initial	14,450	5	21	0
T-1 Mid	17,700	0	15	0
T-2 Final	15,350	0	12	0
Mean	15,833	1.7	16	0

After the 0.1 µm test filter, a 99.99% reduction (4 log) in heterotrophic bacteria and a 100% reduction in *E. coli* counts were found.

Trial # 6 - Pre filter 20µm > pre filter 10µm > pre filter 5µm > Test Filter #5, 0.1µm.
20 Jan 2011

	Heterotrophic Bacteria (CFU / 1 ml)		E. coli (MPN / 100 ml)	
Time Point	**CW**	**Post 0.1 µm**	**CW**	**Post 0.1 µm**
T-0 Initial	16,050	0	12	0
T-1 Mid	17,250	10	16	0
T-2 Final	17,850	0	12	0
Mean	17,050	3.3	13	0

After the 0.1 µm test filter, a 99.98% reduction (3.7 log) in heterotrophic bacteria and a 100% reduction in *E. coli* were found.

5.0 Acknowledgments

The MERC Testing Team included J. Barnes, B. Haley, A. Huq, R. Kanzleiter, T. Mullady, G. Ruiz, G. Smith, D. Sparks, M. Tamburri, E. Taviani, M. Wilkinson, and K. Ziombra. We wish thank the crew of the *MV Cape Washington* who provided critical input and support on all aspects of these trials, and the Maryland Port Administration and U.S. Maritime Administration for funding and supporting this ballast water treatment evaluation.

Appendix A: Additional Comments and Interpretation

A.1. Zooplankton > 50 µm

Data provided by MERC

This data is provided solely to frame the overall zooplankton community on testing days. Since the test filter system challenge water was always pre filtered (35 µm, 50-µm diagonal measure pore-size), the greater-than-50-µm size class was removed; thus, is not considered a challenge condition to the test filter system.

		Size Class 1	**Size Class 2**	**Total**
		>50µm to <250µm	**>250-µm**	**>50-µm**
Date	**Test #**	(#/m3)	(#/m3)	(#/m3)
13-Jan-11	Tests 3, 4	42,250	8,188	50,438
19-Jan-11	Tests 1, 2, 5	99,000	10,750	109,750
20-Jan-11	Tests 6	155,800	11,750	167,550

Size-class distinctions or measures are determined by considering the greatest available measure among the x, y, and z body axis, exclusive of appendages such as legs, swimming appendages, sensory apparatus, or other fine appendages. Most of the smaller organisms were rotifers or nauplii of copepods. The larger organisms were calanoid copepods.