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TECHNICAL REPORT

LAND-BASED PERFORMANCE EVALUATION IN AMBIENT AND AUGMENTED DULUTH-SUPERIOR HARBOR WATER OF EIGHT COMMERCIALLY AVAILABLE BALLAST WATER TREATMENT SYSTEM FILTER UNITS

December 2, 2014

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Technical Report: Land-Based Performance Evaluation in Ambient and Augmented Duluth-Superior Harbor Water of Eight Commercially Available Ballast Water Treatment System Filter Units

December 2, 2014

Approved for Release by:

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LIST OF ACRONYMS

%D: Percent Difference
%T: Percent Transmittance
***μ*M:** Micrometer
BWMS: Ballast Water Management System
BWT: Ballast Water Treatment
CFD: Computational Fluid Dynamics
CMFDA: 5-Chloromethylfluorescein Diacetate
COC: Chain of Custody
DI: Deionized
DSH: Duluth Superior Harbor
ETV: Environmental Technology Verification
FDA: Fluorescein Diacetate
GSI: Great Ships Initiative
HMI: Human Machine Interface
ID: Internal Diameter
IMO: International Maritime Organization
LAN: Local Area Network
LSRI: Lake Superior Research Institute
MARAD: United State Maritime Administration
NEMWI: Northeast Midwest Institute
NRRI: Natural Resources Research Institute
PI: Principal Investigator
PLC: Programmable Logic Controller
POM: Particulate Organic Matter
PSC: Percent Similarity
QA: Quality Assurance
QA/QC: Quality Assurance/Quality Control
QAPP: Quality Assurance Project Plan
QC: Quality Control
RDTE: Research, Development, Testing, and Evaluation
RPD: Relative Percent Difference
SD: Secure Digital
SOP: Standard Operating Procedure
TQAP: Test/Quality Assurance Plan
TSS: Total Suspended Solids
USCG: United States Coast Guard
USEPA: United States Environmental Protection Agency
UV: Ultraviolet
UWS: University of Wisconsin-Superior
YSI: Yellow Springs Instruments

EXECUTIVE SUMMARY

This Great Ships Initiative (GSI) technical report describes outcomes from controlled freshwater operational and biological evaluations of the performance of eight commercially available filter systems (FSs). Tests took place at the GSI Land-Based Research, Development, Testing and Evaluation (RDTE) Facility located in the Duluth-Superior Harbor (DSH) of Lake Superior (Superior, Wisconsin, USA) during September and October of 2013. Test objectives were:

- To provide reliable information on FS operational and biological performance in freshwater under controlled conditions, and to support limited performance comparisons across FSs;
- To explore any trade-offs between operational and biological performance endpoints; and
- To support FS, and thus ballast water management system (BWMS), freshwater performance improvements.

The eight commercially available FS units GSI tested represented a range of filtering technologies and nominal pore sizes. Tests took place over a five week period, with each FS unit subjected to four test cycles of 3-4 hours each, at a rate of one test cycle per day. GSI tested FSs sequentially in test "rounds", involving, to the greatest extent possible, two FSs at a time. The paired FS unit test cycles were scheduled on alternating mornings and afternoons of consecutive days to provide for the greatest similarity and consistency of biological, physical and chemical intake conditions possible across FS evaluations within each round. Each test cycle duration was based on a target volume of water processed. The target volume for each FS was equivalent to three times the design flow rate (designated by the developer) per one hour of operation, hereafter referred to as the "unit volume". Thus, for a FS with a target flow rate of 250 cubic meters per hour, the FS processed 750 cubic meters of water per test cycle. The intake water for the first two unit-volumes was ambient DSH water, while the third unit-volume was amended with ISO 12103-1, A2 Arizona Fine Test Dust (Powder Technology, Inc.; Burnsville, Minnesota, USA) to achieve a minimum concentration of 24 mg/L total suspended solids (TSS) in the intake water.

Biological efficacy performance endpoints assessed in this study were density of zooplankton (including total and live zooplankton ≥ 50 μm in minimum dimension), and organisms in the ≥ 10 μm and < 50 μm size class. These endpoints were measured in FS discharge both in absolute terms and as a percent reduction from intake. Operational performance endpoints were pre-FS flow rate, post-FS flow rate, backflush flow rate (calculated from the difference between pre- and post-FS flow rates), pre-FS pressure, post-FS pressure, and differential pressure (calculated from the difference between pre- and post-FS pressure). GSI's study **did not assess** FS performance under identical challenge conditions, long term FS performance capacity, space requirements, FS energy demands, FS durability in actual shipboard conditions, or the extent of FS developer support for FS operation in the field.

GSI analyzed biological and physical/chemical parameters during each test cycle's intake operation to determine the degree of similarity in challenge conditions across and within FS test cycles, and any influence these intake conditions may have had on FS performance. GSI also

monitored and documented operational parameters during the test cycles for later comparison to FS operational targets specified by the FS developer. Variations in biological and physical/chemical intake conditions were controlled for statistically in evaluating biological performance across FSs.

FS biological performance expressed as percent reduction of total organisms in the ≥ 50 μm size class (i.e., zooplankton) ranged from 31.2 to 99.9 percent. FS performance was clearly challenged by the large number of smaller-sized soft-bodied organisms (i.e., microzooplankton) present in this regulated size class in the DSH. Performance relative to larger zooplankton (i.e., macrozooplankton) in the ≥ 50 μm size class was consistently high across nominal pore sizes. FS removal of organisms in the ≥ 10 μm and < 50 μm size class (i.e., protists) ranged from 22 to 89 percent. There was a statistically significant and large magnitude negative relationship between FS nominal pore size and percent reduction for microzooplankton in the ≥ 50 μm size class, as well as for organisms in the ≥ 10 μm and < 50 μm size class (i.e., protists). That is, the smaller the nominal pore size the greater the percent reduction of organisms. These estimates of FS effectiveness relative to the smaller organisms in the ≥ 50 μm size class are conservative, in that live/dead status was not taken into account.

Operationally, each FS performed without significant mechanical failure and without requiring manual servicing for the duration of testing. Operational performance of the FSs in terms of pressure differential and percent flow lost to backflush as a percent of total water processed ranged from 12.8 to undetectably low (i.e., under 2 percent). Operational performance parameters measured did not strongly correlate (positively or negatively) with biological performance such that clear and necessary "trade-offs" could be asserted. In particular, based on GSI findings, volume lost to backflush is not necessarily greater with higher organism removal, though unmeasured operational parameters, such as energy consumption may be.

Clearly, developers of FSs design units for diverse FS performance strengths, consistent with diverse performance needs in the marketplace. For example, a BWMS developer or ship owner may choose a FS based on one or more specific performance priorities, including mechanical reliability, through-put rate, energy consumption, removal efficiency, pressure drop, the requirements of a secondary treatment, and/or the amount of otherwise untapped operational capacity of the ship. GSI's study helps inform those choices to increase BWMS efficiency and effectiveness for end users and the environment.

ACKNOWLEDGMENTS

This project was a remarkable collaborative effort. We thank project funders: the U.S. Environmental Protection Agency's (USEPA's) Great Lakes Restoration Initiative (GLRI), and the U.S. Department of Transportation's Maritime Administration. We thank the City of Superior, Wisconsin, USA, for leasing us land for the GSI test facility. We thank Rick Harkins and the Canadian Shipowners Association for in-kind support in test design and filter system selection for this project. We are sincerely grateful to the participating filter system developers, including Filtersafe®, Amiad Water Systems, Kuraray Co. Ltd., and GEA Westfalia, who agreed to participate in the study, supported the transportation of their filter systems to and from the GSI facility, supplied technical support to test plan development, and had personnel on site throughout installation and test implementation. We wish to acknowledge the administrative support of several academic and professional organizations at which GSI personnel are based. These include the Northeast-Midwest Institute, the University of Wisconsin Superior, the University of Minnesota Duluth, the University of Oregon, and AMI Consulting Engineers.

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1 INTRODUCTION

Ships take up aquatic organisms in ballast water and discharge them in distant waters where the organisms may become invasive. The International Maritime Organization (IMO) and individual port states like the United States (US) have imposed requirements on ships to prevent further ship-mediated introductions of aquatic invasive species. Ballast water management system (BWMS) developers are creating BWMSs that combine treatment processes in novel ways to meet the standards safely and reliably over time and across geographic locations. Many such systems involve some form of filtration as one of the treatment steps.

The intended role of a filter system (FS) within an entire BWMS varies. Factors influencing the intended role include the nature and function of the secondary BWMS component, and the ballasting patterns and operational priorities of the ships targeted as a market for the BWMS. As a result, a solid understanding of operational and biological removal functionality of a FS component of a BWMS is necessary for optimizing overall BWMS performance under a range of natural conditions. Unfortunately, performance patterns of various FS alternatives in natural freshwater conditions are not well understood. In the absence of this information, it is difficult for a BWMS developer to effectively design and corroborate overall BWMS performance to prospective customers. In particular, developers of secondary treatment processes would benefit from knowing the potential post-filtration treatment burden in freshwater. Finally, ship owners need the information to make informed selections among alternative BWMSs.

In July 2013, the Great Ships Initiative (GSI) responded to a request by a group of ship owners, including Groupe Desgagnés Inc., Sterling Fuels, Lower Lakes Towing Ltd., Algoma Central Corporation, Canada Steamship Lines, MCA Shipping, Canada Ship Owners Association, American Steamship Company, and FedNav Ltd., to develop this information. GSI offered FS developers worldwide an opportunity to participate in organized and standardized freshwater BWMS performance evaluations. Test objectives were to:

- Provide reliable information on FS operational and biological performance in freshwater under controlled conditions, and to support limited performance comparisons across FSs;
- Explore any trade-offs between operational and biological performance endpoints; and
- Support FS, and thus BWMS, freshwater performance improvements.

Test objectives explicitly were NOT to:

- Investigate long-term operational and biological FS performance trade-offs or trends; such an investigation was beyond the scope of the project and would have outstripped funds available;
- Rate performance across individual FSs; reasons include: a) environmental conditions, intake water contents, FS nominal pore sizes and target flow rates were not identical across FS tests, and b) not all relevant parameters were measured, such as energy consumption and long-term reliability and durability;
- Factor-in FS footprint or filter element surface area; such considerations would require scale-up analysis beyond the scope of this study; and/or

- Corroborate FS developer claims as to FS nominal pore size or other aspects of the FS physical mechanism; in particular, the FS developer was the sole-source of FS nominal pore size information.

With input from the groups of ship owners listed above, GSI selected eight FSs for evaluation. Qualifying FSs (as manifold subunits or a single unit) were: a) representative of models provided to ships (i.e., capable of continuous ballasting without creating damaging pressure swings or deadheading the ballast pump); and b) capable of flow rates between 150 and 340 cubic meters (m^3) per hour.

GSI undertook the FS performance evaluations in September and October of 2013 at the GSI Land-Based Research, Development, Testing and Evaluation (RDTE) Facility, hereafter GSI Facility, located in the Duluth-Superior Harbor (DSH) of Lake Superior (Superior, Wisconsin, USA). Four test cycles of each FS unit were undertaken at a rate of two FSs per week. Intake samples were carefully characterized for each FS test cycle to determine the extent to which intake conditions were consistent across FS evaluations, and to determine consistency with challenge conditions stipulated in the U.S. Environmental Protection Agency (USEPA), Environmental Technology Verification Program (ETV) protocol for land-based verification of BWMSs (USEPA, 2010). Specifically, samples were collected and analyzed to assess water quality, i.e., temperature, total suspended solids (TSS), and particulate organic matter (POM), and density of two size classes of organisms, i.e., live/dead of those generally $\geq$ 50 μm in minimum dimension such as zooplankton, and those generally $\geq$ 10 μm and < 50 μm in minimum dimension such as protists. Operational data, i.e., pre-FS flow rate, post-FS flow rate, pre-FS pressure, and post-FS pressure were collected throughout the sampling events. Results were analyzed across FSs for categorical relationships between biological and/or operational performance and (known or nominal) FS characteristics. Detailed FS-specific work-ups of data were provided to each participating FS developer for their individual use.

The GSI evaluation experiment was entirely independent and objective; only the FS mechanical and physical descriptive information presented in this report was not directly corroborated by GSI.

1.1 The Testing Organization

The testing organization, GSI, is a regional research initiative managed by the Northeast-Midwest Institute (NEMWI) devoted to ending the problem of ship-mediated invasive species in the Great Lakes-St. Lawrence Seaway System and globally. Since its establishment in 2006, GSI has provided independent performance/verification testing services to developers of BWMSs at the bench, land-based and shipboard scales. GSI performs informal "status" tests for systems that are in the research and development stage and formal certification/verification tests appropriate to market-ready BWMSs.

NEMWI, GSI's managing entity, is a Washington, D.C-based private, non-profit, and non-partisan research organization dedicated to the economic vitality, environmental quality, and regional equity of Northeast and Midwest states. The NEMWI directly collaborates with contracting entities including the University of Wisconsin-Superior's (UWS's) Lake Superior

Research Institute (LSRI), the University of Minnesota-Duluth (UMD's) Natural Resources Research Institute (NRRI), the University of Oregon, and AMI Consulting Engineers, to achieve GSI research objectives.

1.2 Filter Systems Tested

The eight commercially ready FSs selected for testing spanned a range of FS processes and nominal pore sizes. GSI agreed to hold the participating FS trade names confidential unless the specific FS developer explicitly authorized its release. FS developers that chose to release their FS trade names in this report have been identified by those trade names, and were granted the opportunity to incorporate additional information on their FS in Appendix 1 of this report, and an explanation of testing outcomes, including outcomes of optional pre-test commissioning exercises at GSI. FS developers that chose not to disclose their FS trade name are identified solely by the upper-case code letter GSI used in the testing and very limited FS process information. This section and Table 1 provides FS description information in accordance with this system of nomenclature. The FS nominal pore size information presented in Table 1 was provided by the FS developers, and not objectively validated by GSI. All FS tested were self-cleaning.

Table 1. Summary of Filter Systems Evaluated.

Filter System (Nominal Pore Size)	Approach	Model (if Relevant)	Target Flow rate (m^3/hr)
Kuraray (10 μm)	Polyolefin	MICROFADE BWMS	250
GEA (20 μm)	Multi-Screen	--	250
Filtersafe® (25 μm)	Screen	Model BS-100	150
Amiad (30 μm)	Multi-Screen	Amiad Omega IE	340
Filter A (40 μm)	Candle	--	300
Filtersafe® (40 μm)	Screen	Model BS-100	200
Amiad (40 μm)	Multi-Screen	Amiad Omega IE	340
Filter F (40 μm)	Screen	--	250

1.2.1 Optional Additional Filter System Developer Provided Information

GSI provided FS developers which associated their trade name with the FS subject to testing the opportunity to provide additional descriptive information about their FS. The information provided by the FS developers appears below.

Filtersafe® (i.e., FS B and FS G, in these tests): The filter unit used in the tests represents the wide range of ballast water treatment filters offered by Filtersafe® to the industry during the past seven years, with a proven track record of hundreds of installations worldwide.

Amiad Water Systems (i.e., FS C and FS H, in these tests): Amiad offers automatic self-cleaning screen filters with suction scanners cleaning mechanisms. Amiad Omega line offers eight models with flows ranging from 100 m^3/hr to 3,000 m^3/hr for a single filter unit. Amiad has over 50 years of experience in fine filtration down to 3 micron. Every day, around the world, Amiad filters handle the full spectrum of water contaminants from variable water sources – organic and inorganic solids, algae bloom, storm-driven turbidity, changing flow rates, shifting salinity, changing temperatures and varying water quality conditions

Kuraray Co. Ltd. (i.e., FS E, in these tests): The MICROFADE Filtration Unit, MF-250, is equipped with two filter housings, each of which is backwashed at regular intervals. The system is designed to treat a rated flow of water, 250 m^3/hr, at all times, even when one housing is being backwashed. MICROFADE's Filtration Unit, MF-250 fine filter elements are installed in the filter housing and can be replaced periodically after a designated number of hours of filtration operation.

GEA Westfalia (i.e., FS D, in these tests): The filter consists of five layers of sintered stainless steel mesh that is produced from corrosion-resistant steel and has a nominal depth of 20 μm. The filter is equipped with a fully-automatic cleaning device that removes particles with high cleaning forces from the inner surface of the filter screen. This cleaning device consists of a suction tube with four suction nozzles (mounted with overlap). The cleaning process is based on a pressure difference. A portion of the water that enters into the filter is sucked from the inside of the filter into the concentrate pump by the suction nozzles and is discharged. The suction tube is driven by the motor located at the top of the filter housing.

1.3 Roles and Responsibilities of Organizations Involved

Roles and responsibilities for these GSI-sponsored FS evaluations were shared among GSI, the FS developers, participating ship owners, and the GSI funders.

1.3.1 The Great Ships Initiative

GSI was responsible for procuring funding for the FS evaluations described here, developing the Test/Quality Assurance Plan (TQAP; GSI, 2013) for the evaluations, and subjecting the document to review by the FS developers and participating ship owners prior to testing. GSI prepared and maintained the testing facility, organized the testing schedule, monitored source water conditions, supervised FS installation, supported FS developer commissioning exercises,

and operated the FSs during testing in accordance with developer-provided instructions or monitored the FS developer while they operated their specific FS. GSI was responsible for all sample collection, sample analysis, and statistical analysis of data. In addition, GSI was responsible for assuring data quality, and evaluating and reporting on the performance data from the FS evaluations, maintaining security for testing activities, and assuring site safety for all personnel. Finally, GSI was responsible for subjecting the data and data analysis to FS developer review, and being as responsive to FS developer comments as possible within the bounds of fairness, scientific and process constraints prior to publication.

1.3.2 Filter System Developers

FS developers were responsible for the delivery of their specific FSs to the GSI Facility, for providing instructions to the GSI Engineers for proper installation of the units at the facility, designating the installation requirements and operating conditions for their FSs during the evaluations (including line pressure, flow rate, startup and shutdown procedures), and signing off on successful commissioning outcomes of their specific FSs. FS developers were invited to observe testing or, if they did not have representatives on site, to have a representative available via phone and/or email during the testing period.

1.3.3 Test Funders

This project was supported by funds from the USEPA's Great Lakes Restoration Initiative (GLRI), and the U.S. Maritime Administration. Tests took place on land owned by the City of Superior, Wisconsin. In-kind support in test design and FS selection was provided by the Canadian Shipowners Association.

2 THE TESTING FACILITY

The FS performance evaluations took place at GSI's Land-Based RDTE Facility located in the DSH of Lake Superior (Figures 1-3). Relevant features of the GSI Facility include:

- Control and treatment intake flows up to 340 m^3/hour each;
- Highly automated flow and pressure control, monitoring and data logging;
- A freshwater estuary with diverse and plentiful aquatic life as a challenge water intake source (during normal testing season May to October);
- Capacity to amend intake challenge water to intensify challenge conditions;
- Validated facility sanitation before and between test cycles;
- High quality in-line sampling systems associated with identical 3.8 m^3 sample collection tubs;
- On-site laboratory space for most live analyses, additional space minutes away; and
- Easy plug-in connections for BWMSs.

Figure 1. Location of GSI's Land-Based RDTE Facility in Superior, Wisconsin, USA. (Source: Google Earth).

Figure 2. Aerial Photo of the GSI Land-Based RDTE Facility (Source: Google Earth).

Figure 3. Photo of the GSI Land-Based RDTE Facility.

The GSI Facility draws challenge water from the DSH, generally at a flow rate between 400 - 680 m^3/hr. This main intake flow can be augmented with solids (i.e., TSS) and/or organisms (i.e., protists) at injection points A and B (Figure 4). A Y-split in the facility intake piping, just after a static mixer, simultaneously channels one half of the well-mixed flow to a treatment track and the other half to a matched control track (not relevant to these tests). Thus, the facility delivers a specified flow rate in the treatment track in the range of 200 – 340 m^3/hr. The treatment track directs water through a subject BWMS prior to discharging water to a 200 m^3 cylindrical retention tank, or to the harbor (Figure 4), and the flow can be toggled between two installed BWMSs.

Flow control valves and control system logic assure that sample flow rates are equivalent and proportional to intake and discharge flow rates throughout each operation. Flow rates are recorded by magnetic flux flow meters. Pressure readings are also recorded using pressure transducers at multiple points throughout the facility. GSI measures and records these data, and other operational and maintenance parameters, using the facility's Programmable Logic Controller (PLC). This information is accessible by a Human Machine Interface (HMI). The HMI has a 38.1 cm color touch display and is capable of detailing valve positions, pressure from the pressure meters, and flow rates. The PLC reads, and a separate data logging computer records and saves data from all the limit switches, positioners, pressure sensors, flow meters and level indicators every five seconds for the entire duration of the operational cycle. Challenge water quality/chemistry is also monitored and recorded in the same manner using in-line temperature/pH, dissolved oxygen, turbidity and chlorophyll-a sensors installed in the main piping system just prior to the BWMS.

Sample water for biological analysis is generally collected continuously throughout each intake and discharge operation via the facility's in-line sample points (SPs). Samples for water quality/chemistry analysis are collected from designated SPs during intake, tank retention and discharge. All SPs, with the exception of SP#15, consist of three identical sample ports spaced at regular intervals in a length of straight pipe (SP#15 consists of one sample port). Each port is fitted with a center-located elbow-shaped tube (90 ^{o}) which samples the water. This design is based on a design developed and validated analytically by the U.S. Naval Research Laboratory in Key West, Florida. The design and lay-out of these replicate sample ports has also been validated empirically at GSI, and shown to produce equivalent, representative and unbiased samples of water flow.

On-site laboratories (Figure 4) support time sensitive analyses associated with GSI land-based tests, including live analysis of organisms $\geq$ 50 μm (i.e., zooplankton) and organisms $\geq$ 10 and $<$ 50 μm (i.e., protists). The laboratories are climate-controlled, and have enough bench space to allow for simultaneous analysis of samples by multiple personnel. All other analyses are conducted in laboratories of LSRI on the UWS campus; approximately 5 km from the facility.

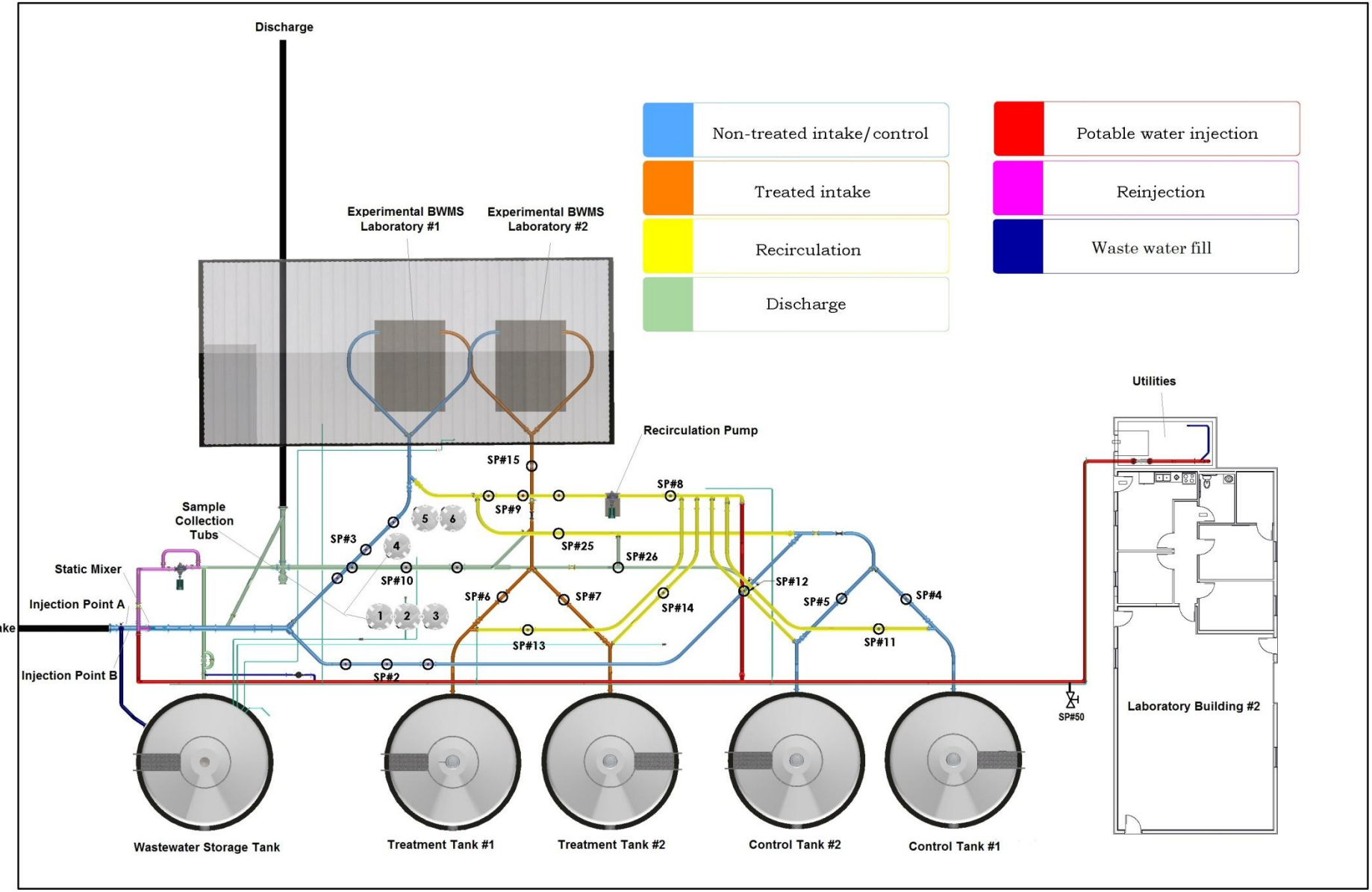


Figure 4. Simplified Schematic of the GSI Land-Based RDTE Facility Showing Location of Sample Points, Sample Collection Tubs, Injection Points, Retention Tanks, and Treatment and Control Tracks.

3 METHODS

3.1 Experimental Design

The GSI experimental design for this set of FS evaluations revolved around reducing variables other than FS type to the greatest extent possible through establishing a common approach to determining the experimental unit volume and target pressure for each FS, amending test water to meet at least a common threshold of challenge conditions across evaluations, scheduling evaluations to minimize the amount of variability in ambient test conditions across FSs, and statistically controlling for any remaining variability in ambient test conditions.

3.1.1 Target Filter System Operational Window

GSI established a single target flow rate (m^3/hour; measured downstream of the FS units) and inlet pressure (bar) for each FS based on FS developer specifications. Thereafter, average flow rates within 85 to 100 % of the target rate and inlet pressure within 90 to 110 % of the target pressure in the non-backflush period, defined valid conditions for each test cycle. Table 2 summarizes the target flow-rate and inlet pressures of the participating FSs.

Table 2. Valid Range of Operational Parameters for Filter Systems Evaluated.

Filter System (Nominal Pore Size)	Post-Filter Target Flow Rate (m^3/hr) and Experimental Unit-Volume (m^3)	Valid Range (m^3/hour)	Inlet Pressure (bar)	Valid Range (bar)
Kuraray (10 μm)	250	212.5 - 250	1.66	1.49 - 1.83
GEA (20 μm)	250	212.5 - 250	2.55	2.3 - 2.81
Filtersafe (25 μm)	150	127.5 - 150	3.00	2.70 - 3.30
Amiad (30 μm)	340	289 - 340	2.21	1.99 - 2.43
Filter A (40 μm)	300	255 - 300	2.34	2.11 - 2.57
Filtersafe (40 μm)	200	170 - 200	2.48	2.23 - 2.73
Amiad (40 μm)	340	289 - 340	2.21	1.99 - 2.43
Filter F (40 μm)	250	212.5 - 250	3.00	2.70 - 3.30

3.1.2 Testing Sequence and Test Cycle Components

For experimental design purposes, the volume each FS was designed to process in one hour (based on design flow rate) became the GSI-designated "unit-volume" for that specific FS. For example, GSI assigned a unit-volume of 250 m^3 to a FS whose design flow rate is 250 m^3/hr. Table 2 lists the unit-volumes for each of the eight FSs tested. In all cases, unit-volumes were within the GSI Facility's capacity range of 150 - 340 m^3 (Table 2).

GSI tested FSs sequentially, in FS pairings or test "rounds" over four days. Each test day within each round comprised testing of two paired FSs constituting one test cycle per day. Each test cycle consisted of two FSs tested in sequence (one FS within the pairing was tested in the AM and the other tested in the PM).[1] The order in which the two FSs were tested was alternated each day over the four day period. For each FS test cycle, the FS processed three "unit volumes" of water, in discrete steps, hereafter, Steps 1, 2 and 3. Each step was separated by no more than 30 minutes. Steps 1 and 2 were always carried out under ambient water conditions, while Step 3 was carried out using ambient water that was amended, as needed, to meet a common set of minimum challenge conditions. Table 3 describes the sequence of testing events for the entire FS performance evaluations. Step 3 acceptable intake conditions were based on minimum biological and TSS characteristics required by the ETV Protocol (USEPA, 2010), and appear in Table 4.

Table 3. GSI Land-Based Filter System Performance Evaluation Sequence.

Round (Dates)	Test Cycle (Date)	Filter (Time of Testing)	Step # (Test Duration: Water Type)
Round 1 (9/13/13 – 9/16/13)	Test Cycle 1 (9/13/13)	Filter A (Morning)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		Filtersafe (40 μm) (Afternoon)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
	Test Cycle 2 (9/14/13)	Filtersafe (40 μm) (Morning)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		N/A*	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
	Test Cycle 3 (9/15/13)	Filter A (Morning)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		Filtersafe (40 μm) (Afternoon)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
	Test Cycle 4 (9/16/13)	Filtersafe (40 μm) (Morning)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		Filter A (Afternoon)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)

[1] In some instances, this pattern was altered to accommodate late deliveries or installation issues of filter systems.

Round (Dates)	Test Cycle (Date)	Filter (Time of Testing)	Step # (Test Duration: Water Type)
Round 2 (9/21/13 – 9/24/13)	Test Cycle 1 (9/21/13)	GEA (20 μm) (Morning)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		N/A**	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
	Test Cycle 2 (9/22/13)	N/A**	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		GEA (20 μm) (Afternoon)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
	Test Cycle 3 (9/23/13)	GEA (20 μm) (Morning)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		N/A**	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
	Test Cycle 4 (9/24/13)	N/A**	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		GEA (20 μm) (Afternoon)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
Round 3 (9/29/13 – 10/2/13)	Test Cycle 1 (9/29/13)	Kuraray (10 μm) (Morning)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		Amiad (30 μm) (Afternoon)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
	Test Cycle 2 (9/30/13)	Amiad (30 μm) (Morning)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		Kuraray (10 μm) (Afternoon)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
	Test Cycle 3 (10/1/13)	Kuraray (10 μm) (Morning)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		Amiad (30 μm) (Afternoon)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
	Test Cycle 4 (10/2/13)	Amiad (30 μm) (Morning)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		Kuraray (10 μm) (Afternoon)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
Round 4 (10/6/13 – 10/9/13)	Test Cycle 1 (10/6/13)	Amiad (40 μm) (Morning)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		Filtersafe (25 μm) (Afternoon)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)

Round (Dates)	Test Cycle (Date)	Filter (Time of Testing)	Step # (Test Duration: Water Type)
	Test Cycle 2 (10/7/13)	Filtersafe (25 μm) (Morning)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		Amiad (40 μm) (Afternoon)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
	Test Cycle 3 (10/8/13)	Amiad (40 μm) (Morning)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		Filtersafe (25 μm) (Afternoon)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
	Test Cycle 4 (10/9/13)	Filtersafe (25 μm) (Morning)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		Amiad (40 μm) (Afternoon)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
Round 5 (10/13/13 – 10/15/13)	Test Cycle 1 (10/13/13)	Filter F (Morning)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		Filter F (Afternoon)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
	Test Cycle 2 (10/14/13)	Filter F (Morning)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
	Test Cycle 3 (10/15/13)	Filter F (Morning)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)
		Filter A (Afternoon)	Step 1 (1 hour; Ambient)
			Step 2 (1 hour; Ambient)
			Step 3 (1 hour; Amended)

* Invalid test due to malfunction of GSI injecting system, which resulted in a nine minute gap in the solids injection.

** Tests withdrawn at request of filter developer due to improper filter system assembly

Table 4. Target Values for GSI Amended Challenge Water Compared to those detailed in the Environmental Technology Verification Program's Generic Protocol, v. 5.1 (September 2010).

Parameter	Minimum Values detailed in the USEPA ETV Generic Protocol	Target Values for GSI Amended Challenge Water
Total Suspended Solids (TSS)	Min. 24 mg/L	Min. 24 mg/L* (Step 3 Only)
Temperature	4 – 35 °C	4 – 35 °C
Live organisms ≥ 50 μm	Minimum of 10^5 organisms/m^3 with at least 5 species present across 3 phyla.	Minimum of 10^5 organisms/m^3 with at least 5 species present across 3 phyla.
Live organisms ≥ 10 μm and < 50 μm	Minimum of 10^3 organisms/mL with at least 5 species present across 3 phyla.	Minimum of 10^3 organisms/mL with at least 5 species present across 3 phyla.

* Achieved through augmentation using Arizona Fine Test Dust.

3.1.3 Measured Endpoints

The measured endpoints for the FS evaluations were TSS, POM, and organism concentrations in intake and filtered discharge with respect to two size classes: organisms ≥ 50 μm (live and total across taxa) and organisms ≥ 10 μm and < 50 μm (total cells and entities across taxa and morphological groups). These values were expressed as percent reduction (intake to discharge) and numbers per unit volume of water (Table 5). GSI also measured the operational parameters listed in Table 5. GSI collected chemistry, biological and operational data and/or samples to assess FS performance endpoints. In addition, intake samples were analyzed relative to target values for GSI amended challenge water (achieved through augmentation of TSS) as detailed in Table 4, and for similarity across FS test cycles.

Table 5. Filter System Performance Endpoints.

Parameter	End Point	Description	Unit
Water Chemistry	Total Suspended Solids (TSS) Removal	Percent reduction from intake relative to filtered discharge of TSS.	%
	Particulate Organic Matter (POM) Removal	Percent reduction from intake relative to filtered discharge of POM.	%
Biology	Organism Removal	Percent reduction from intake relative to filtered discharge for two size classes of organisms: ≥ 50 μm (both microzooplankton and macrozooplankton) and ≥ 10 and < 50 μm (protists)	%
	Total Protists Remaining in Discharge (Steps 1, 2, and 3; Steps 1 and 3 Presented)	Absolute numbers of total organisms in filtered discharge in the ≥ 10 and < 50 μm size class (protists)	Cells/mL
	Total Zooplankton Remaining in Discharge (Step 1 and 3)	Absolute numbers of total organisms in filtered discharge in the ≥ 50 μm size class (microzooplankton and macrozooplankton)	#/m^3
	Live Zooplankton Remaining in Discharge (Step 3 Only)	Absolute numbers of live organisms in filtered discharge in the ≥ 50 μm size class (microzooplankton and macrozooplankton)	#/m^3
Operational	Pre-Filter Flow Rate	Measure of flow rate up-stream of the filter	m^3/hr
	Post-Filter Flow Rate	Measure of flow rate down-stream of the filter	m^3/hr
	Back-Flush Volume	Water lost to backflushing (Pre-Filter Flow Rate – Post-Filter Flow Rate)	m^3/hr
	Backflush Flow Ratio	Percent of the total volume filtered that was back-flushed	%
	Pre-Filter Pressure	Pressure near the filter inlet	bar
	Post-Filter Pressure	Pressure near the filter outlet	bar
	Differential Pressure	Pressure loss over the filter (inlet pressure – outlet pressure)	bar

3.1.4 Challenge Condition and Augmentation Methods

Since ambient zooplankton and protist densities in the DSH naturally met the minimum target value specified in Table 4, augmentation of organisms to meet target thresholds in Step 3 was not necessary for these FS evaluations (Table 4). However, natural levels of TSS in DSH water were not adequate to meet target values for Step 3 of these tests. Therefore, in Step 3 only, GSI augmented intake water using a metering system. ISO 12103-1, A2 Arizona Fine Test Dust (Powder Technology, Inc.; Burnsville, Minnesota, USA) was injected into the intake stream (see injection ports A and B; Figure 4). The particle size distribution for Arizona Fine Test Dust

ranges from 0.97 μm to 124.50 μm, with ~ 88.7 % less than 40.00 μm[2]. The specific injection procedure is detailed in *GSI/SOP/LB/G/O/5 – Procedure for Injecting Organisms and Solids into the GSI Land-Based RDTE Facility*. To summarize, DSH water chemistry was monitored twice daily (once prior to starting each test cycle) by GSI personnel allowing for close approximation of the ambient TSS values. The weight of Fine Test Dust to be used in the Solids Injection System (SIS) tank was determined based on the approximate ambient DSH concentrations and desired intake concentration of ETV target levels (i.e., ≥ 24mg/L TSS; Table 4). The Fine Test Dust was sterilized at LSRI prior to injection. Following, the SIS tank was filled with DSH water and Fine Test Dust was poured into the SIS tank slowly to prevent clumping. The solids were then mixed for a minimum of 20 minutes prior to the start of the sampling operation. The contents of the SIS tank were injected into the intake water for the entire duration of the Step 3 sampling operation at a constant rate using a peristaltic pump located at Injection Point A (Figure 4).

3.2 Filter System Installation and Commissioning Methods

Installation of the FSs took place in accordance with the documentation provided by the FS developers, including plumbing the units into the GSI Facility using temporary schedule 80 PVC and flexible hose for backflush lines, wiring required power connections to the facility, connecting the FSs to facility air, and installing the FSs backflush signal cable. Installation procedures and deviations from commissioning procedures were documented and reported by the GSI Engineers. Once installation was complete, GSI Engineers conducted several installation commissioning tests which required: passing a pressure test of 3.4 bar (49 psi), completing all FS developer specified commissioning checks, and passing backflush signal tests. Figure 5 provides a schematic of the GSI Facility's piping layout relevant to the installation of the eight FSs.

The following connections were made available to the FS developers at the GSI Facility:

- 8 inch, 150 lb. ANSI flanges for inlet and outlet (ID 22.2 cm);
- Local filtrate holding tank that could be plumbed to the FS backflush outlet;
- 100 Amp, 480 Volt, 3 Phase;
- Compressed air up to 80 psi (FS developers provided regulators);
- 4-20 mA inputs for GSI to record analogue data output by the FS (upon FS developer request); and
- Filter backflush signal (other discrete inputs were also available if requested).

After installation, FSs that arrived on schedule were offered a two phase optional performance commissioning trial. The optional trial was intended to help FS developers gather operational data, including FS response to GSI challenge conditions and/or to identify the preferred flow rate to declare for the tests. GSI required all FSs to participate in a third commissioning phase to assure sufficient FS functionality to protect the GSI Facility assets. Each commissioning trial phase is summarized in Table 6. FS developers whose FSs received Phase 1 and 2

[2]Determined using linear interpolation based on the data provided in the following link: http://www.powdertechnologyinc.com/product/iso-12103-1-a2-fine-test-dust/

commissioning trials had the option of including their data in Appendix 1 of this report to allow for further explanation of FS performance in the context of these tests.

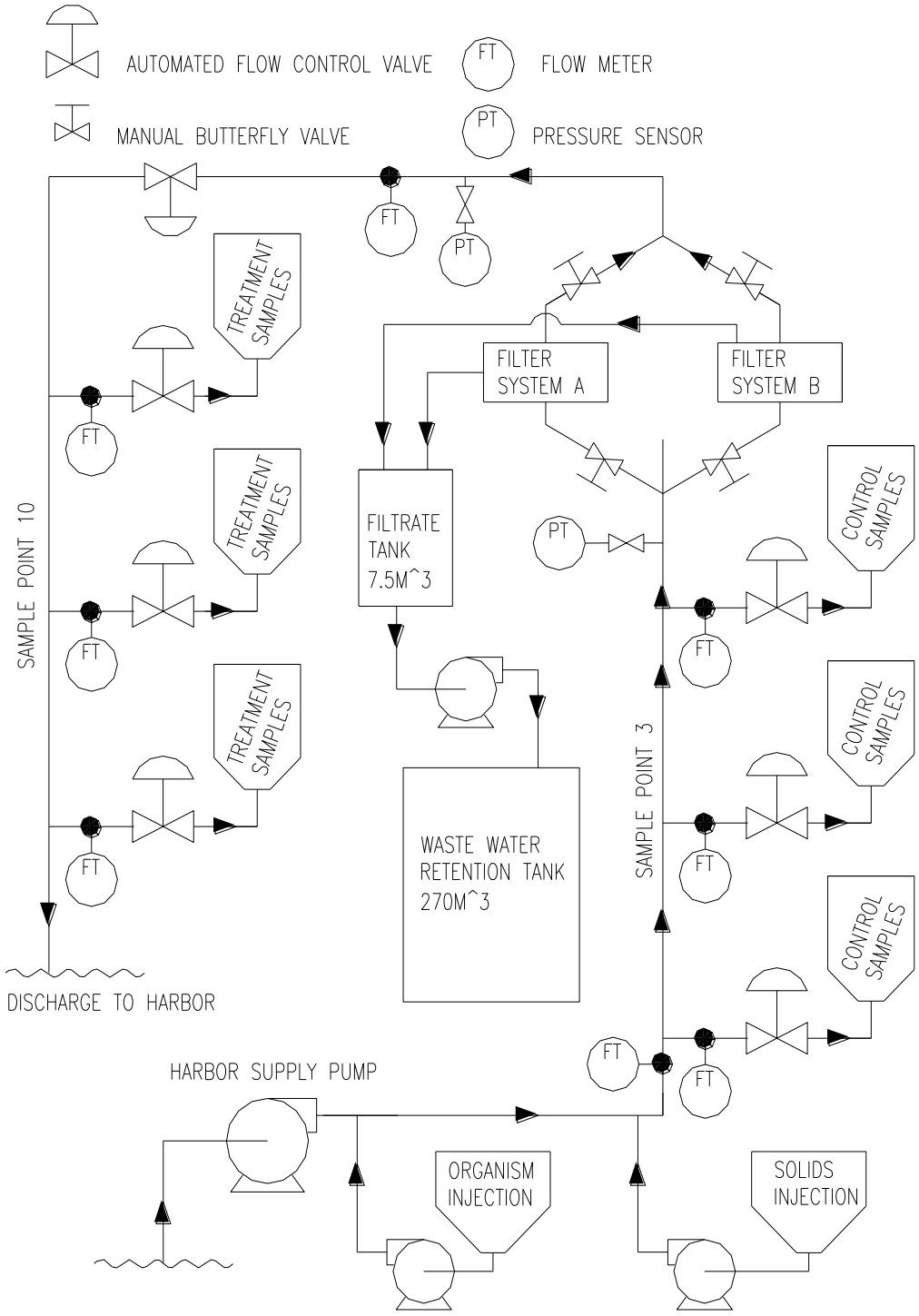


Figure 5. GSI Land-Based RDTE Facility Piping Diagram for FS Evaluation (Excluding Unused Portions of the Facility and Seep Samplers).

Table 6. Phases of Filter System Commissioning Trials.

	Phase 1 (Elective)	Phase 2 (Elective)	Phase 3 (Required)
Duration	**0 - 4 hrs of flowing water. Pauses in flow do not count against duration.**	**Time used to process a maximum 500 m^3 of water.**	**Minimum of 20 minutes and three consecutive (3) back flushes with no performance degradation.**
Inlet Pressure	**At the discretion of the Filter System (FS) developer**	**At the discretion of the FS developer**	**Inlet pressure specified by FS Developer. Pressure specified here was used for the remainder of testing**
Flow Rate	**At the discretion of the FS developer.**	**At the discretion of the FS developer**	**Flow rate specified by FS developer. Flow Rate specified here was used for the remainder of testing.**
Water Quality	**Ambient Duluth-Superior Harbor (DSH) water quality augmented with up to 10 mg/L total suspended solids (TSS) at the FS developer's request**	**Ambient DSH water quality augmented to USEPA ETV levels of TSS and protist densities**	**Ambient DSH water quality augmented to USEPA ETV levels of TSS and protist densities.**

3.3 Collection of Samples and Measurements

Water for evaluation of FS biological performance was sampled continuously throughout each of the three steps of each test cycle at pre- and post-FS SPs. Pre-FS sampling took place at SP#3 and immediate post-FS sampling at SP#10 (Figure 4). GSI collected water chemistry samples at SP#15 (Figure 4). Table 7 summarizes the number and volume of operational, water chemistry, and biological samples collected pre- and post-FS, respectively, during Steps 1, 2 and 3 of each test cycle. Table 8 details sample handling and storage requirements.

Table 7. Operational, Water Chemistry, and Biological Samples and Measurements Collected from Pre- and Post-Filter System Water During Steps 1, 2 and 3 of each Test Cycle.

Treatment	Analysis Category	Parameter	Measurement Class	Sample Type	Instrument Type (Where Applicable)	Number of Samples	Sample Volume	Sample Location
Pre-Filtration	Operational	Main Line Flow Rate	Core	In-Line, Continuous	In-Line Sensor	N/A	N/A	Pre-Treatment Line
		Main Line Pressure	Core					
		Sampling Flow Rate	Core					
	Water Chemistry	Temperature	Core	Sample Collection Tub	YSI Multiparameter Sonde	Not Applicable	Not Applicable	SP#3
		Total Suspended Solids and Particulate Organic Matter[3]	Core	Discrete Grabs	Not Applicable	3 per step, 9 total (Beginning, Middle, End)	0.9 L - 1 L	SP#3
	Biological	Organisms ≥ 50 μm	Core	Time-Integrated Samples	Not Applicable	1 per step, 3 total	3 m^3 ± 2%	SP#3
		Organisms ≥ 10 μm to < 50 μm	Core	Time-Integrated Samples (19 L Carboys)		1 per step, 3 total	0.9 L -1 L	SP#3
Post-Filtration	Operational	Sampling Flow Rate	Core	In-Line, Continuous	In-Line Sensor	Not Applicable	Not Applicable	Post-Treatment Line
		Sample Collection Tub Volume	Auxiliary	Calculated Based on Flow Rate (Flow meters accurate to ±0.5 %)	Not Applicable			
	Water Chemistry	Temperature	Core	Sample Collection Tub	YSI Multiparameter Sonde	Not Applicable	Not Applicable	SP#10
		Total Suspended Solids and Particulate Organic Matter[4]	Core	Discrete Grabs	Not Applicable	3 from each step, 9 total (Beginning, Middle, End)	0.9 L - 1 L	SP#15
	Biological	Organisms ≥ 50 μm	Core	Time-Integrated Samples	Not Applicable	1 from each step, 3 total	3 m^3 ± 2%	SP#10
		Organisms ≥ 10 μm to < 50 μm	Core	Time-Integrated Samples (19 L Carboys)	Not Applicable	1 from each step, 3 total	0.9 L - 1 L	SP#10

[3] Not all samples were analyzed for particulate organic matter (POM).
[4] As above.

Table 8. Operational, Water Chemistry and Biological Sample Handling and Storage Requirements.

Parameter	Container	Minimum Sample Size	Sample Type	Processing/Preservation	Maximum Storage
Electronic Sample Collection Tub Data (Temperature)	Not Applicable	Not Applicable	Discrete Grab from Sample Collection Tub	Maintain digital archive.	Not Applicable
Total Suspended Solids	1 L HDPE	200 mL ± 1 %	Discrete Grab	Analyze immediately; or refrigerate.	7 days
Particulate Organic Matter	1 L HDPE	200 mL ± 1 %	Discrete Grab	Analyze immediately; or refrigerate.	7 days
≥ 10 and < 50 μm Size Class (Protists)	1 L HDPE	1000 mL	Time-Integrated Sample using 19 L Carboy	Preserved with Lugols solution within 1.5 hours of sample collection.	1 year for preserved samples
≥ 50 μm Size Class (Zooplankton)	1 L Cod End	3.0 m^3 (concentrated to 1000 mL	Time-Integrated	Samples from Steps 1 and 2: Preserve with formalin within 2 hours of sample collection. Samples from Step 3: Enumerate with compound microscope within 2 hours of sample concentration.	1 year for preserved samples

3.3.1 Water Chemistry

Three, 1 L discrete grab samples for TSS and POM analysis were collected pre- and post-FS as detailed in Table 7 during each step of each test cycle. Samples were collected at approximately 15, 30, and 45 minutes after the start of each step. The exact times of sample collection were recorded on the water chemistry sample collection datasheet following the procedure outlined in *GSI/SOP/LB/RA/SC/2 – Procedure for Collecting Water Chemistry Samples and Data*. Samples were transported to the LSRI chemistry laboratory in a cooler, and analyzed immediately or stored in a refrigerator for up to a maximum of seven days (see Table 8 for sample handling and storage requirements). Temperature was measured in one grab sample prior to each test cycle using a calibrated Fisher digital thermometer.

3.3.2 Biological

Sample water for biological samples in the ≥ 10 μm and < 50 μm size class was continuously collected into replicate, 19 L plastic carboys via 0.32 cm ID Tygon® tubing which branches off the main line of each sample port. The water in each carboy was considered to be an independent, time-integrated subsample of the entire volume of sample water collected during each step of the test cycle operation. Sample collection occurred consistent with *GSI/SOP/LB/RA/SC/7 - Procedure for Protist and Microbial Sample Collection Using Seep Samplers*, i.e., the contents of each carboy was mixed by inverting the carboy several times and 1 L subsample was collected immediately as detailed in Table 7. The 1 L whole water samples were then placed into a cooler to protect the sample from exposure to sunlight, and processed and preserved at the GSI Facility within 1.5 hours of collection (Table 8).

Sample water for organisms in the ≥ 50 μm size class was drawn by the relevant sample ports and transferred simultaneously and continuously into replicate 3.8 m^3 sample collection tubs via clean 3.8 cm ID flexible hoses and automated flow-controlled pneumatic diaphragm valves. The water in each sample collection tub was considered to be an independent, time-integrated sample of the experimental water mass associated with each unit volume of flow. GSI has validated the independence and equivalency of these sample ports and collection tub apparatus. Samples were collected both pre-FS and post-FS for each step of the test cycle (Table 7). Sample processing took place within two hours of collection and involved the entire contents of each sample collection tub being drained and concentrated through a 35 μm mesh (50 μm diagonal dimensions) plankton net into 1 L cod-ends as described in *GSI/SOP/LB/RA/SC/6 - Procedure for Zooplankton Sample Collection*. Samples from Step 1 and Step 2 of each test cycle were preserved with formalin for later enumeration of total organisms, while the samples from Step 3 were examined immediately for enumeration of live and total organisms and then preserved.

3.4 Sample and Measurement Analysis

3.4.1 Physical/Chemistry Measurements

TSS analysis was conducted according to *GSI/SOP/BS/RA/C/8– Procedure for Analyzing Total Suspended Solids (TSS), Particulate Organic Matter (POM), and Mineral Matter (MM*). Accurately measured sample volumes (± 1 %) were vacuum filtered through pre-washed, dried, and pre-weighed glass fiber filters (i.e. Whatman 934-AH). After each sample was filtered it was dried in an oven and brought to constant weight. TSS values were determined based on the weight of particulates collected on the filter and the volume of water filtered. In addition, the POM concentration was determined on some of the samples following Standard Method 2540 E (American Public Health Association, 2012). The residue from the TSS analysis was ignited to a constant weight at 550 °C in a muffle furnace.

3.4.2 Biological Samples

Sample analysis for organisms ≥ 10 μm to < 50 μm was performed on samples collected from Steps 1, 2, and 3 that were preserved with Lugol's solution within 1.5 hours of sample collection. Prior to analysis, samples were concentrated through a 7 μm mesh plankton sieve and stored in a 25 mL sample container. This concentration step is estimated to result in 3 % - 8 % organism loss based on analyses performed during GSI validation experiments. Sample analysis was conducted according to *GSI/SOP/MS/RA/SA/1 - Procedure for Protist Sample Analysis* though procedures involving staining with fluorescein diacetate (FDA) and epifluorescence microscopy were not used. A 1.1 mL subsample from the concentrated slurry was transferred to a Sedgwick-Rafter cell, covered and placed on the stage of a compound microscope that was set for brightfield observation. At least two horizontal transects were analyzed (an area known to reflect greater than 1 mL of original sample water), aiming for at least 100 entities (i.e., unicellular organism, colony, or filament) counted. Records were kept of transect lengths and widths so that the total counted area and volume analyzed could be calculated. Counting and measurement of all other entities followed standard procedures for individuals (length and width), colonies (e.g., number of cells, cell length and width) and filaments (e.g., number of cells, cell length and width

or total filament length if cells cannot be discerned). Unlike samples containing FDA, viable cells were identified as those with cell contents; i.e., empty diatom frustules were not counted. The remaining concentrated sample in the 25 mL bottle served as the sample archive.

Note that analysis of the ≥ 10 and < 50 μm size class of organisms for GSI varies from the ETV Generic Protocol, v. 5.1 (USEPA, 2010) in two notable ways: (1) instead of concentrating a 1 m^3 volume of water to 1 L for analysis, GSI protocols follow collection of a 1 L sample using a time-integrated seep sampler; and (2) ETV protocols do not include analyses of preserved samples. These deviations are necessary given the high densities of protists and other water augmentations, such that there is no effective method to rapidly concentrate 1 m^3 of water for protist analysis without damaging the organisms or delaying analysis until die-off becomes a possibility. Other variations from Generic Protocol, v. 5.1 (USEPA, 2010) include slight variations in microscopy equipment, lack of vital staining (due to use of preserved samples) and use of standard translucent HDPE bottles (kept in a cooler) for sampling instead of dark bottles, but these variations are not expected to have an impact on results.

Analysis of samples for live and total organisms ≥ 50 μm in pre- and post-FS samples from Step 3 of each test cycle was conducted according to *GSI/SOP/MS/RA/SA/2 - Procedure for Zooplankton Sample Analysis*, and took place within two hours of collecting, and concentrating the individual samples. Microzooplankton (e.g., rotifers, copepod nauplii, and dreissenid veligers) and macrozooplankton (e.g., copepods, cladocerans, and macroinvertebrates), all generally greater than 50 μm in maximum dimension on the smallest axis, were analyzed together in a Sedgewick Rafter counting chamber by examination under a compound microscope at a magnification of 40X to 100X.

The preserved samples collected from Step 1 were analyzed at a later date to determine total density of organisms passing through the FSs. Two replicate subsamples containing a minimum of 200 organisms each were examined for each of the preserved samples. Intact organisms that contained organic matter were identified and enumerated using a compound microscope. The preserved samples collected from Steps 2 and 3 were set aside for later analysis, if required. Taxa that were known to occasionally contain individuals below 50 μm in minimum dimension were measured at this time.

3.4.3 Operational Measurements

Flow rates were recorded by magnetic flux flow meters. Pressure readings were also recorded using pressure transducers at multiple points throughout the GSI Facility. However, FS D differential pressure was monitored and calculated differently from the other FSs because this specific FS had a built-in flow control valve located in a position that interfered with GSI monitoring during normal testing. Instead, the FS D developer disabled the flow control for 10 minutes so GSI could measure differential pressure using the GSI pressure sensors.

GSI measured and recorded data on operational and maintenance parameters, including from all the limit switches, positioners, pressure sensors, flow meters and level indicators, using the facility's PLC. A separate data logging computer recorded and saved data from all the limit

switches, positioners, pressure sensors, flow meters and level indicators every five seconds for the entire duration of each test cycle. This information was accessed by the facility's HMI.

All operational data were exported to Microsoft Excel for subsequent analysis. GSI summarized the data by providing averages and standard deviations for the parameters listed below.

- Inlet pressure;
- Outlet pressure;
- Inlet flow; and
- Outlet flow.

From these parameters differential pressure and flow lost to back flushing were calculated. GSI summarized data for each step of each test cycle to evaluate FS operational performance and consistency across test cycles. Data from each step was then averaged across test cycles and divided so that augmented water and non-augmented water could be compared. GSI also documented and reported any mechanical failures, required maintenance events and modifications made to individual FSs during testing.

3.5 Data Processing, Storage, Verification and Validation

GSI personnel recorded sample collection and analysis data by hand (using indelible ink) on pre-printed data collection forms and/or in bound laboratory notebooks that were uniquely-identified and were specific to the GSI FS performance evaluations. The GSI Engineer recorded relevant information and data generated from operation of the various FSs in a bound laboratory notebook that was uniquely-identified (i.e., coded) and specific to the performance evaluations.

Completed data collection forms were secured in uniquely-identified three ring binders, specific to the FS performance evaluations. Biological and water chemistry data that were recorded by hand were manually entered into either a Microsoft Access Database that was designed, developed, and is maintained by the GSI Database Manager, or the data were entered into a Microsoft Excel spreadsheet.

A percentage of biological, chemical and physical data that was recorded by hand and entered into Microsoft Access or Excel was verified against the original raw data by the GSI Senior Quality Assurance/Quality Control (QAQC) Officer. This procedure also included verification of the accuracy of computer-generated data through hand-calculation. The percentage of verified raw data depended upon the amount of raw data that was generated, and ranged from 10 % to 100 % of the original raw data.

All electronic data files are stored on the LSRI's secured Local Area Network (LAN) that can be accessed only by relevant GSI personnel. The GSI Database Manager is the single point of control for access to the LSRI LAN. The LSRI LAN is automatically backed up every 24 hours. The electronic data files are also stored on the GSI's internal SharePoint website (greatshipsinitiative.net), which acts as a secondary data backup/storage mechanism. The GSI Senior QAQC Officer is responsible for archiving and storing all original raw data applicable to

the FS performance evaluations in a climate-controlled, secure archive room at the LSRI for a period of seven years.

3.6 Statistical Analysis

As noted above, biological performance was characterized in terms of absolute organism densities, i.e., total and/or live concentrations per unit volume, in discharge, and as percent reduction of organisms:

$$Percent\,Reduction = \left[1 - \left(\frac{Post\ Density}{Pre\ Density}\right)\right] \times 100\ \%$$

Also as noted above, differential pressure and percent backflush flow ratio were the main operational performance measures for Steps 1 and 3. Differential pressure was calculated as the difference between the average measured pressure post-filter and the average measured pressure pre-filter. The percent backflush flow was a measure of the percentage of intake (i.e., ballast) flow lost to FS backflushing. It was defined using the following equation:

$$Percent\ Backflush\ Flow = \left(\frac{Average\ Backflush\ Flow\ Rate}{Average\ Pre\ Filter\ Flow\ Rate}\right) \times 100\ \%$$

Solids (TSS and POM) removal performance was determined separately for TSS and POM in Step 1 (ambient) and Step 3 (augmented). Percent solids removal of solids performance was defined as the ratio of pre-filter and post-filter TSS concentration or POM concentration:

$$Percent\,Solids\ Removal = \left[1 - \left(\frac{Post\ Filter\ TSS\ or\ POM\ Concentration}{Pre\ Filter\ TSS\ or\ POM\ Concentration}\right)\right] \times 100\ \%$$

Two levels of statistical analysis were applied to FS performance data to determine relationships among operational and biological variables. The first was simple aggregation which involved averaging repeated measurements across the eight test cycles for Step 1 and Step 3 values (per FS) for each of the eight cases (i.e., FS units). The FS units were then ranked in terms of percent removal of total organisms based on two categories of organisms, i.e., organisms ≥ 10 and < 50 μm (i.e., protists) and organisms ≥ 50 μm. The latter category was further analyzed in terms of two size subcategories: microzooplankton, such as rotifers, copepod nauplii, and dreissenid veligers; and macrozooplankton, such as copepods, cladocerans, and macroinvertebrates). Scatter plots and estimated linear regressions were constructed and plotted (i.e., fitted) to determine if:

- FS nominal pore size, differential pressure, or percent backflush flow were related to percent reduction in organisms; and
- FS differential pressure was related to percent backflush flow.

In the second and more complex statistical approach, we applied a multi-level or mixed model analysis to the data. All eight test cycles for each FS were analyzed as individual cases, while still accounting for the correlations associated with repeated measures within FS unit tests i.e. the random effects statistical model.

Within this framework test cycle characteristics like intake density, and filter characteristics like pore size, were analyzed as predictors of outcomes, such as percent reduction or post-filter density, across all test cycles. This analysis was used to assess influences on and associations between FS performance outcomes as if variable conditions under consideration (e.g. intake conditions) were constant across FSs.

4 FILTER SYSTEM PERFORMANCE EVALUATION RESULTS

This section presents results in the following sequence:

- Intake conditions across FS evaluations;
- FS operational performance;
- FS solids removal;
- FS biological performance;
- Correlations and predictors of performance characteristics; and
- Test validity and data quality indicators.

4.1 Intake Conditions Across FS Evaluations

Intake water chemistry and biological composition were assessed for Steps 1 and 3 of each of the four test cycles within each FS unit evaluation to support later analysis of whether intake conditions influence FS performance outcomes. Consolidated information over the course of the evaluation is presented here.

4.1.1 Temperature, Total Suspended Solids, and Particulate Organic Matter

The temperature of the DSH water (as measured daily) decreased throughout the test period (Figure 6), dropping from 18.4 °C at the start of testing (i.e., for FS A and Filtersafe – 40 μm) to 12.3 °C at the end of the test period (i.e., for FSs A and F). Figure 6 shows water temperatures measured over the FS testing period (letters indicate timing of specific FS test cycles, the black line is an estimated linear regression, the downward slope is statistically significant at $p<0.001$).

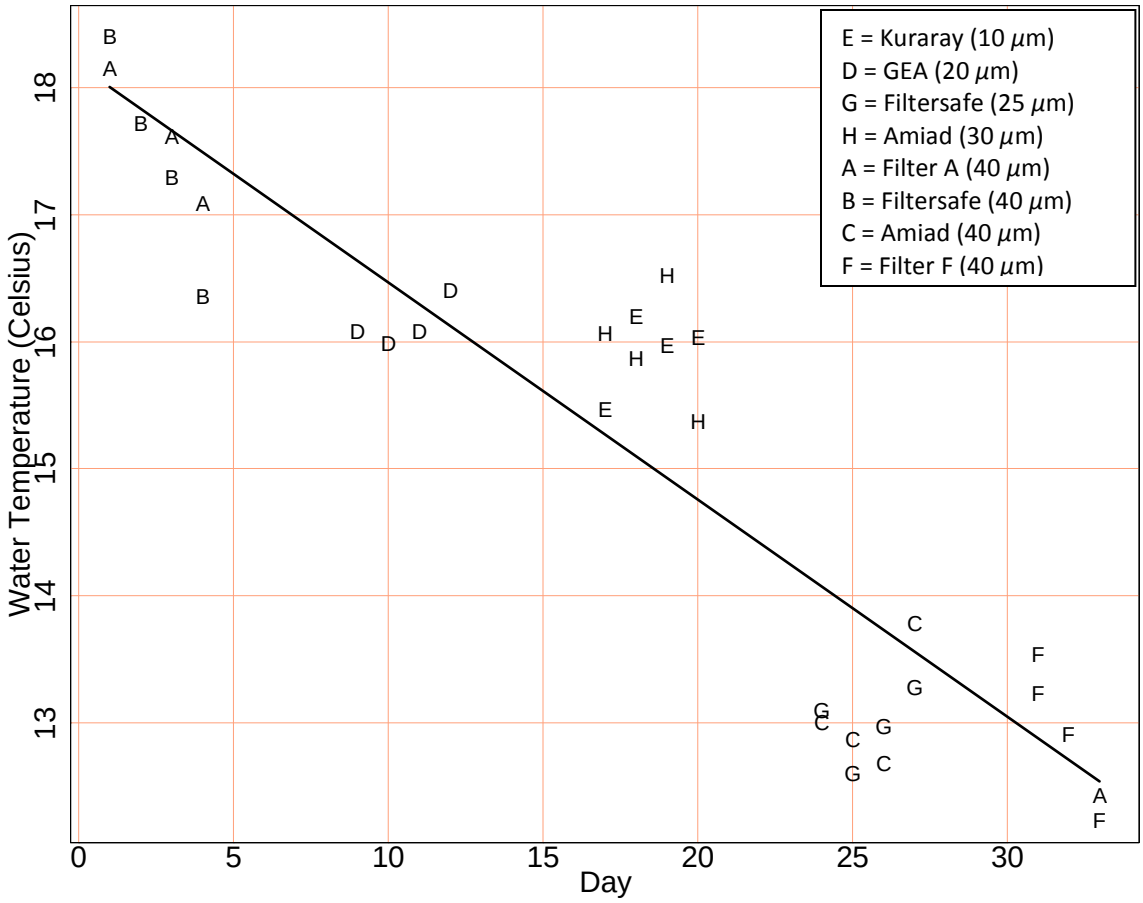


Figure 6. Daily Water Temperature of the Duluth Superior Harbor Measured Prior to the Start of Step 1. Black line is estimated linear regression line indicating a statistically significant (p<0.001) downward trend.

Levels of TSS were fairly uniform on average across FS test cycles, with one notable exception. Figure 7 shows the range of TSS measured in grab samples collected from pre-FS intake water. The slopes of the fitted red (Step 3) and black (Step 1) linear trend lines in Figure 7 are not statistically significant, indicating an absence of statistically significant change across FS unit test cycles. The only significant difference (p<0.05) was between TSS levels across FSs in Step 1 vs. Step 3, due to the experimental manipulation (i.e., augmentation of the water) during Step 3. Step 1 values, reflecting ambient TSS concentration in the DSH, ranged from 5.9 mg/L to 19.5 mg/L (Figure 7). Step 3 TSS values, reflecting ambient conditions augmented with Arizona Fine Test Dust, ranged mostly from 16.4 mg/L to 33.2 mg/L. On one test day (i.e., 14 September 2013), TSS reached an average of 55.1 mg/L for FS A (data not presented) and 43.5 mg/L for Filtersafe (40 μm) due to a GSI Facility error (Figure 7). The GSI team consulted with the FS developers involved (i.e., developer of FS A and Filtersafe) as to whether they would like to repeat the test cycles at a lower TSS, but both developers elected to keep the test cycle to test FS A's and the Filtersafe (40 μm)'s capacity to handle higher loads. However, on that same test day there was also a nine minute gap in the solids injection during the test cycle with FS A. Therefore, GSI deemed the test cycle with FS A invalid and repeated the test cycle in mid-October. The GSI target minimum TSS level for Step 3 (horizontal green line in Figure 7) was

always met except for in three test cycles. The below target TSS levels in these test cycles were a result of DSH TSS levels dropping precipitously during the course of the test cycles such that GSI supplementation, based on pre-test harbor TSS assessments, proved insufficient. Because the TSS levels were nonetheless robust and the end of the testing season was approaching, GSI accepted the below target conditions.

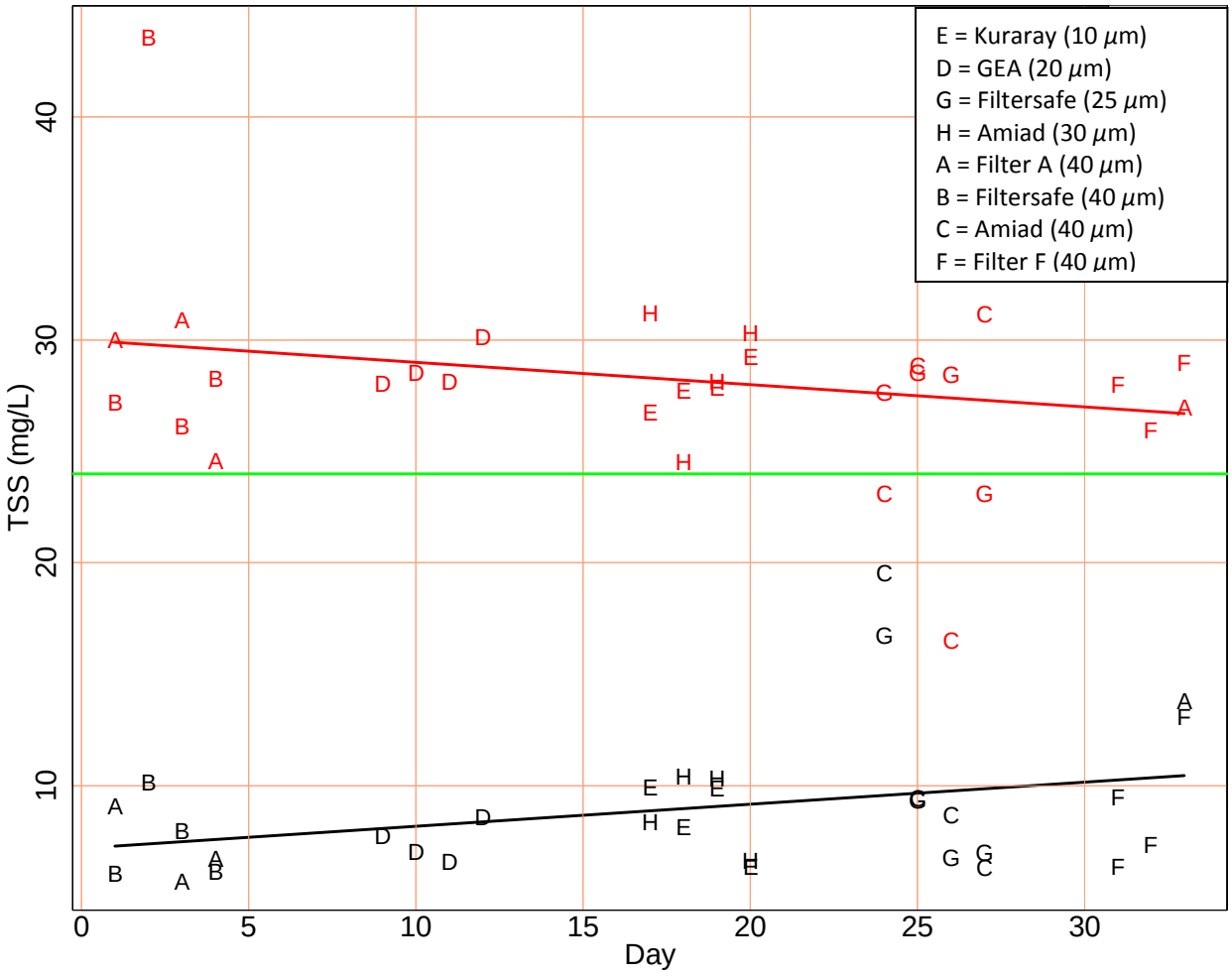


Figure 7. Range of Total Suspended Solids (TSS) Concentration Measured in Pre-Filter Grab Samples Collected During Step 1 (Ambient; Black font) and Step 3 (Augmented; Red font). Green line indicates target minimum TSS level in Step 3. Black and red lines are estimated linear regression lines showing no statistical difference across FS test cycles.

The addition of Fine Arizona Test Dust in Step 3 also led to slightly but significantly (p<0.001) elevated POM levels relative to Step 1 (Figure 8). The range of POM concentration during Step 1 was 0.9 mg/L to 3.0 mg/L (Figure 8). The range of POM concentration during Step 3 was 1.6 mg/L to 3.1 mg/L (Figure 8). However, average POM for each step was generally consistent across FS evaluations.

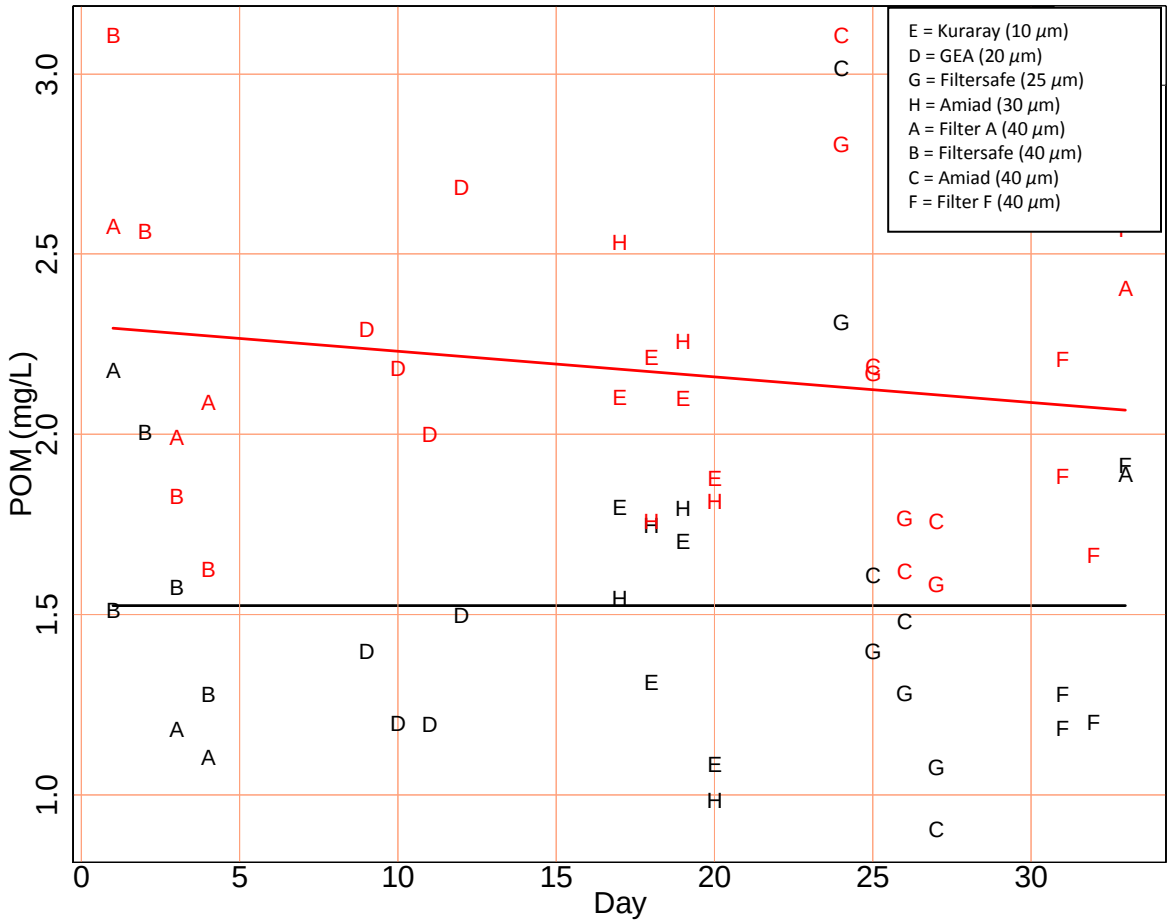


Figure 8. Range of Particulate Organic Matter (POM) Concentration Measured in Pre-Filter Grab Samples Collected During Step 1 (Ambient; Black font) and Step 3 (Augmented; Red font). Black and red lines are estimated linear regression lines showing no statistically significant change across FS test cycles.

4.1.2 Intake Organism Density and Diversity

For the > 10 μm and < 50 μm size class (i.e., protists), the average total cell density at intake (i.e., pre-FS) was approximately 5,500 cells/mL on the first day of the test period (Figure 9). This starting density decreased linearly by an average of 133 total cells/mL per day (significant linear trend at p<0.001, green line in Figure 9 for Steps 1 and 3 combined data) to an approximate average of 1,300 total cells/mL on the final day of the test period (Figure 9) consistent with seasonal trends.

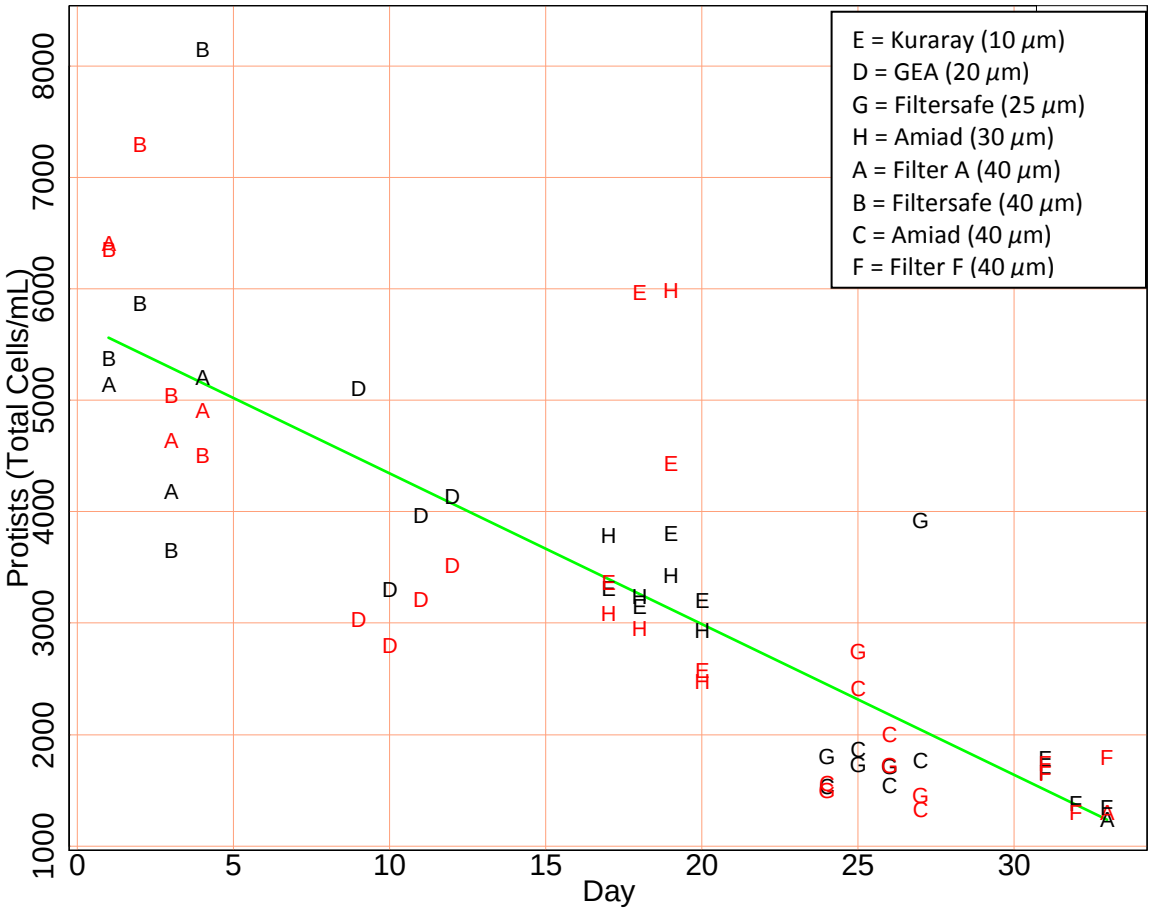


Figure 9. Total Cell Density of Organisms in the > 10 μm and < 50 μm Size Class (i.e., Protists) as Measured in Step 1 (Ambient; Black font) and Step 3 (Augmented; Red font) Intake Samples. Black font is Step 1; red font is Step 3. Mean pre-filter system protist density dropped in a significant (*p*<0.001) linear trend by about 133 total cells per day (green line).

Common protist taxa collected during these tests included filamentous diatoms; free-living centric diatoms; filamentous blue-green algae; colonial, motile green algae; and *Cryptomonas*- and *Chroomonas*-type flagellates. Community composition in terms of morphological categories was similar across test cycles (Figure 10). Needle forms varied from 2% to 4% of the assemblage, and large globular forms ranged from 4% to 6%. More dominant were small globular forms, which ranged from 21% to 52% of the assemblage, and filamentous forms were the most dominant, varying from 41% to 71% of the assemblage. (Figure 10).

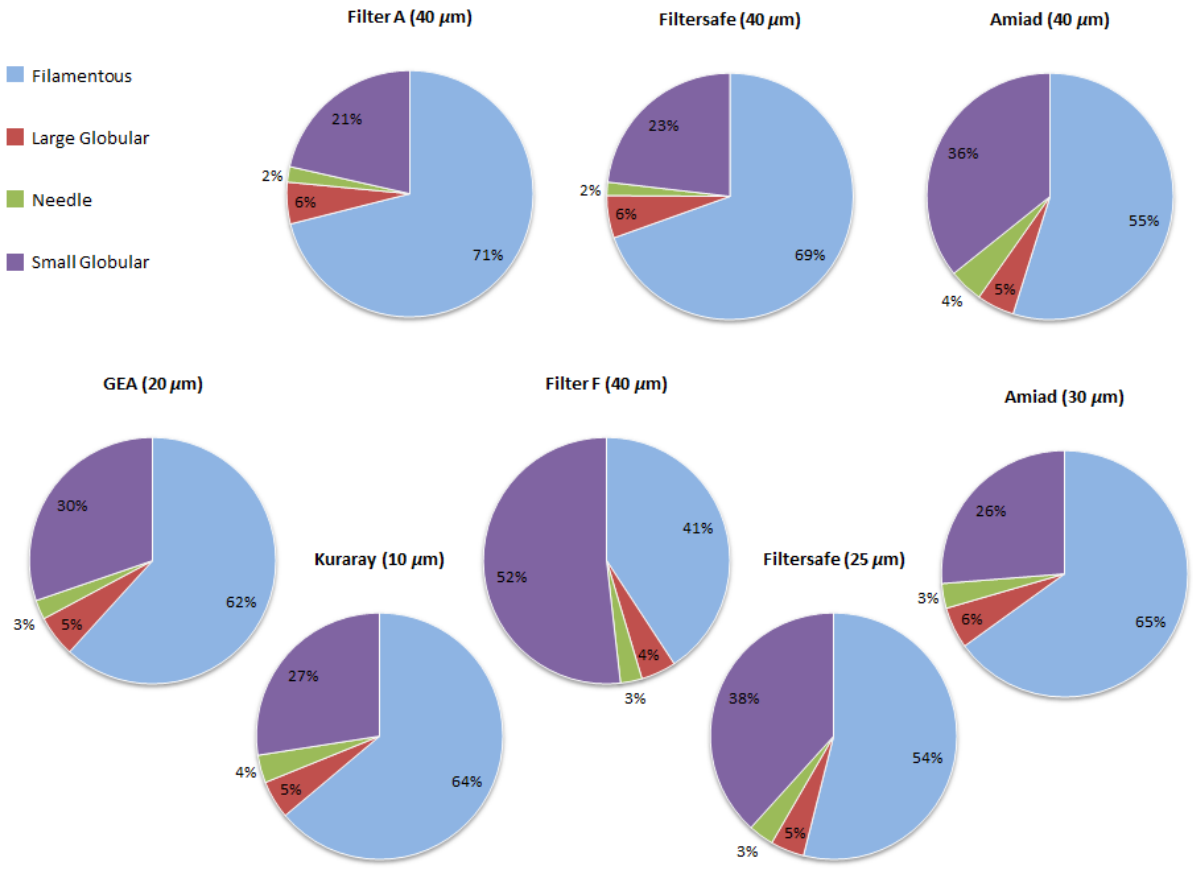


Figure 10. Protist Community Composition in Terms of Morphological Classification as Measured in Intake Samples. Each pie diagram represents the average of all 12 samples collected for Steps 1, 2 and 3.

For the ≥ 50 μm size class, total zooplankton intake densities were high (i.e., > 200,000/m^3) during the entire test period. On average, 54 % of the zooplankton in the intake samples were live (data not shown). The source water always contained more than five species from at least three distinct phyla, meeting ETV protocol requirements for organism diversity (USEPA, 2010). As noted above, DSH zooplankton fall into two size subcategories, both largely ≥ 50 μm in minimum dimension[5]. During these tests, densities of the smaller subcategory of zooplankton, i.e., microzooplankton, were largely stable over the entire test period and not significantly related to time of day (i.e., AM vs. PM), or test cycle; the estimated green linear trend line shown in Figure 11 shows an apparent drop in density over the testing period, but the trend is not statistically significant. For samples collected during Step 3, the microzooplankton size subclass was dominated by the phylum Rotifera, including soft bodied (illoricate) species, as well as, hard bodied species possessing lorica (Figure 12). Similar to microzooplankton, the density of the macrozooplankton also was stable over the course of testing, with a positive, non-significant linear trend over time (plot not shown).

[5] A proportion (historically less than 20 %) of the microzooplankton have minimum dimensions slightly less than 50 μm; these smaller organisms were not excluded from this analysis.

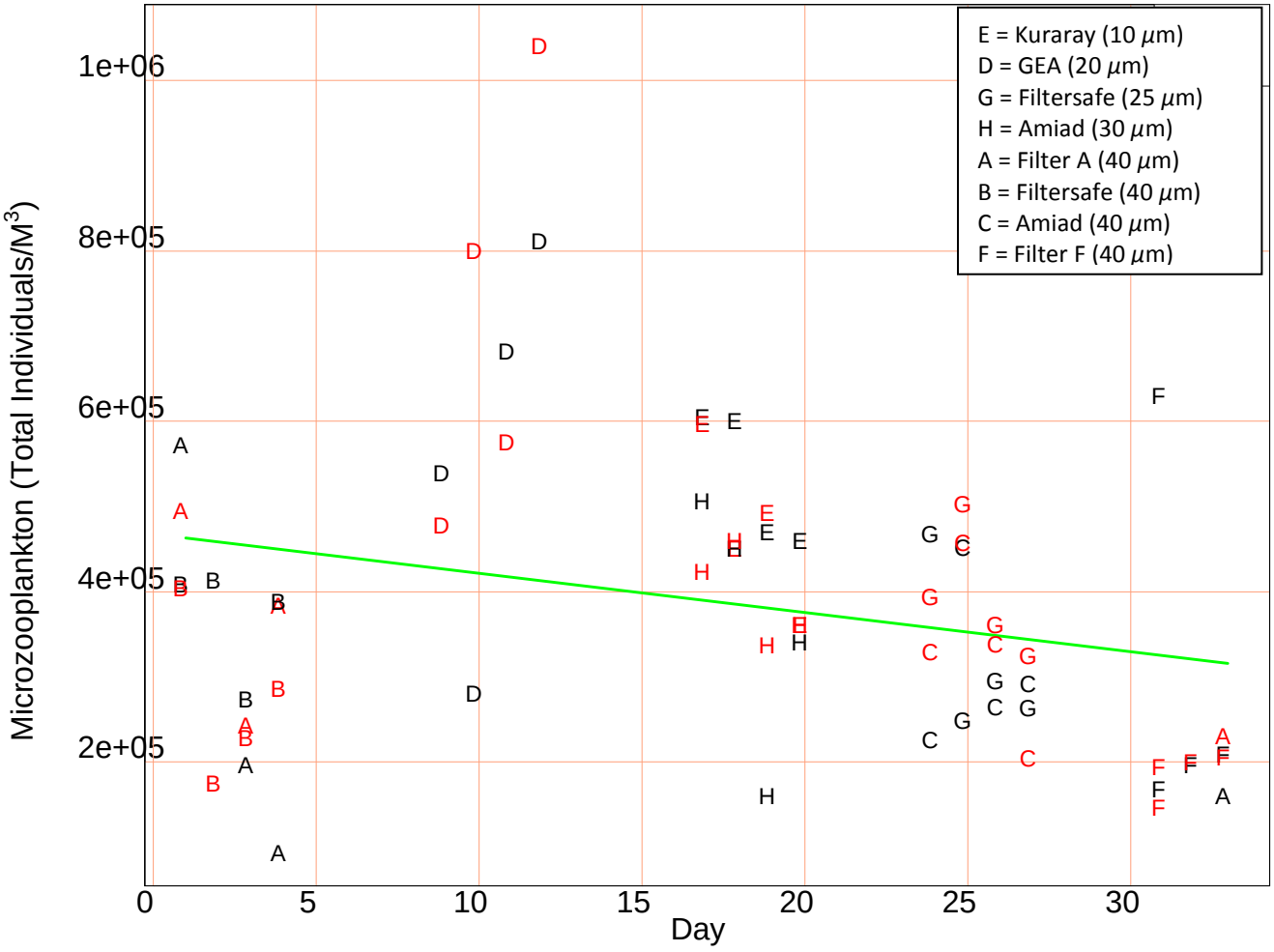


Figure 11. Total Microzooplankton Density as Measured in Step 1 (Ambient; Black font) and Step 3 (Augmented; Red font) Intake Samples. Linear decline in mean densities over time (green line) is not statistically significant.

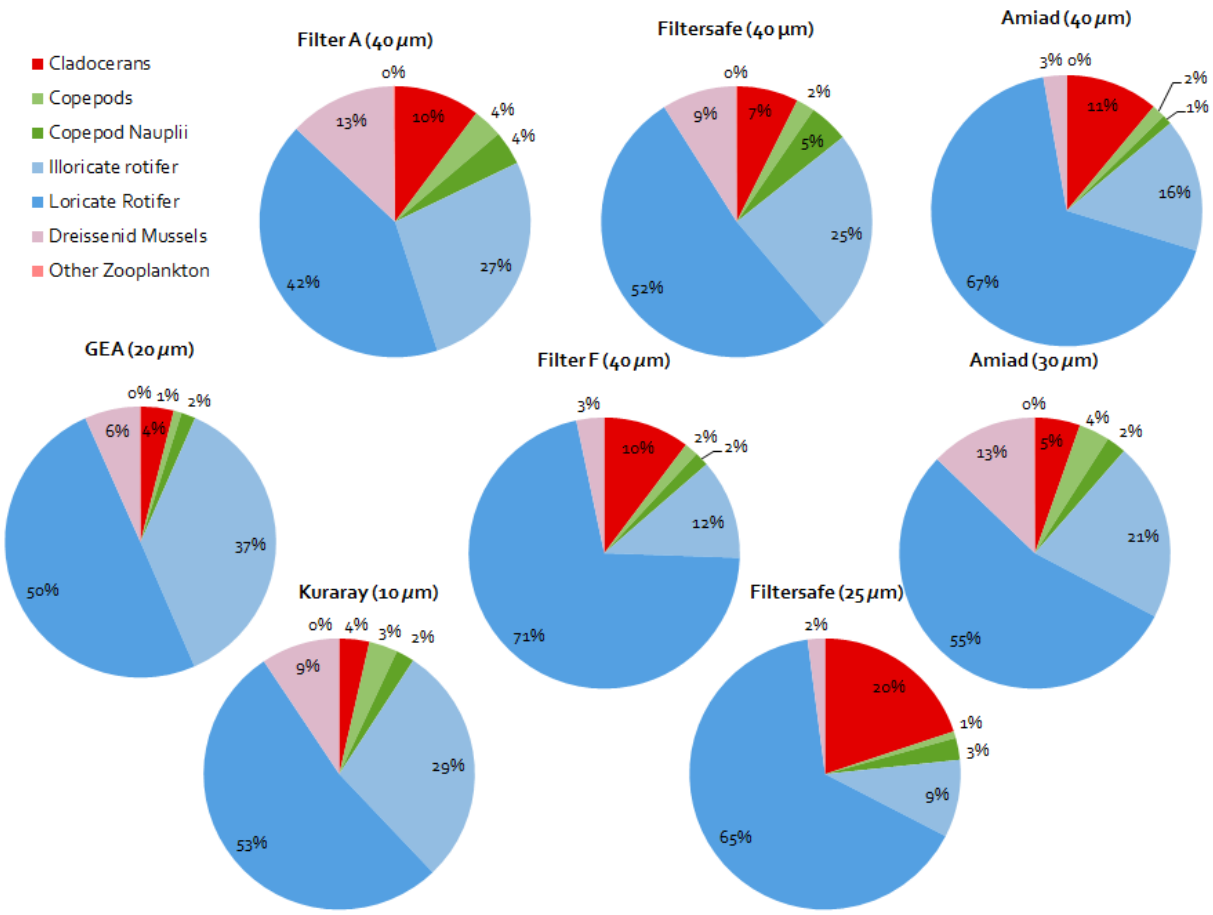


Figure 12. Zooplankton Community Composition in Terms of Major Taxonomic Group as Measured in Intake Samples from Step 3.

4.2 FS Operational Performance

Each FS performed without mechanical failure and without requiring manual servicing for the duration of testing. Operational performance of the FSs in terms of pressure differential and percent flow lost to backflush as a percent of total water processed (Table 9) ranged from 12.8 to undetectably low (under 2 %; Table 9). Each FS backflushed at least some water to clean its filter material, but at times that volume was below the GSI level of detection; in these instances, the values are reported as 0 % backflush.

Table 9. Filter System Operational Performance in Terms of Pressure Differential and Percent Flow Lost to Backflush as a Percent of Total Water Processed for Steps 1 and 3.

Step 1 (Non-Augmented Water)								
	Kuraray (10 μm)	GEA (20 μm)	Filtersafe (25 μm)	Amiad (30 μm)	Filter A (40 μm)	Filtersafe (40 μm)	Amiad (40 μm)	Filter F (40 μm)
Avg. Pre-Filter Line Pressure (bar)	1.67	2.56	2.97	2.13	2.30	2.43	2.17	3.02
Avg. Post-Filter Line Pressure (bar)	1.10	1.12	2.74	1.72	1.71	1.89	1.78	2.57
Avg. Differential Pressure (bar)	0.58	*	0.24	0.41	0.59	0.54	0.39	0.45
Backflush Flow Ratio (%)	0.0	12.8	0.0	7.7	0.5	0.0	7.8	2.4
Avg. Pre-Filter Flow Rate (m3/hr)	243	268	146	375	307	196	375	255
Avg. Post-Filter Flow Rate (m^3/hr)	244	238	147	348	305	197	348	249
Step 3 (Augmented Water)								
	Kuraray (10 μm)	GEA (20 μm)	Filtersafe (25 μm)	Amiad (30 μm)	Filter A (40 μm)	Filtersafe (40 μm)	Amiad (40 μm)	Filter F (40 μm)
Avg. Pre-Filter Line Pressure (bar)	1.69	2.48*	2.96	2.13	2.23	2.42	2.18	2.98
Avg. Post-Filter Line Pressure (bar)	1.06	2.11*	2.74	1.71	1.69	1.96	1.78	2.62
Avg. Differential Pressure (bar)	0.64	0.36*	0.23	0.41	0.54	0.45	0.40	0.36
Backflush Flow Ratio (%)	0	10*	2	6	5	0	6	4
Avg. Pre-Filter Flow Rate (m^3/hr)	238	275*	151	373	324	199	373	262
Avg. Post-Filter Flow Rate (m^3/hr)	243	249*	147	348	305	197	348	249

* As noted in Section 3.4.3, the GEA (20 μm) FS differential pressure value was based on a different amount of monitoring time than for the other FSs. This specific FS had a built-in flow control valve located in a position that interfered with GSI monitoring during normal testing.

4.3 FS Solids Removal Performance

4.3.1 Total Suspended Solids

TSS removal efficiency for Step 1 (i.e., non-augmented) test cycles ranged from 7.2 % to 29.2 % (Table 10). TSS removal efficiency for Step 3 (i.e., augmented) test cycles ranged from 11.2 % to 63.1 % (Table 11). Thus, TSS removal efficiency was generally higher with augmented TSS in Step 3 (augmented particle size ranged from 1 μm to 120 μm, with 99.5 % of the Test Dust under 80 μm).

Table 10. Total Suspended Solids (TSS) Removal Efficiency during Step 1 (i.e., Non-Augmented) Test Cycles.

Filter System (Nominal Pore Size)	Step	Pre-Filtration Average TSS (mg/L)	Post-Filtration Average TSS (mg/L)	Solids Removal Efficiency (%)
Kuraray (10 μm)	1	8.6	6.1	29.2
GEA (20 μm)	1	7.6	6.6	12.6
Filtersafe® (25 μm)	1	10.0	8.7	12.8
Amiad (30 μm)	1	9.0	7.9	11.9
Filter A (40 μm)	1	8.9	8.1	8.2
Filtersafe® (40 μm)	1	7.6	6.2	18.4
Amiad (40 μm)	1	11.1	10.2	8.1
Filter F (40 μm)	1	9.0	8.4	7.2

Table 11. Total Suspended Solids (TSS) Removal Efficiency during Step 3 (i.e., Augmented) Test Cycles.

Filter System (Nominal Pore Size)	Step	Pre-Filtration Average TSS (mg/L)	Post-Filtration Average TSS (mg/L)	Solids Removal Efficiency (%)
Kuraray (10 μm)	3	27.9	10.3	63.1
GEA (20 μm)	3	28.8	21.0	27.2
Filtersafe® (25 μm)	3	27.0	19.5	27.8
Amiad (30 μm)	3	28.5	22.9	19.8
Filter A (40 μm)	3	28.1	22.3	20.6
Filtersafe® (40 μm)	3	31.3	27.0	13.8
Amiad (40 μm)	3	25.0	22.2	11.2
Filter F (40 μm)	3	29.1	23.8	18.4

4.3.2 Particulate Organic Matter

The removal efficiency for POM ranged from 5.4 % to 52.5 % for Step 1 (i.e., non-augmented) test cycles (Table 12), and from 11.9 % to 49.4 % in Step 3 (i.e., augmented) test cycles (Table 13). The addition, the Arizona Fine Test Dust in Step 3 resulted in pre-filtration POM levels about 0.5 mg/L higher than in Step 1.

Table 12. Percent Removal of Particulate Organic Matter (POM) Across Filters during Step 1 (i.e., Non-Augmented) Test Cycles.

Filter System (Nominal Pore Size)	Step	Pre-Filter Average POM (mg/L)	Post-Filter Average POM (mg/L)	Solids Removal Efficiency (%)
Kuraray (10 μm)	1	1.5	0.7	52.5
GEA (20 μm)	1	1.3	1.0	26.4
Filtersafe® (25 μm)	1	1.5	1.0	34.4
Amiad (30 μm)	1	1.5	1.1	26.2
Filter A (40 μm)	1	1.6	1.3	20.3
Filtersafe® (40 μm)	1	1.6	1.1	31.3
Amiad (40 μm)	1	1.8	1.4	18.6
Filter F (40 μm)	1	1.4	1.3	5.4

Table 13. Percent Removal of Particulate Organic Matter (POM) Across Filters during Step 3 (i.e., Augmented) Test Cycles.

Filter System (Nominal Pore Size)	Step	Pre-Filtration Average POM (mg/L)	Post-Filtration Average POM (mg/L)	Solids Removal Efficiency (%)
Kuraray (10 μm)	3	2.1	1.1	49.4
GEA (20 μm)	3	2.3	1.7	26.1
Filtersafe® (25 μm)	3	2.1	1.5	29.8
Amiad (30 μm)	3	2.1	1.7	20.2
Filter A (40 μm)	3	2.3	1.8	19.8
Filtersafe® (40 μm)	3	2.3	1.9	17.6
Amiad (40 μm)	3	2.2	1.9	13.8
Filter F (40 μm)	3	2.1	1.9	11.9

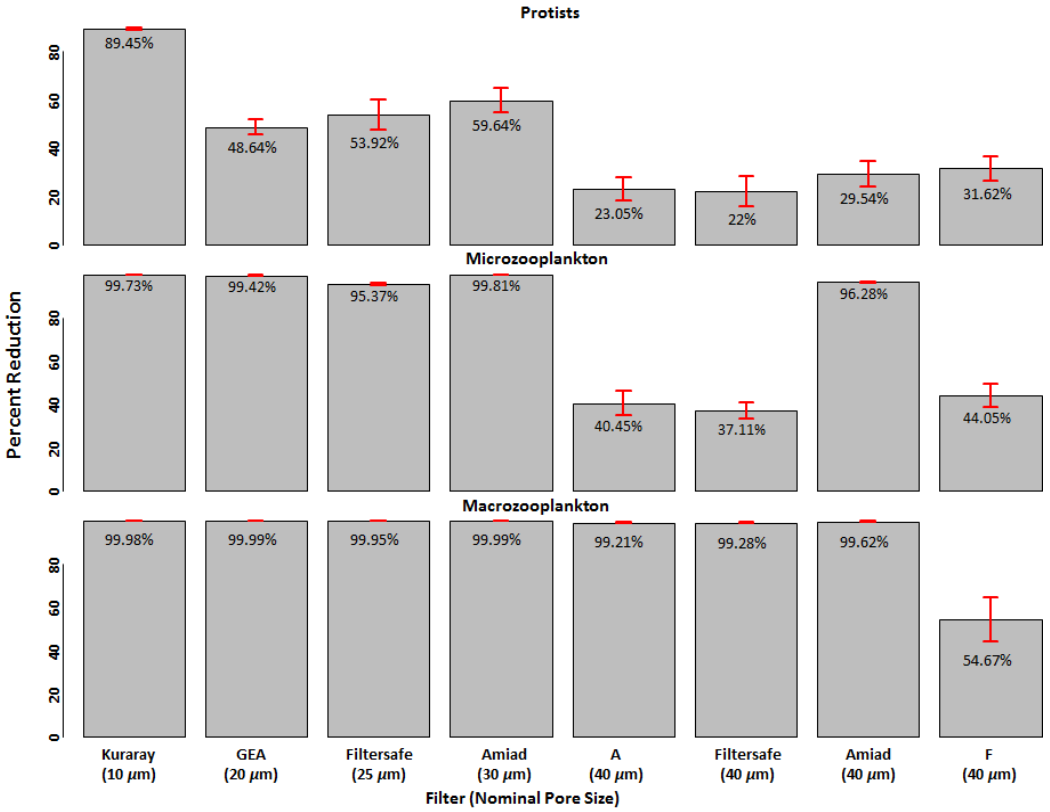
4.4 FS Biological Performance

In this section, biological performance results are presented as average percent reduction of total organisms in both Step 1 and Step 3 combined (n=8 test cycles per FS), and absolute numbers of

live zooplankton and total protists in discharge averaged over all Step 3 values (*n*=4 test cycles per FS).

As noted earlier, zooplankton in freshwater assemblages fall into two distinct size subcategories: macrozooplankton, in which all individuals are significantly greater than 50 μm in minimum dimension; and the smaller microzooplankton, the populations of which are almost entirely above the 50 μm in minimum dimension size, but may include a small proportion of individuals which straddle the regulatory size cut-off (Figure 12). The microzooplankton within the $\geq$ 50 μm size class, and the > 10 μm and < 50 μm size class (i.e., protists) were by far the most numerous in the DSH assemblage during these tests, and the most challenging for the FSs tested.

The results for protists, microzooplankton, and macrozooplankton are summarized as average percent reductions across FSs (Figure 13). In general, the mean percent reductions of protists across FSs ranged widely from 22 % to 89 % (Figure 13; top graph). Microzooplankton removal efficiencies also ranged widely across FSs, from 37 % to 99.9 % (Figure 13; middle graph). Macrozooplankton, the least abundant and least challenging size class for the FSs were almost completely removed by all but FS F (i.e., average percent reduction ranging from 54.65 % to 99.98 %; Figure 13).



Size Class	Parameter	Filter (Nominal Pore Size)							
		Kuraray (10 μm)	GEA (20 μm)	Filtersafe® (25 μm)	Amiad (30 μm)	Filter A (40 μm)	Filtersafe® (40 μm)	Amiad (40 μm)	Filter F (40 μm)
Protists (≥ 10 and < 50 μm)	Pre-Filter Density, #/mL	3,730 ± 370	3,655 ± 269	2,085 ± 299	3,496 ± 379	4,139 ± 661	5,777 ± 523	1,755 ± 121	1,591 ± 72
	Post-Filter Density, #/mL	385 ± 30	1,828 ± 79	886 ± 146	1,367 ± 168	3,102 ± 474	4,306 ± 215	1,208 ± 63	1,068 ± 44
	Reduction, %	89.5 ± 0.7	48.6 ± 3.2	53.9 ± 6.3	59.6 ± 5.1	23.1 ± 4.7	22.0 ± 6.1	29.5 ± 5.3	31.6 ± 5.1
Microzooplankton (≥ 50 μm*)	Pre-Filter Density, #/m^3	504,636 ± 32,014	648,329 ± 81,548	358,858 ± 33,297	383,166 ± 38,682	296,994 ± 59,477	322,719 ± 32,731	320,989 ± 33,593	245,404 ± 55,557
	Post-Filter Density, #/m^3	1,990 ± 485	4,437 ± 1,633	16,591 ± 2,053	783 ± 163	169,279 ± 34,902	198,122 ± 18,644	11,786 ± 1,633	121,415 ± 9,823
	Reduction, %	99.7 ± 0.1	99.4 ± 0.1	95.4 ± 0.5	99.8 ± 0.1	40.4 ± 5.6	37.1 ± 3.7	96.3 ± 0.3	44.0 ± 5.2
Macrozooplankton (≥ 50 μm)	Pre-Filter Density, #/m^3	33,107 ± 2,959	46,895 ± 5,877	82,428 ± 12,906	38,210 ± 7,573	56,496 ± 6,978	37,645 ± 5,418	66,277 ± 21,566	52,917 ± 14,764
	Post-Filter Density, #/m^3	15 ± 5	8 ± 5	119 ± 39	7 ± 2	429 ± 137	261 ± 134	163 ± 130	24,370 ± 9,980
	Reduction, %	99.96 ± 0.01	99.98 ± 0.01	99.87 ± 0.03	99.98 ± 0.01	99.26 ± 0.18	99.32 ± 0.39	99.53 ± 0.27	54.65 ± 10.11

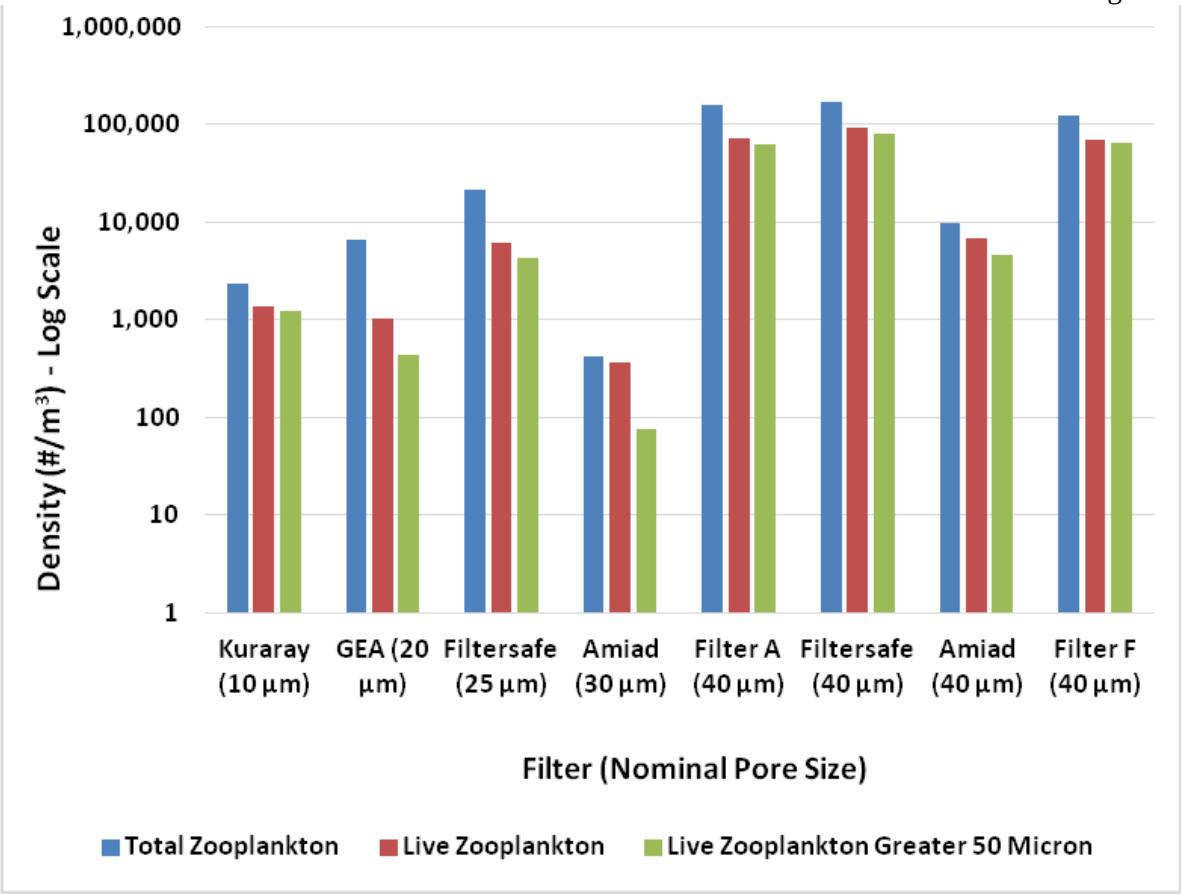
*See Section 4.4.1.1 for proportion of subsized and dead zooplankton in post-FS counts.

Figure 13. Average (± Standard Error of the Mean, N=8) Percent Reduction of Protists (Organisms in the ≥ 10 μm and < 50 μm Size Class; top third), Microzooplankton (the Majority of Organisms in the ≥ 50 μm Size Class; middle), and Macrozooplankton (Organisms in the ≥ 50 μm Size Class; bottom third) by Filter System Unit.

Mixed model results indicate that within all organism size and size sub-classes, the majority of the total variation in performance was attributable to differences in performance across the FS units themselves, rather than other effects like variable intake conditions. For protists, FSs accounted for 73 % of the total variation (Intra-class correlation = 0.73), a highly significant proportion of the overall data variation (chi-square = 55.11, df = 1, $p<0.001$). For microzooplankton, FSs accounted for 92 % of the total variation (Intra-class correlation = 0.9292), which was a highly significant proportion (chi-square = 123.72, df = 1, $p<0.001$). For macrozooplankton, FSs accounted for 70 % of the total variation (Intra-class correlation = 0.70), a highly significant proportion of the overall data variation (chi-square = 50.12, df = 1, $p<0.001$) although this was largely due to a single FS (F).

4.4.1.1 Proportion of Subsized and Dead Zooplankton in Post-FS Counts

As noted previously, the microzooplankton size subclass may include some percentage of organisms which fall outside the regulatory size class of "live organisms ≥ 50 μm in minimum dimension." Some are less than 50 μm in minimum dimension, and some proportion of organism densities at intake and discharge will be dead, a natural condition of the assemblage potentially amplified by lethal effects of the FSs. The density estimates for total zooplankton, live zooplankton, and live zooplankton ≥ 50 μm in Step 3 post-FS samples are shown in Figure 14. The graph shows that total organism densities, largely analyzed in this report, are a conservative estimate of FS performance *vis a vis* the USCG regulatory metric of live organisms ≥ 50 μm. It also shows that the relative ranking of FSs is almost perfectly preserved from assessments of total zooplankton, to only live zooplankton, to only live zooplankton ≥ 50 μm (Figure 14).



Filter System (Nominal Pore Size)	Post-Filtration Average Total Zooplankton (#/m^3)	Post-Filtration Average Live Zooplankton (#/m^3)	Post Filtration Average Live Zooplankton ≥50 µm (#/m^3)
Kuraray (10 µm)	2,336 ± 834	1,355 ± 582	1,209 ± 573
GEA (20 µm)	6,555 ± 2,978	1,029 ± 96	431 ± 32
Filtersafe® (25 µm)	21,219 ± 999	6,078 ± 906	4,243 ± 660
Amiad (30 µm)	419 ± 66	368 ± 63	75 ± 3
Filter A (40 µm)	159,622 ± 24,889	71,272 ± 9,158	62,841 ± 6,953
Filtersafe® (40 µm)	171,661 ± 17,743	93,345 ± 12,950	79,297 ± 11,323
Amiad (40 µm)	9,790 ± 1,340	6,907 ± 1,066	4,551 ± 904
Filter F (40 µm)	124,441 ± 19,408	69,322 ± 14,234	64,211 ± 15,061

Figure 14. Comparison of the Average Densities (#/m^3) of Total Zooplankton, Live Zooplankton, and Estimated Live Zooplankton ≥ 50 µm in Post-Filter Samples (Step 3 Data Only).

4.5 Correlations and Predictors of FS Performance Characteristics

As noted above, the simple aggregation model describes the simple relationships evident across measured parameters and FS characteristics without controlling for random influences, such as variations in intake conditions, or nominal pore sizes. The results from the mixed model analysis describe relationships between FS biological and operational performance controlling for variability in intake conditions and nominal pore sizes.

4.5.1 Simple Relationships Between Biological Performance and Operational Performance Characteristics

Nominal pore size, pressure differential and percent backflush flow were analyzed using simple aggregation to detect linkages with FS organism percent reductions across organism size classes. There was only a marginally significant correlation between FS nominal pore size and percent reduction of total microzooplankton (negative, p=0.06, Figure 16), and between FS nominal pore size and post filtration absolute density of live zooplankton $\geq$ 50 μm (positive, p=0.06, Figure 17). However, FS nominal pore size was significantly negatively correlated with percent reduction of protists (p=0.003, Figure 18). Nominal pore size was not significantly correlated with percent removal of organisms in the larger zooplankton size subclass (p=0.38, Figure 19), i.e., macrozooplankton, as these organisms were almost completely removed across all FSs tested irrespective of nominal pore size.

FS nominal pore size was not a predictor of pressure differential (p=0.89, Figure 20) or backflush flow percent (p = 0.80, Figure 21). FS backflush flow percent and pressure differential also were not significantly related to percent removal of organisms across taxa (plots not shown).

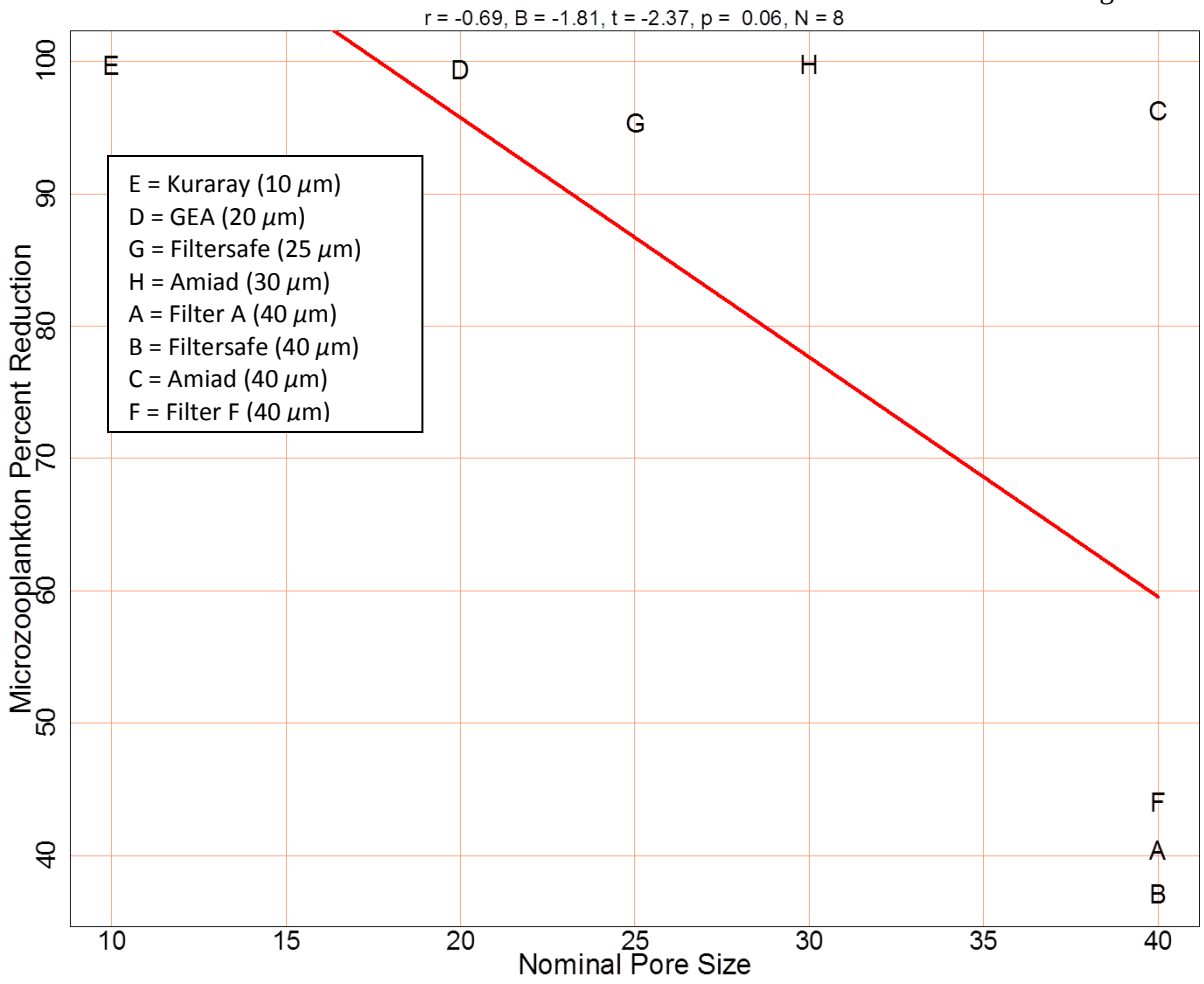


Figure 15. Marginally Significant (*p*=0.06), Negative Linear Relationship (Red Line) Between Average Percent Reduction in Total Microzooplankton (N=8) and Filter System (FS) Nominal Pore Size.

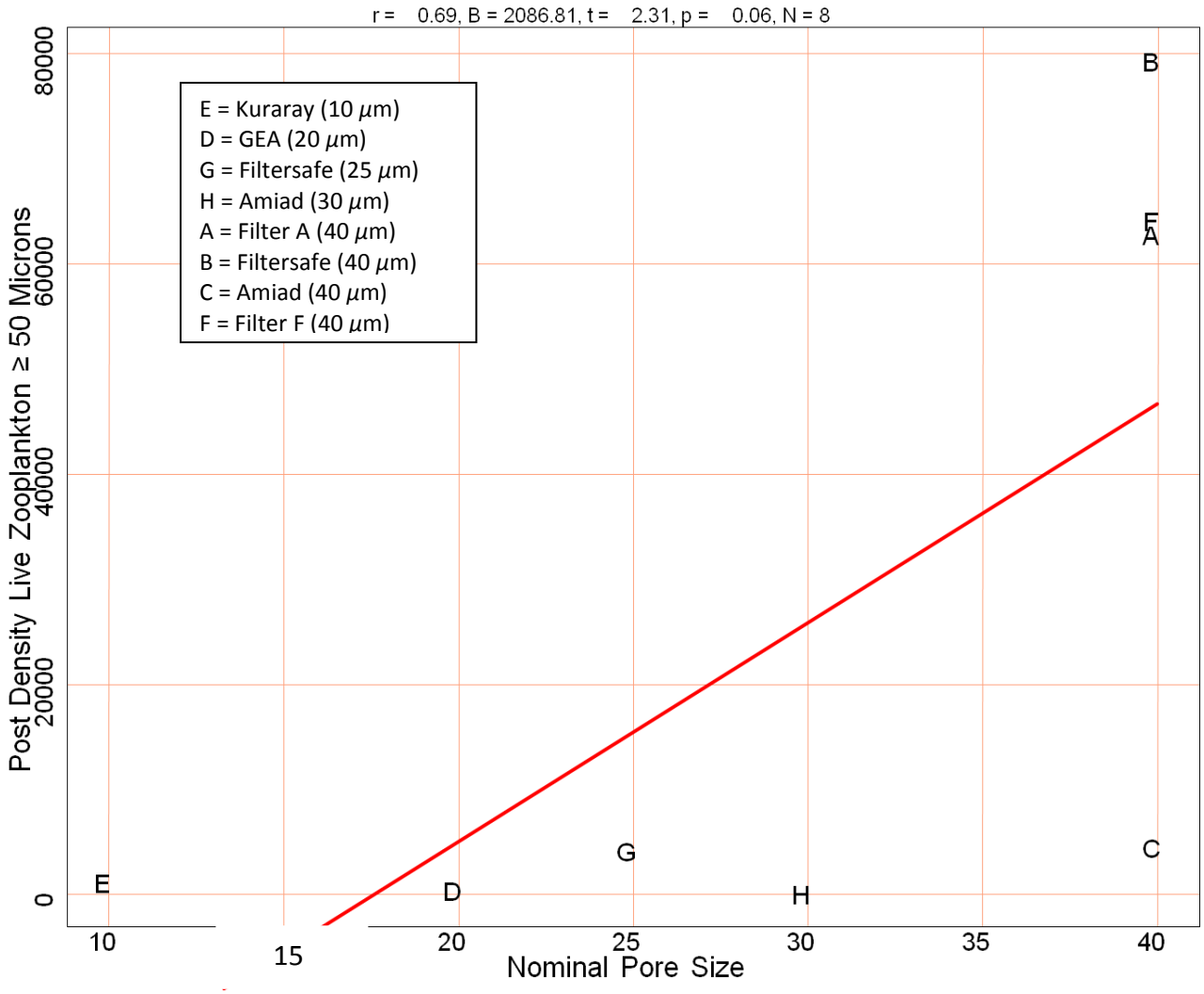


Figure 16. Marginally Significant (*p*=0.06), Positive Linear Relationship (Red Line) Between Post-Filtration Density of Live Zooplankton ≥ 50 microns (N=8) and Filter System (FS) Nominal Pore Size.

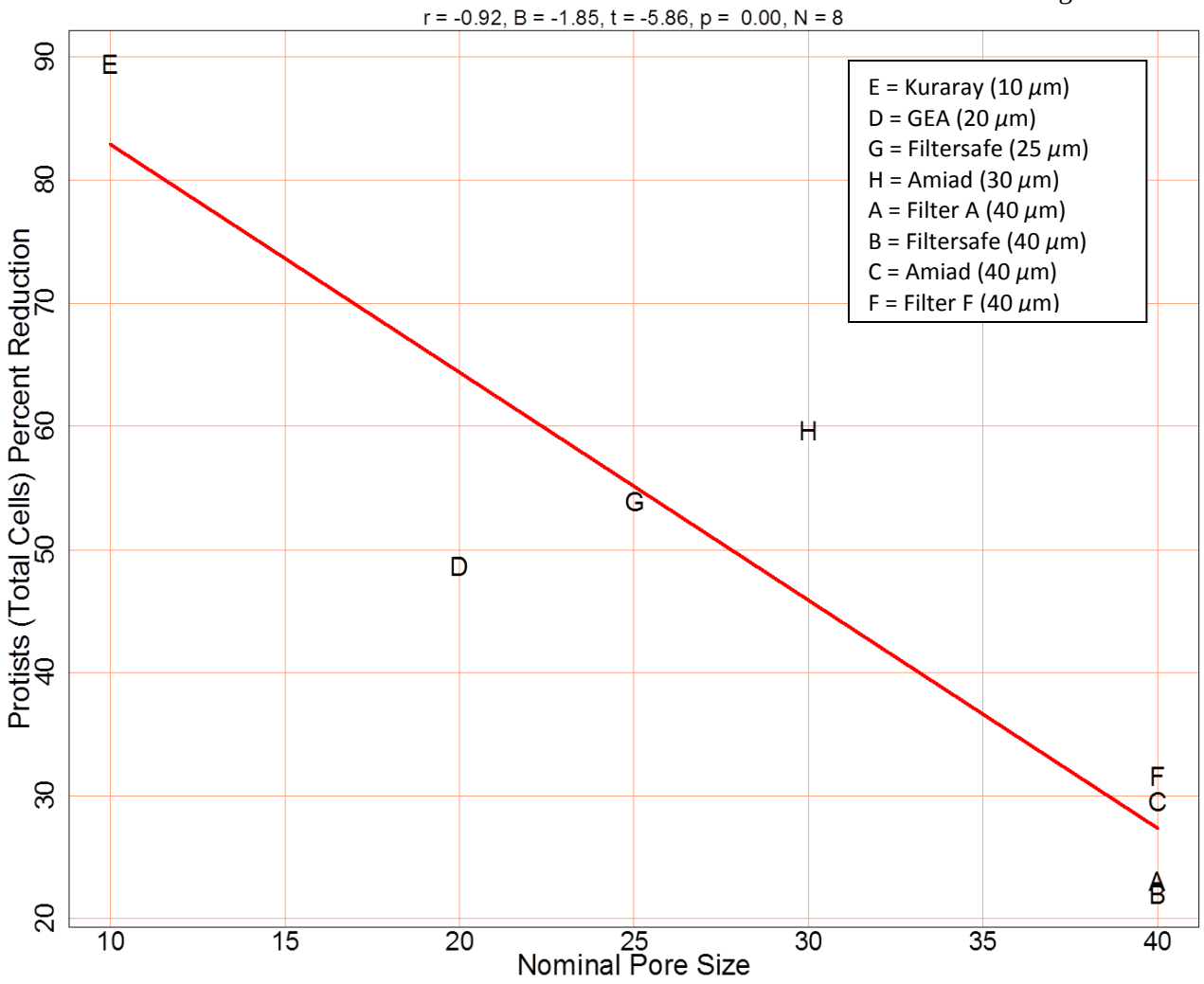


Figure 17. Significant (p<0.05) Negative Linear Relationship (Red Line) Between Average Percent Reduction (N=8) of Total Protists and Nominal Pore Size.

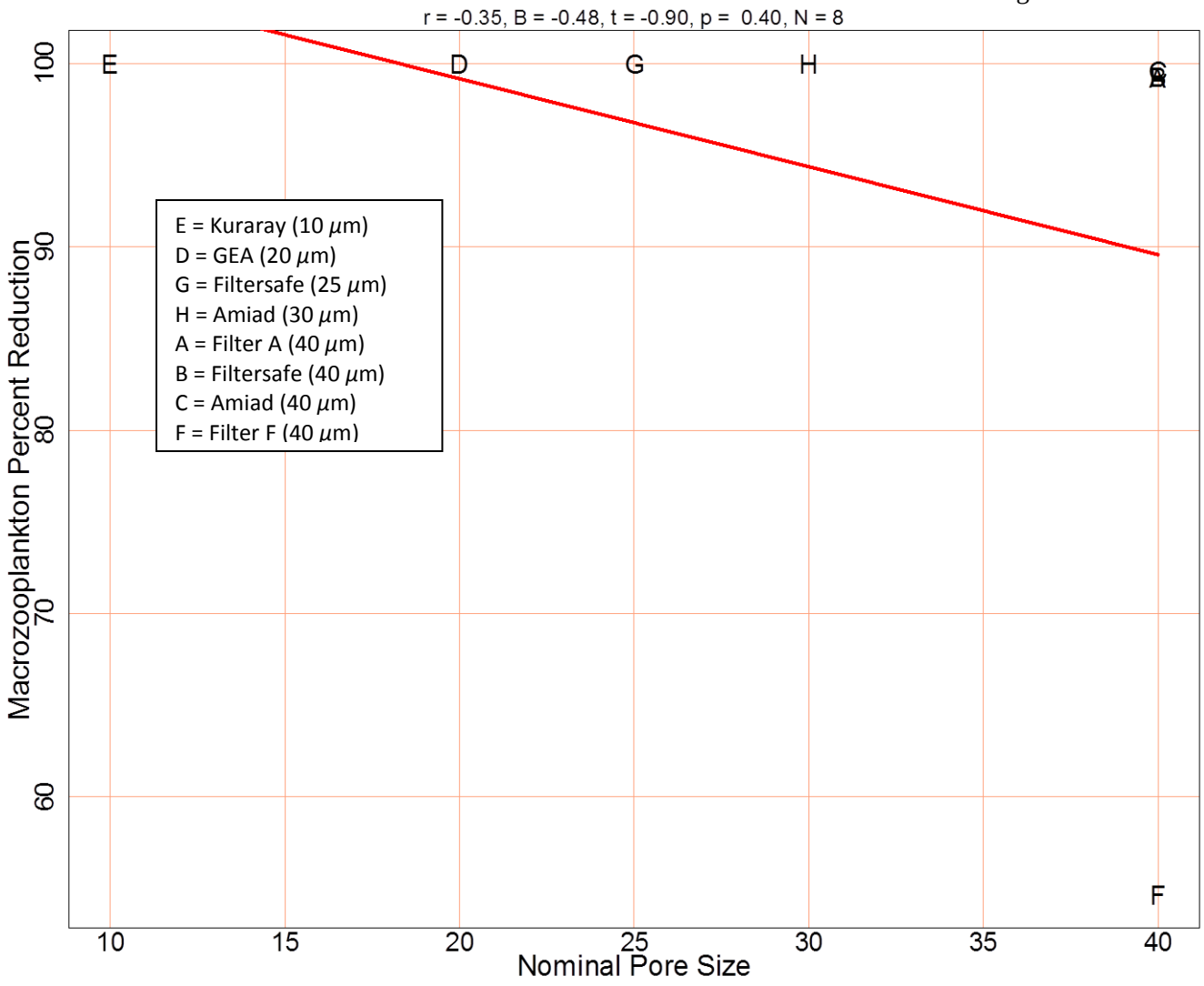


Figure 18. Non-Significant Linear Relationship Between Average Percent Reduction in Total Macrozooplankton (N=8) and Nominal Pore Size.

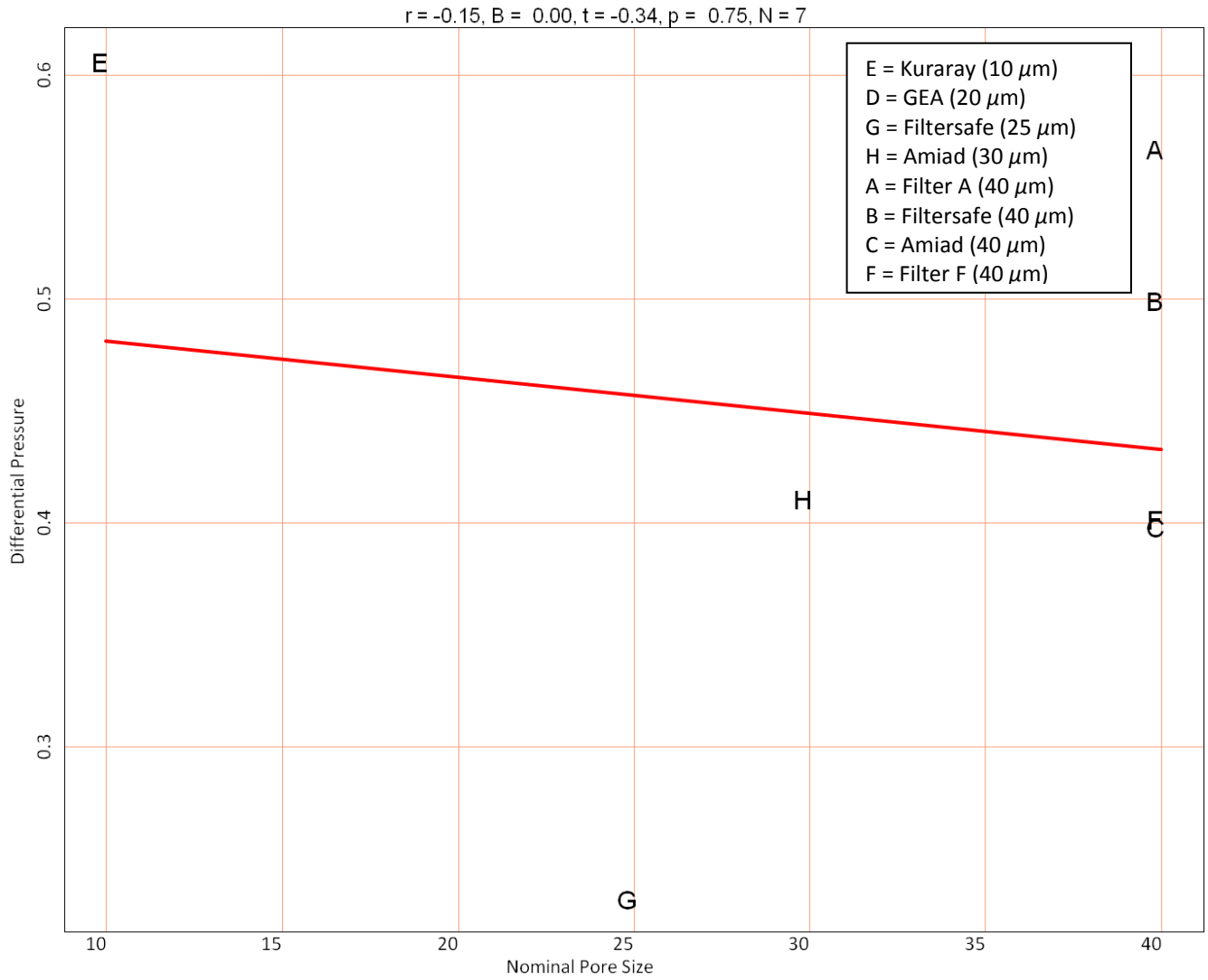


Figure 19. Non-Significant Linear Relationship Between Average Differential Pressure (N=7*) and Nominal Pore Size.

* GEA (20 μm) FS not included due to flow control valve location.

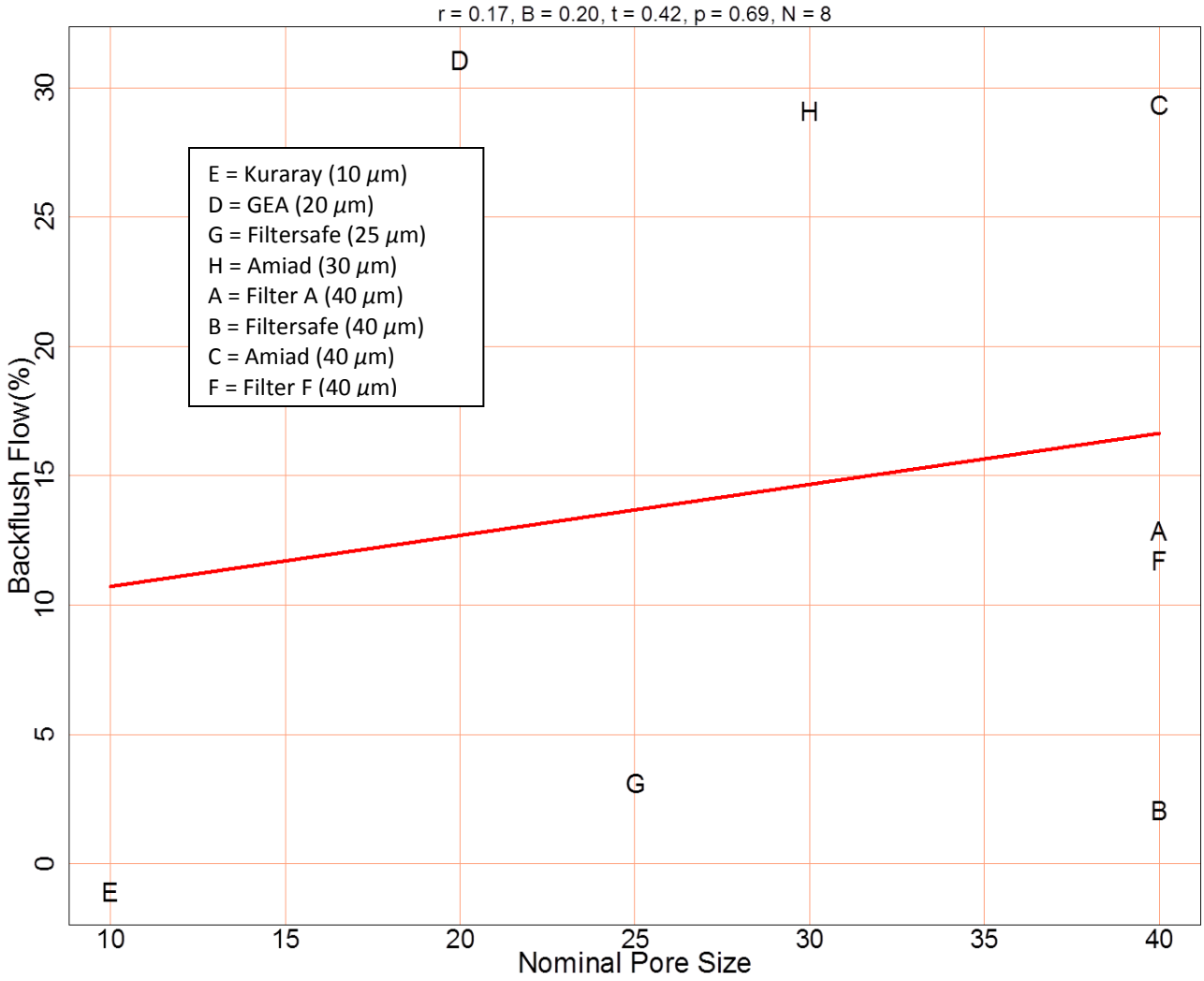


Figure 20. Non-Significant Linear Relationship Between Average Backflush Flow Rate (N=8) and Nominal Pore Size.

4.5.2 Relationships between Biological Performance and Operational Performance Characteristics: Mixed Model Results

Controlling for intake water conditions (i.e., density of organisms across size classes and subclasses, or TSS) did not alter the pattern of significance of findings obtained through simple aggregation, though *p* values changed slightly. The mixed model results showed across FS tested:

- The relationship between FS nominal pore size and percent reduction of microzooplankton was weaker (p = 0.078) than in the simple aggregation model (p = 0.06). The relationship between FS nominal pore size and percent reduction of protists though also slightly weaker, remained highly significant (p=0.022).

- From the FS with the smallest nominal pore size (10) to the FS with the largest nominal pore size (40) the predicted delta in capacity for protist reduction was 55 percentage points, and 49 percentage points for microzooplankton.
- As FS nominal pore size increased, post-filtration density of live zooplankton ≥ 50 μm significantly increased (p=0.039).
- TSS did not affect FS organism removal capacity; neither natural fluctuations in Step 1 TSS levels nor the experimental augmentation in Step 3 were significant predictors of percent reduction or post-filtration density of organisms measured.

The mixed model results further showed that:

- *Higher* intake densities of protists and microzooplankton led to *higher* (p<0.05) percent removal rates.
- *Higher* intake density of live zooplankton in Step 3 was only marginally significantly related to higher post-filtration density of live zooplankton ≥ 50 μm (p=0.063).
- *Higher* percent reduction of protists significantly correlated with *higher* percent reduction of microzooplankton, (r=0.733) but the correlation was not perfect (i.e., significantly different from 1). One FS (FS C) had an unusual pattern of performance of relatively lower percent reduction of protists and a relatively higher percent reduction of microzooplankton compared to the other FSs.

Though they may appear contradictory, the first two observations are consistent with each other. The higher intake densities of protists and microzooplankton led to higher percent removal by FSs, likely due to more frequent partial occlusion of FS pores by organisms. Meanwhile, the stepped up percent removal rates were not sufficiently higher to offset the increase in numbers of organisms passing through the FS into post-filtered water.

4.6 Test Validity and Data Quality Indicators

4.6.1 Test Validity

Table 14 shows the biological and water chemistry/quality target values and results for pre-FS water measured during applicable steps of the FS evaluations. For the ≥ 50 μm size class, i.e., zooplankton, the minimum target value was met for all FSs except FS F where live intake densities dropped to 89,000/m^3 and 92,000/m^3 for two of the four test cycles. FS F was tested in mid-October, which is when zooplankton density in the DSH naturally begins to decline. However, this reduction was only slightly below the minimum target of 100,000/m^3. The minimum target value for the ≥ 10 μm and < 50 μm size class was met for all FS test cycles based on total density determined in preserved samples. The temperature target range was also met for all FS test cycles. Finally, the TSS minimum target was met for all Step 3 FS test cycles, except for two test cycles of Amiad (40 μm) and one test cycle of Filtersafe (25 μm).

Table 14. Target Values and Results for GSI Challenge Water (Pre-Filter System) During Applicable Steps of the Filter System Evaluations.

Parameter	Target Values for GSI Challenge Water	Applicable Step	Was Target Met for All Test Cycles?	Comments
Live Density ≥ 50 μm Size Class	10^5 organisms/m^3	Step 3	No	The minimum target was met for all filters except F where live intake densities dropped to 89,000 and 92,000 live organisms per m^3 for two of the four test cycles.
Total Density ≥ 10 μm and < 50 μm Size Class	10^3 organisms/mL*	Steps 1 and 3	Yes	No comments.
Temperature (^{o}C)	4 – 35	Steps 1 and 3	Yes	Temperature measured prior to Step 1 only.
Total Suspended Solids (TSS)	Min. 24 mg/L	Step 3	No	The minimum target was not met during the second set of test cycles with Filter C (Days e and g) and Day d of Filter G testing.

*Only total density of preserved samples was determined during this test.
Conformance with challenge conditions is based on the total cells/mL in each sample.

4.6.2 Data Quality Indicators

GSI used the following USEPA data quality indicators (where applicable) to determine compliance with data quality objectives: representativeness, accuracy, precision, bias, sensitivity, comparability and completeness. Data quality objectives and acceptance criteria for each of these indicators varied by analysis type and are described in *GSI/QAQC/QAPP/LB/1 - Quality Assurance Project Plan for Great Ships Initiative (GSI) Land-Based Tests* (GSI, 2013b).

4.5.2.1 Water Chemistry

Results of the data quality analysis for precision, bias, accuracy, comparability, completeness and sensitivity relative to water chemistry (i.e., TSS) samples analyzed during the FS performance evaluations are summarized in Table 15. In regards to TSS analysis, all data quality objectives were met.

4.5.2.2 Biology

The data quality assessment relative to samples of organisms ≥ 50 μm and organisms ≥ 10 μm and < 50 μm analyzed during the FS performance evaluations are presented in Tables 16 and 17 respectively. All data quality objectives were met for the ≥ 10 μm and < 50 μm size class, with 94 % taxonomic similarity and 4 % relative percent difference (RPD) for total number of cells averaged across FSs for Step 1 and Step 3. All data quality objectives were met for the ≥ 50 μm size class as well, with 85 % taxonomic similarity and 14 % RPD for live zooplankton analyzed during Step 3.

Table 15. Data Quality Objectives, Criteria, and Results from Water Chemistry Analyses during the Filter System Performance Evaluations.

Data Quality Indicator	Evaluation Process/ Performance Measurement	Data Quality Objective	Performance Measurement Result
Precision	**Samples (10 %) are collected in duplicate and analyzed. Performance measured by average relative percent difference (RPD).**	**< 20 % average RPD.**	**4.2 % RPD (TSS only)**
Bias, Blanks and Filter Blanks	**Deionized water samples (2 per day) filtered, dried, and weighed following the procedure outlined in *GSI/SOP/BS/RA/C/8***	**< 2.6 mg/L TSS**	**Below detection**
Accuracy	**Performance measured by average percent difference (%D) between all measured and nominal reference standard values.**	**< 20 % average**	**1.9 % D (TSS only)**
Comparability	**Routine procedures conducted according to appropriate SOPs to ensure consistency between test cycles.**	**Not Applicable – Qualitative.**	**The following GSI SOP was used for all TSS sample analyses: *GSI/SOP/BS/RA/C/8 – Procedure for Analyzing Total Suspended Solids (TSS), Particulate Organic Matter (POM) and Mineral Matter (MM)***
Sensitivity	**The method detection limit (MDL) and limit of quantification (LOQ) for each analyte and analytical method utilized determined annually prior to the start of the testing season.**	**Not Applicable**	**TSS MDL = 0.78 mg/L TSS LOQ = 2.6 mg/L POM MDL = 0.59 mg/L POM LOQ = 1.96 mg/L**

Table 16. Data Quality Objectives, Criteria, and Results from Analyses of Organisms ≥ 50 μm during the Filter System Performance Evaluations.

Data Quality Indicator	Evaluation Process/ Performance Measurement	Data Quality Objective	Performance Measurement Result
Bias	One pre-FS sample and one post-FS (Step 3 only) was analyzed by two separate taxonomists per FS for each round of testing to determine operator bias.	> 80 % average Percent Similarity (PS) and < 20 % average Relative Percent Difference (RPD).	85.76 % PS; 13.64 % RPD
Comparability	Routine procedures are conducted according to appropriate SOPs to ensure consistency between tests.	Not Applicable – Qualitative.	The following GSI SOP was used for all zooplankton sample analyses: *GSI/SOP/MS/RA/SA/2 – Procedure for Zooplankton Sample Analysis*

Table 17. Data Quality Objectives, Criteria, and Results from Analyses of Organisms ≥ 10 and < 50 μm during the Filter System Performance Evaluations.

Data Quality Indicator	Evaluation Process/ Performance Measurement	Data Quality Objective	Performance Measurement Result
Bias	One pre-FS sample and one post-FS sample (ambient or amended water) was analyzed by two separate taxonomists per FS for each test cycle.	> 80 % average Percent Similarity (PS) and < 20 % average Relative Percent Difference (RPD).	94.40% PS; 3.56% RPD
Comparability	Routine procedures are conducted according to appropriate SOPs to ensure consistency between tests.	Not Applicable – Qualitative.	The following GSI SOP was used for all protist sample analyses: *GSI/SOP/MS/RA/SA/1– Procedure for Protist Sample Analysis*

5 DISCUSSION

The FSs evaluated in this study gave a strong performance operationally and biologically, more so than the numbers may indicate at face value. The large proportion and relatively small size of freshwater rotifers within the ≥ 50 μm size class of organisms, which often differentiate natural freshwater challenge conditions from those confronted in saline systems or with cultured organisms, presented a particular, though realistic, filtration challenge. Moreover, the values for zooplankton reduction presented here are based on total numbers of organisms in filtered discharge as opposed to live only, or live strictly ≥ 50 μm in minimum dimension. Therefore, the filtered discharge density values contained in this study are conservative estimates of densities relevant to numeric regulatory discharge standards. These realities make the strong FS performance results in this study all the more remarkable. Still, it is clear from this study that filtration alone, using processes and nominal pore sizes available in today's market, cannot deliver discharge meeting international or the U.S. regulatory standards for live organism concentrations, in either the ≥ 50 μm, or ≥ 10 μm and < 50 μm size class, in fresh water.

Our results are an objective and reliable assessment of the range of FS operational and biological capacities currently available, and conditions which influence them, based on a strong sampling of the market. FS nominal pore size is currently only a marginally significant predictor of FS biological effectiveness zooplankton and protists. Instead, currently, the FS itself (even for those with a common nominal pore size) accounted for the vast majority of performance variability. That is, currently, other FS attributes appeared to largely obscure the effect of nominal pore size as a predictor of FS performance in the field.

In this study, higher organism intake densities affected reduction efficiency only in that higher intake densities of organisms resulted in better removal rates for both protists and microzooplankton; FS clogging effectively reduced FS nominal pore size for a period of time

during FS operation. This reality did not translate to an improved position relative to a regulatory standard, however, as these standards are based on absolute densities of organisms in discharge, and absolute densities on discharge also increased with increased intake densities.

In our study, FS operational performance characteristics were not related (directly) to biological performance trends. This fact runs counter to conventional wisdom that greater percent removal of organisms comes at the expense of key operational performance priorities. Though some important operational parameters such as power consumption were not tracked in these tests, others—including flow rate, pressure differential and percent loss of flow to backflush—which can be logically assumed at risk in the context of high biological removal, were tracked and the relationship to biological performance efficiency proved non-significant.

Some additional important insights that our data may reveal are not yet presented in this preliminary presentation of our results. For example, the relationship of FS nominal pore size to the rate of removal of particular morphological subcategories of organisms within the microzooplankton and protist taxonomic classes. This relationship likely varies, with some taxa more sensitive to FS unit and nominal pore size differences than others. In addition, relationships among pressure differential, backflush flow rate and percent reduction should be investigated in a mixed model before drawing final conclusions. GSI collected a great deal of data not presented here, including a third set of replicates for each FS, which will add power to all performance analyses. These findings will be set forth in a subsequent and more comprehensive presentation of our results.

Finally, GSI intentionally did not use information collected within this study to create an overall ranking of FS performances across participating FS units for many reasons. Specifically, FSs which comprise only one part of a BWMS, are typically designed to deliver specific complementary capacities relative to a secondary treatment process. In addition, some important operational and biological performance considerations were beyond the scope of this study, such as comparative FS performance capacities over identical challenge conditions, long term FS performance, FS energy demands, FS durability in actual shipboard conditions, or the extent of FS developer support for FS operation in the field. GSI provided more detailed operational and biological data to each of the FS developer for their in-house use, and GSI stands ready to corroborate the validity of these data as an outcome of independent and objective assessment.

6 CONCLUSION

Consistent with project goals, this research provides reliable information on FS operational and biological performance in freshwater under controlled conditions to FS developers, interested ship owners, regulators and the public, without compromising the competitive standing of any individual participating FSs in the market place. It explored trade-offs between operational and biological performance endpoints; and supported FS, and thus BWMS performance improvements in freshwater. The research revealed that numerous FSs are in the market place which can perform effectively in challenging freshwater systems. It also showed that nominal pore size, while a powerful predictor of FS performance, does not account for the wide

variability in FS unit performances, and does not predict operational performance characteristics measured here.

7 REFERENCES

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APPENDIX 1

Filter System Company Statements

Company Statement from Manufacturer of Filter System A

Supplier of FS A wishes to thank the GSI for the test series performed and evaluated as well as for the good working relationship. Being one of the filter suppliers not mentioning our names within the report we specifically would like to point out that the decision to do so is purely based on internal policy and not based on dissatisfying test results. On the contrary, we are very satisfied and proud with the performance of our filter within the test.

Company Statement from Filtersafe®

Filtersafe® (www.filtersafe.net) wishes to thank GSI for its extensive efforts in conducting this test trialing various filtration systems. Filtersafe® has participated in two trials, one using our standard 40-50 μm filter and the second utilizing our 25-35 μm filter.

We are pleased with the test results, in particular with the mechanical reliability operation of our filters achieving performance second to none. The zooplankton removal rate was also in line with past experiences representing the screen‘s ratings.

Filtersafe®, the automatic screen filtration company, was founded more than 10 years ago with the intent of servicing the new ballast water treatment (BWT) market. Based in Israel, the company’s extensive experience in filtration and engineering has enabled it to deliver high quality filtration solutions to BWT system vendors worldwide. Its filters are defined by innovation that is directed by client requirements and executed by a strong research and development programme.

Filtersafe’s® EVERCLEAR™ automatic filtration cycle solutions stand out: There are five key factors. First, the company has been involved in the BWT industry from its infancy 12 years ago and as such our products have continually developed with and for this application; they are not off-the-shelf products modified for BWT sales.

Second, the filters were designed to remove high dirt loads of organic matter (D-2 standard), achieving 97 per cent removal rate of zooplankton and 50 per cent of phytoplankton.

Third, Filtersafe® manufactures and supplies a complete range of filter sizes catering for pre-filtration of all BWT technologies; flow rates are from 50 m^3/h up to 4300 m^3/h, and the filters themselves are all single body units.

Fourth, our filters never clog and operate successfully in all water conditions to ensure smooth operation of a BWT system.

Fifth, our advanced and unique Proximity Nozzle and Sintered Screen technologies are used on all filter models.

The Sintered Screen smartweave™ is Filtersafe's® weave-wire technology utilizing four finely meshed layers that are made of stainless steel for maximum durability. It is a standalone screen requiring no further support but integrates perfectly with the Proximity Nozzle solution. The Sintered Screen is available in two models: 316L for standard applications and 904L duplex SST for high corrosion resistance and prolonged usage.

The Proximity Nozzle, nozzlex is Filtersafe's® patented autonomous hydraulic suction system that cleans the screen. It covers less than one per cent of the screen to provide high and consistent suction velocities. In doing so it minimizes residual water and pressure loss without needing to halt the BWT system. Together, the two technologies push Filtersafe's® products to the forefront of the market.

As the company constantly developing its product portfolio, there have been several recent technological developments. In 2010, for example, the first high flow rate model was released as part of the BS-400 series, and in 2012 the first 4200 m3/h high flow rate filter (part of the BS-1200 series) was produced. It has also worked hard to gain class approval from DNV, Lloyds Register, BV, ABS and GL in order to assure clients and potential customers of the high engineering standards across its range.

Filtersafe® currently has D-2 certification with over 15 BWT vendors the world over and maintains a healthy and active relationship with them all. In terms of market share, as it currently stands, this translates to over 20 per cent of the projected world market in BWT new build and retrofit sales. Though we are not able to disclose with whom we currently have contracts, we do have multiple contracts supplying both low and high flow rate filter units to leading maritime hubs including Norway, South Korea, China, Europe and the US to name a few.

Anticipating D-2 ratification, Filtersafe® is opening a second manufacturing facility in 2014. Expanded production capability will enable the company not only to turn out higher volumes of filter units but also shorten the delivery times to its clients, thereby providing an even better customer service. The site's location in Asia was chosen for its strategic proximity to the company's important Chinese, Korean, Japanese, and Singaporean markets. Though located in Asia, the plant will be owned and operated under supervision of the Israeli head office.

Filtersafe's® plans for the coming years: "With time, and after selling and installing **several hundreds** of filters onboard vessels, it is becoming clear that durability and ability to operate the systems under all water conditions is the main challenge of BWT systems. Filtersafe® will keep on investing heavily during the next two years in improvement of our filtration technologies. Filtration will remain the backbone of BWT systems and constant R&D for this application will dominate our activities in years to come.

Company Statement from Amiad Water Systems

Amiad (www.amiad.com) wishes to thank GSI for the very professional and empirical manner of research long awaited for by the market. The Amiad Omega Series of automatic self-cleaning multi-screen filters provides high efficiency and a small footprint, combining Amiad's Superior Suction Scanning mechanism with a multi-screen design. Amiad's robust, simple & efficient filtration systems deliver the highest removal rates & filtration efficiency in the context of changing and challenging solids loads. It is a proven filter that maintains performance integrity and operation under the most challenging conditions.

The Amiad Omega Series designed for the Ballast Water market with multiple screens is operated by a single electric self-cleaning mechanism. The "Omega" filter series range in flow rates of up to 5,000 m^3/h (22,000 gpm). Nominal pore sizes range from 500 microns down to 10 microns. Inlet/outlet flanges are available from 8"-24" diameter.

- Based on Amiad's proven suction scanning screen filtration technology
- Highly efficient self-cleaning mechanism
- Small footprint
- High flow per unit
- Back wash flow from 1% to 8% of total flow
- High reliability
- Easy and simple minimal maintenance
- low energy consumption
- Low-pressure operation
- ASME / Ex Proof design optional
- Applications: Membrane Protection, Ballast Water, Oil & Gas, Industrial Water and Irrigation
- Lloyds and DNV class approval

Company Overview

Amiad Water Systems is a leading global producer of automatic, self-cleaning water treatment and filtration solutions. It has developed a range of innovative products and systems that provide environmentally-sustainable solutions with low operating costs and a rapid return on capital investment.

Amiad services the industrial, municipal, irrigation, oil & gas and ballast water markets. In these segments, our patented products are being integrated into the core of systems for filtration and water treatment, injection water, membrane protection, wastewater and potable water treatment, industrial application, cooling systems and sea water filtration.

Since its establishment in 1962, Amiad has grown to include ten subsidiaries worldwide with over 600 employees. Amiad solutions are delivered through its subsidiaries and extensive distributor network to organizations spanning more than 80 countries. Amiad has built its global reputation on high-quality standards, outstanding performance, product reliability, prompt delivery, and excellent customer service.

The Filtration Process

Raw water enters from the filter inlet and passes through the multi-screens. Clean water flows through the filter outlet. Organisms and suspended solids, greater than the given filtration degree accumulates on the screen surface, causing gradual buildup of differential pressure. A PLC continuously monitors the DP across the filter and initiates the self-cleaning process according to a pre-set program.

Global Presence

Amiad has ten subsidiaries and eight production sites across the globe; including: Australia, Singapore, China, India, Turkey, Israel, Europe, Brazil, Mexico & USA east and west coast

Amiad invests extensive resources in R&D. Amiad is proud to be a technological leader with broad engineering and research and development capabilities. Amiad constantly strives to develop more efficient and superior water treatment and filtration solutions for both simple and high-complexity projects.

Amiad's mission is to continue to develop advanced and innovative water filtration solutions in order to enhance production process, protecting infrastructure, reduce carbon footprint & comply with regulations.

Notes on FS Performance in GSI Tests

Backwash flow: The back flush flow rate of Omega IE in continuous flushing mode is 36 m^3/hr which is 7.2 % of 500 m^3/hr. the designed flow rate for Omega 1E. Since the filter in the test was operating at 340 m^3/hr than the flushing flow was about 10 % from the total flow

Removal rate: Amiad actual filtration degree in the GSI tests proves a persistent, high and continually effective removal rate relevant to the declared filtration degree. Amiad removal rate of organisms between of 10 to 50 μm indicates a strong correlation to the filtration degree and a very efficient retention capacity of the screens as well efficient cleaning

Company Statement from KURARAY CO., LTD.

We are grateful to GSI and NEMWI for the opportunity to join the filter system evaluation. Kuraray Co., Ltd. is a manufacturer of the ballast water management system MICROFADE.

MICROFADE has a dual stage process of filtration followed by chemical infusion of calcium hypochlorite. A neutralization step prior to discharge ensures environmental compliance of the treated ballast water.

For this study, Kuraray Co., Ltd offered MIDROFADE's filtration unit to GSI for the evaluation. General information of MICROFADE is available at the following URL:
http://www.kuraray.co.jp/en/products/medical/microfade.html

Company Statement from GEA Westfalia

GEA Westfalia Separator Group offers leading technologies and individual systems for marine use. Westfalia Separator® BallastMaster ultraV is a highly efficient mechanical/physical system solution for treating ballast water including that with a high concentration of organisms and sedimentary particles. The mechanical filtration used in the BallastMaster 250 ultraV is developed by GEA Westfalia especially for the most challenging task of treating ships ballast water with possible physical water parameters exiting worldwide.

The filter process upstream removes organisms and sedimentary particles larger than 20 microns with a high reduction rate. According to the IMO convention, this prevents sedimentary deposits accumulating in the ballast water tanks, as well as guaranteeing in the second stage an optimum result for ballast water disinfecting. The filter modules are cleaned automatically by vacuum extraction (self-cleaning).