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TESTING OF FILTER TECHNOLOGIES FOR TREATMENT OF BALLAST WATER

FINAL REPORT
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Prepared for:

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United States Coast Guard
Assistant Commandant for Prevention (G-P)
Washington, DC 20593-0001

N O T I C E

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A variety of filtration technologies exist on the market today which may be viable candidates for the removal of biological organisms from ships' ballast water. This document presents the results of testing several types of filters at a pilot-scale facility. Filter systems tested included a disc, a screen and a media filtration system which were evaluated singly and in combination. These filters were evaluated for their relative ability to reduce particulate concentrations and biological organisms in ambient water drawn from the Gulf of Mexico. Where appropriate or necessary, the test waters were supplemented with concentrations of Arizona Test Dust to alter the total suspended solids and overall turbidity. Particle counting was used on the input and output stream of each filtration system to evaluate filter capability to remove particles. Direct enumeration of organisms in the feed water and filtrate was utilized to evaluate effectiveness in the removal of organisms. Filter systems and their combinations were evaluated over the size ranges 10-30, 50-80 and 100-200 microns. Suggestions for improving test water definitions are provided.</td></tr>
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Executive Summary

Ballast water, carried in ships' tanks, serves a variety of purposes including management of ship trim and list as well as adjusting ship waterline during loading and off-loading of cargo or as a function of ambient weather conditions. Frequently, ships' tanks will be ballasted in one port and de-ballasted in another, a process identified as a major vector for the translocation of invasive species. Both the U. S. Coast Guard (USCG) and the International Maritime Organization are promulgating regulations regarding both mid-ocean ballast water exchange and treatment of ballast water. Treatment technologies must be able to pass stringent evaluations of their ability to kill, remove, or incapacitate organisms entrained in ballast water.

Filtration appears to be a technology with a potential to treat ballast water, and USCG Research and Development Center (R&D Center) investigated a number of filter types for suitability for shipboard treatment of ballast water. After this initial investigation, three promising filter types were selected for testing at the ballast water treatment test facility at the Naval Research Laboratory in Key West, FL (NRL-KW). The filtration tests were based on recommendations from the R&D Center's study, the test protocol being developed under the Environmental Protection Agency's Environmental Technology Verification (ETV) program, and NRL-KW's capabilities. This document reports on those filtration tests.

The filters included a self-cleaning screen filter, a self-cleaning disc filter, and a multi-media filter. Two separate tests were conducted using the screen filter and the media filter arranged in series in one test and the disc and media filter in the second test. Each pair of filters was tested for efficacy (ability to remove organisms and sediment) and efficiency (ability to operate properly without maintenance problems). Ambient water from the Gulf of Mexico was augmented with commercially-available test dust to bring the total suspended sediment (TSS) load up to ETV recommendations. Samples taken before and after each filter unit were obtained at four separate times during a 100-hour operational test and were analyzed for biological constituents and TSS load.

Significant results include the determination that the TSS loading described in the ETV protocol is insufficient as currently written. It is also necessary to define size classes to insure that TSS loadings are realistic. Investigations revealed that it was possible to use a 50/50 mixture of medium and coarse Arizona Test Dusts to mimic sediments found in No Ballast On Board ship's ballast tanks.

Although the 50/50 mixture was realistic, it did not provide a challenge for the screen and disc filters (50-micron and 55-micron mesh sizes, respectively) since the bulk of the TSS was less than 50 microns in size. No significant removal of particles or organisms was seen for either the screen or disc filter. Despite the relatively small particle size, both the screen and disc filtration units exhibited a steady increase in back-flush frequency, presumably the result of fine particles "caking" on the filtration surfaces.

The media filter received the filtrate from the screen and disc filters as feed water, which included virtually the entire TSS loading seen by the other filters. The media filter showed a significantly superior removal capability as it removed more than 70 percent of the TSS load with minimal back-flushing.

Analysis of biological samples revealed four major groups of organisms, all of which were less than 50 microns in size. Again, neither the screen nor the disc filter removed significant numbers of ambient organisms. The media filter removed organisms down to 25 microns in size.

In summary, within the confines of the sediment and organism loadings of these experiments, neither the screen filter nor the disc filter significantly removed organisms or sediment from the challenge water. The media filter successfully removed both sediments and organisms from the flow; however, its size and weight make it an unlikely candidate for shipboard use.

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List of Acronyms

α = Alpha at 95% confidence interval

amp = Amplifier

ANOVA = Analysis of Variance

ANSI = American National Standards Institute

ASTM = American Society for Testing and Materials

BWT = Ballast Water Treatment

CG = U. S. Coast Guard

cts/mL = counts per milliliter

DP = differential pressure

EPA = Environmental Protection Agency

ETV = Environmental Technology Verification

ft^2 = square feet

°F = Fahrenheit

FL = Florida

FNPT= female national pipe thread

gpm = gallons per minute

gpm/ft^2 = gallons per minute per square foot

hrs = hours

lbs = pounds

IMO = International Maritime Organization

L = liters

µL = micro-liter

µm = micron

mA = milli-amp

mg/L = milligrams per liter

mL = milliliter

mm = millimeter

MMF = Multi-Media Filter

MS = Microsoft®

NISA = National Invasive Species Act

NRL-KW = Naval Research Laboratory in Key West, FL

= number

% = percent

PLC = Programmable Logic Controller

ppm = parts per million

psi = pounds per square inch

psig = pounds per square inch gauge

® = Registered sign

R&DC = Research and Development Center

Spp = species

Std Dev = Standard Deviation

SOP = Standard Operating Procedure

TSS = Total Suspended Solids

VAC = voltage, alternating current

1. Introduction

Ballast water is a significant pathway for introduction of non-indigenous species into coastal waters. Recognizing that alternatives to ballast water exchange are necessary, the National Invasive Species Act (NISA) of 1996 and proposed reauthorization language included provision for a mandatory ballast water management plan specifying either ballast water exchange or ballast water treatment. Ballast water exchange is considered an interim method for controlling species migration as both safety and route issues limit the practicality of mid-ocean exchange as a general means of minimizing the risks of introductions via the discharge of ballast water. Ballast water treatment (BWT) holds significant promise in achieving the level of treatment that is currently required in the international arena under the recent diplomatic convention adopted by the International Maritime Organization (IMO).

Now that IMO standards have been adopted, though not yet ratified, an important next step is to consider how ballast water treatment systems ought to be tested, validated, and qualified for use. The testing may or may not include such factors as fitness-for-service, biological effectiveness, safety, maintenance, manning requirements, etc. While the development of candidate treatment technologies is important, the various methods used to proof-test them are equally important. Currently, there is diversity in testing facilities and approaches with little conformity globally (Voigt and Gollasch, 2000), (Mountfort, Dodgshun, Taylor, 2003), (Herwig, Perrins, Cordell, Dinnel, Gensemer, Ruiz, Cooper, 2003), (Waite, Kazumi, Lane, Farmer, Smith, Smith, Hitchcock, Capo, 2003), (Holdo, 2001). Tests should be standardized such that comparable results are achieved at varying geographical locations and testing facilities (land-based or ship-based), and that they afford a high degree of scientific and statistical rigor. The latter points are critical to protect all interested parties including regulatory agencies, technology vendors and the customers (industry).

The U. S. Coast Guard (CG) and the Environmental Protection Agency (EPA) have worked cooperatively through EPA's Environmental Technology Verification (ETV) Program to develop a draft protocol for testing BWT technologies. The draft protocol (Tanis and Hunt, 2003) calls for testing at realistic flow rates and durations (nominal 1500 gallons per minute (gpm) for one hour). The intent is to provide the shipping industry, regulators, and resource managers with reliable information about the effectiveness, costs, and environmental risks associated with BWT technologies.

As part of this effort, the Naval Research Laboratory at Key West, FL (NRL-KW) has installed a 96,000-gallon holding tank and developed piping configurations and a control system which will allow the NRL-KW facility to conduct tests according to the draft ETV protocol. The intent is to test shipboard equipment as close to full-scale as possible with increased control of various parameters that can affect performance. These factors are typically unknown or uncontrolled in the ship's environment. For example, input water properties are controlled by the surface waters in which the ship typically operates whereas the water used at the test facility may be supplemented to adjust organism densities, salinity or suspended solids. In the past year, the NRL-KW facility has been conducting experiments to evaluate the test facility itself and one type of BWT equipment.

From an initial look, filtration appears to be a technology suited for BWT. A number of different types of filters exist, each with its own flow and size range limitations. The CG Research and Development Center (R&DC) contracted an engineering firm to survey filter types, recommend which filter types might be suitable as BWT systems, and provide a basic test plan for evaluating the recommended filters. That basic test plan recommended testing several types of self-cleaning filters at 100 gallons per minute (gpm) rather than at 1500 gpm and then scaling up the filters to meet actual shipboard requirements. Based on these recommendations and the ETV draft protocol, NRL-KW set up and tested three filtration systems: a Village MarineTec® media filter, an Amiad® self-cleaning screen filter, and an ARKAL® self-cleaning disc filter. Filters were set up according to manufacturer's specifications and incorporated into the NRL-KW test facility such that flow rates, water quality, and filter activity could be monitored. Flow was set at 100 gpm per the basic test plan recommendation. Multiple tests were conducted for each filter. Physical and biological parameters were evaluated according to engineering requirements and the ETV draft protocol.

This document describes the experimental procedure including details of the design and construction of the NRL-KW test facility. The layout, capabilities and performance of the filtration systems are discussed. The biological, physiochemical and component performance results are discussed. Relevant factors associated with the realism of pilot/full scale testing of BWT technologies are discussed. These include insight into the effects of in-line treatment on entrained organisms and the relative importance of pilot scale testing compared to small scale experiments.

2. Experimental Procedure

2.1 Equipment, Materials, and Methods

2.1.1 Test Stand

The test stand is an assembly of hardware that will prepare and deliver a feed stream to the test filtration systems at a constant flow rate and will receive all effluents from the test filtration systems. The test assembly is comprised of multiple components, the significant portions of which are shown in Figure 1**.** Essentially pumps draw water from the Gulf of Mexico for piping through the test bed. A series of valves allows the water to be directed past monitoring sensors, through the filter systems, and out via sample ports or discharges into holding tanks. Flow rates can be controlled, and dissolved or particulate matter can be added as required. Because the self-cleaning screen filter and the self-cleaning disc filer were not designed to remove particles smaller than 50 microns, they could be considered as pre-filters for the media filter, which was expected to remove particles in the 10-40 micron range. Thus, two test configurations were used. In the first, the test was conducted with a self-cleaning screen filtration unit operated in series with a media filtration system. Subsequently, the self-cleaning screen system was replaced with a self-cleaning disc filtration system. The components are described in the following sections.

2.1.1.1 Test Filtration Systems

The three filtration units tested were the Village Marine Tec® Media Filter, Amiad® Screen Filtration Unit, and the Arkal® Disc Filtration Unit. The Amiad® Screen and Arkal® Disc were both tested as precursors to the Village Marine Tec® media filter, but test durations differed. The media and screen filters were units that NRL-KW had available on-site and that had been used for other programs. Prior to conducting these experiments, both units were refurbished by manufacturer personnel. The disc filtration unit was procured new.

Village MarineTec® 400GPM Media Filter

This system consists of a four-vessel multi-media filter (MMF), and a 400 gpm self-cleaning filter system as pictured in Figure 2. It is supplied with a control system, pressure and temperature gauges, differential pressure transducers, flow meters, particle counter, pH meter, control valves, and a data-log system. The system is designed for a nominal feed flow of 400 gpm, or 100 gpm per vessel. Based on the selected flow rate of 100 gpm, only one vessel was tested during this evaluation, and the same vessel was tested for each train configuration. Each vessel is designed for a flux rate of 2 gpm/ft^2. In order to effectively evaluate the MMF performance, the system was required to operate at its nominal working performance for all system flow rates.

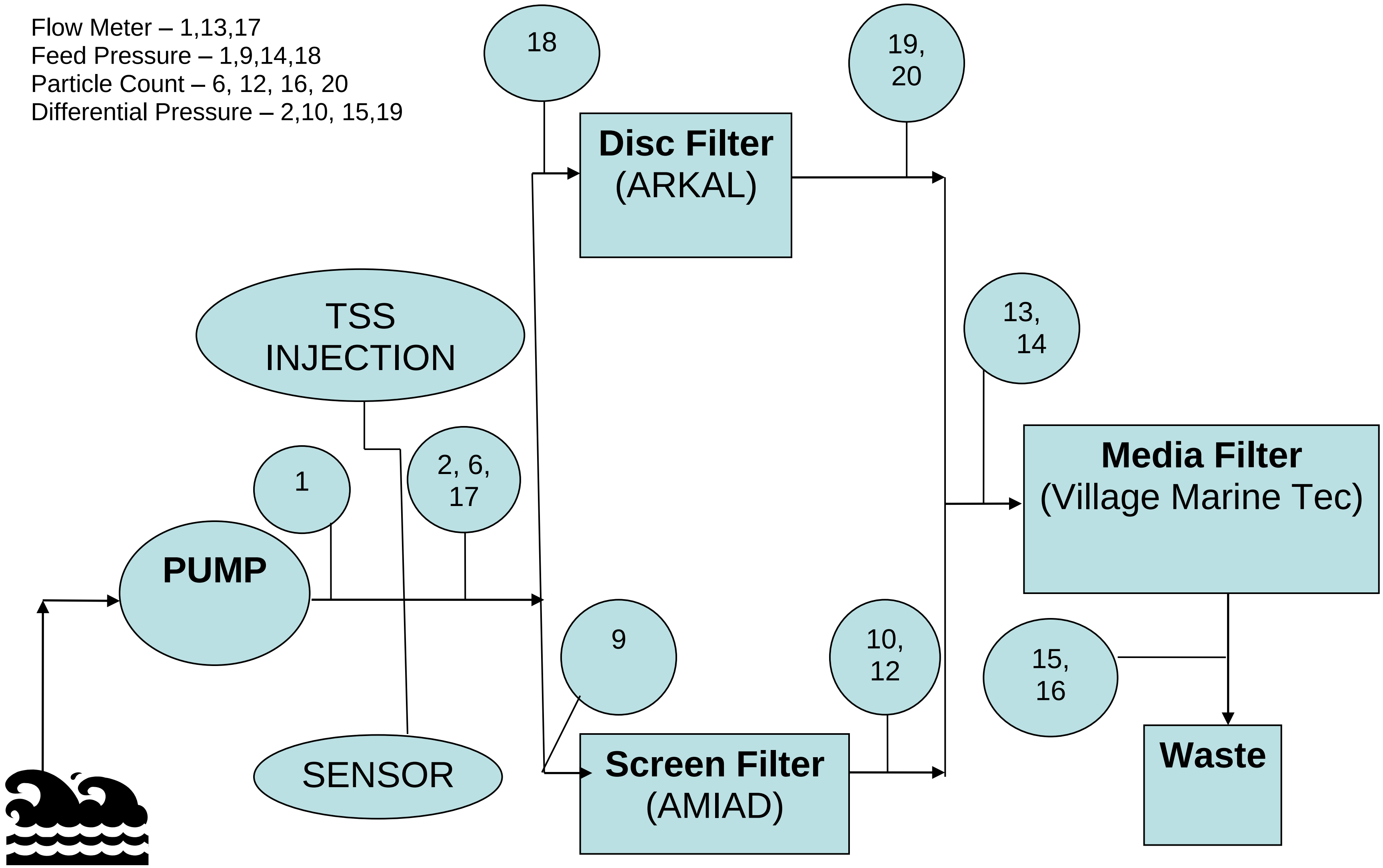


Figure 1. Generalized Plan for Filtration Tests. Sensors include pH, salinity, temperature, dissolved oxygen, and turbidity. TSS = total suspended solids.

Figure 2. Photograph of Village Marine Multi-Media Filtration System.

The MMF has sample valves located upstream and downstream of the filter skid as well as between vessels. The MMF itself has two pressure gauges, one immediately upstream and one downstream to determine differential pressure across the filter vessel to indicate the need for a back flush cycle. The maximum design pressure of the skid is 150 pounds per square inch gauge (psig). When all tanks are operational, the working pressure for 100 gpm per tank is 175-190 psig. A sequential back-flush is initiated by a manually set timer and/or automatically when the inlet and outlet pressure differential exceeds 15 psig for the system. During sequential back-flush, the tank being back-washed requires twice the normal flow rate or 200 gpm. The back-flush cycle is designed to operate for 30 minutes, and rinse for five minutes for each tank of the system. System specifications include:

- Skid Size: 240” long, 60” wide, and 96” height (45” vessel diameter)
- Weight: 18,000 pounds (dry)
- Design pressure: 100 psi (pounds per square inch)
- Inlet and Outlet Interfaces: 6” Class 150 flange 1-1/2” ANSI (American National Standards Institute) flange
- Electrical: 110 VAC (Voltage, Alternating Current), 4-A, Single Phase
- Air: ½” FNPT (Female National Pipe Thread), for 100 psi
- Media Type: Sequential layers of the following: Gravel, Garnet, Sand, Anthracite (0.85), and Anthracite (2.0).
- 25 micron filter rating
- PLC (Programmable Logic Controller): The PLC provides means to initiate back-flush by pushbutton or by timer. The PLC is designed to back-flush one tank at a time, while the others operate in filtration mode. It can also back-flush all four tanks at the same time when selected. This system is designed to provide means for controlling the feed and back-flush. It can incrementally increase or decrease the flow rate to desired values, modify, and adjust the back-flushing frequency and duration, and alter pressure variations.
- System Shutdown Criteria: All fluid flow to all filter skids is redirected to the system by-pass if the by-pass alarm signal is received from the PLC. This signifies a differential pressure above 12 psig following a back-flush cycle.
- MMF Alternate Back-flush Shutdown Criteria: If a differential pressure of 40 psig is exceeded across the Alternate Back-flush Feed and MMF filtrate, the flow is redirected to the MMF Skid Bypass.

AMIAD® SAF-1500 Self-cleaning Screen Filtration System

The Amiad® unit is a screen filtration system which has an automatic self-cleaning mechanism driven by an electric motor which allows for back-flushing of the screen filter. A schematic of this unit is provided as Figure 3. The mesh sizes normally available by AMIAD® range from 130 microns up to 200 micron screens. Amiad® supplied a 50-micron screen for these tests to allow for a better comparison between the disc and screen systems. System specifications include:

- Skid Size: 240” long, 60” wide, and 96” high (45” vessel diameter)
- Weight: 232 pounds (dry)
- Maximum Flow Rate: 293 gpm
- Maximum Working Pressure: 150 psi
- Minimum Working pressure: 21 psi

- Inlet and Outlet Interfaces: 3" Class 150 flange
- Exhaust Outlet: 1 ½" Class 150 flange
- Electrical: 110 VAC, Single Phase
- Flushing Cycle Time: 15 seconds (sec)
- Screen mesh: 130 or 200 micron normally available; 50 micron used
- Filter Area: 1.6 ft^2 (square feet)

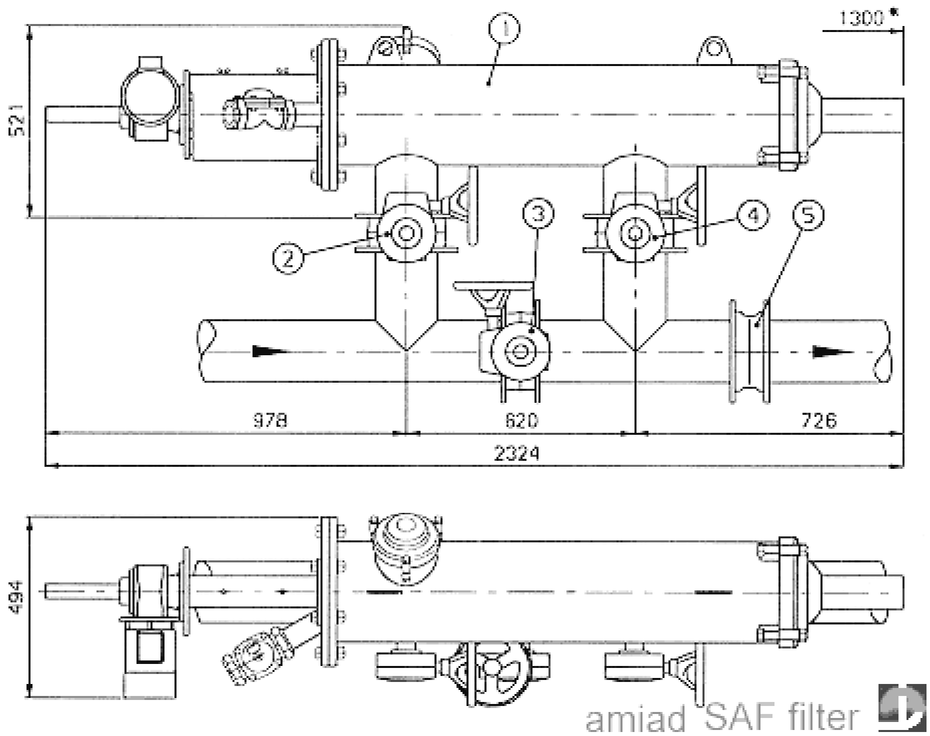


Figure 3. Schematic of AMIAD® SAF-1500 Screen Filtration System.

ARKAL® Disc Filtration

The disc filtration system is a stack of grooved discs sized to filter fine particles. The micron size range available by Arkal® ranges from 10-microns up to a maximum disc size to 400 microns (Figure 4). For this test a 55 micron grade was used. During filtration, the compressed disc stack retains particles while clean filtrate passes through at the center. Once the disc stack is loaded with particles, the back-wash cycle initiates automatically. First, the reversal of the water flow decompresses the disc stack allowing the discs to move freely. Then a series of nozzles spray a mixture of high-pressure water and air onto the grooved discs, which causes them to spin rapidly. The combination of the spray and spinning action cleans the discs very quickly. The filtration design parameters for the equipment are as follow:

- Nominal continuous filtrate flow rate: 100-gpm
- Percentage of water to be filtered: 100% of total flow
- Inlet suspended solids water quality: < 50 ppm (parts per million) TSS
- Filtration Grade: 55 microns
- Maximum pressure: 142 psi
- Maximum temperature: 140 ^{O}F

- Approx Weight: 220 pounds
- Length (in inches): 50
- Width (in inches): 32
- Height (in inches): 46
- Compressed air available for valve control
- Continuous filtration even during back-wash
- Flushing cycle time: 80 Seconds

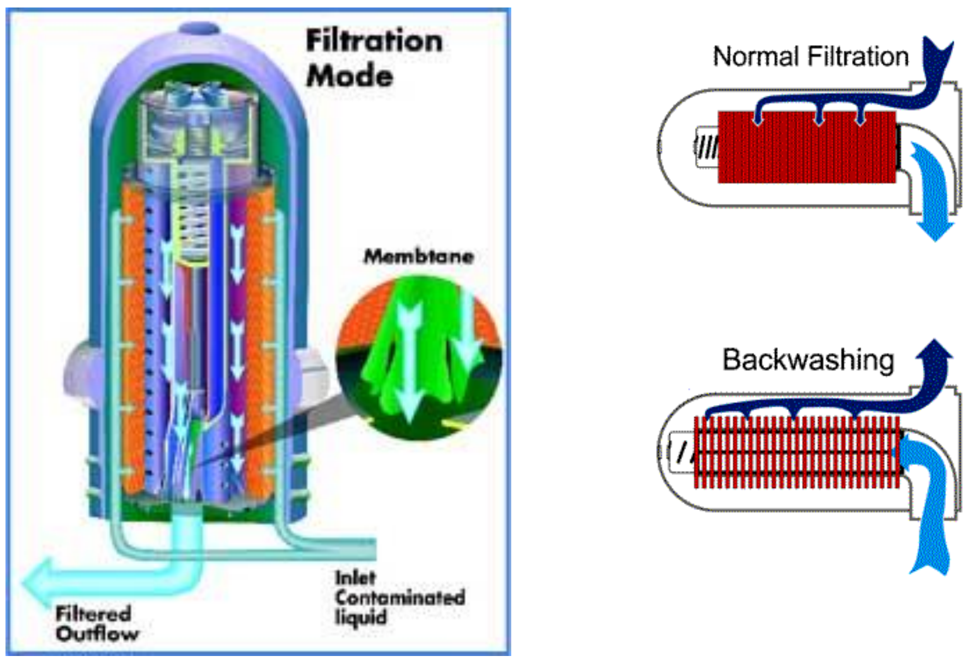


Figure 4. Schematic of ARKAL® Spin Kiln Filtration Method (www.arkal-filters.com).

2.1.2 Test Fluid (ambient water)

NRL-KW is located on Fleming Key adjacent to the island of Key West, FL. Historically, the laboratory has been located on the same site for approximately 30 years and has an unparalleled database for natural seawater exposure testing and marine related materials evaluation. Physically, the laboratory receives a plentiful, unpolluted supply of natural undisturbed Gulf of Mexico seawater throughout the year. The tropical climate is ideally suited for marine exposure testing and, along with the high quality seawater, provides small climatic variation and a stable biomass throughout the year.

Testing was conducted under open-loop conditions. The natural seawater, which has the seasonal conditions shown in Figure 5, was obtained directly from the ocean. The particulate distribution of natural seawater at NRL-KW has been characterized by the water chemistry analysis detailed in a later section.

2.1.3 In-Line Water Analysis and Operational Parameters

In addition to the sensors and monitoring devices which were pre-installed on each of the filtration units previously discussed, each filtration unit was outfitted with additional sensors placed as shown in Figure 1 and listed in Table 1.

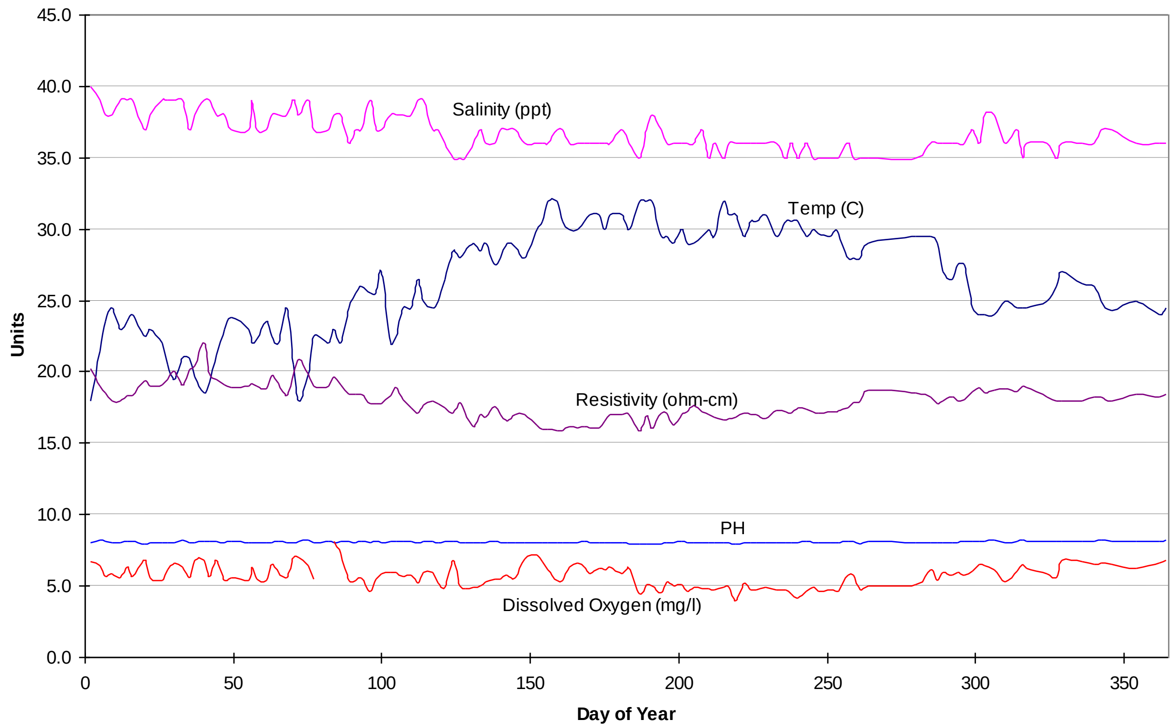


Figure 5. NRLKW Seawater Properties for One Year.

2.1.3.1 Pressure

A GF Signet 2450 Pressure Sensor with GF Signet 8450 Pressure Transmitter was used to monitor pressure at the various points detailed in Figure 1. The 4 - 20 milli-amp (mA) signals were recorded using a HP Data-link Data logger and transferred to an MS Excel worksheet weekly. Generally, data was recorded at a rate of once per minute unless a slower acquisition rate was deemed sufficient.

Table 1. Additional Components Applied to Filtration Skid to Direct Flow and Record Essential Data.

Component Name	Manufacturer	Product
Raw Seawater Feed Pump	VANTON	100HP Centrifugal Pump
Particle Counter	Chemtrac	PC2400D2 Laser Track
Turbidity Sensor	HACH	1720 D Low Range Turbid-meter
Flow Rate Sensor/Gauge	George Fischer	GF 515 Flow Sensor and 8550 Flow Transmitter
Pressure Sensor/Gauge	George Fischer	GF Signet 2450 and GF Signet 8450
pH Electrode/Sensor	George Fischer	GF2716
Temperature Sensor	George Fischer	GF 2350
Flow Control Valves	George Fischer	2" Diaphragm Valves
Static Line Mixers	RYAN HERCO	2" Static Mixer, PVC

2.1.3.2 Flow Rates

A GF Signet 515 Flow Sensor with GF Signet 8550 Flow Transmitter was utilized to monitor flow rate at the points noted in Figure 1. The 4 - 20 mA signals were also recorded with an HP Data-link Data logger and transferred to MS Excel spreadsheet weekly. Data was recorded generally at a rate of once per minute unless a slower acquisition rate was deemed sufficient.

2.1.3.3 Monitoring Total Suspended Solids (TSS)

During the tests, samples of both the feed stream and filtrate were taken simultaneously for subsequent TSS analysis, while in-line analytical instruments were used to continuously monitor the particle contents of these streams. At the moment the test samples were taken, the date, time, and pressures were recorded. Weather conditions and other remarks considered appropriate were registered as well.

Water analysis for TSS was performed on all samples from the feed and filtrate streams to properly evaluate each filter's performance. Test samples of 1 liter (L) were taken once each day as close to the filter medium feed and filtrate stream as possible. Sample valves were placed such that sharp bends, dips, and low points were avoided. The NALGENE sample containers, made of materials that do not contaminate the samples, were cleaned thoroughly prior to use to remove all extraneous surface dirt.

2.1.3.4 Particle Counting

A Chemtrac Model PC 2400 D Particle Counter was used for monitoring particle size and distribution. This unit measured the concentration (in counts/mL) of the following size ranges: 2-5 µm, 5-10 µm, 10-15µm, 15-25 µm, 25-50 µm, 50-75 µm, and 75-100 µm. The size range 75-100 µm was referred to as the TSS_{PC} or the Total Suspended Solids from the Particle Counter due to its particle size. Samples of at least 1 liter (L) were simultaneously acquired from each sample port and then analyzed sequentially. Analysis of each 1-L sample required 20 minutes; thus, a 20-minute data stream was retrieved from each port. Average and standard deviations for each size range over the 20-minute period were recorded and raw data streams stored.

Since the ambient water's sediment concentration was insufficient to provide a realistic test of the filtration assemblies, sediments had to be added to the ambient water prior to entry into either filtration system. The intent was to provide a moderate total suspended solids load of 12-16 milligrams per liter (mg/L). This was accomplished by adding Arizona Test Dust (ISO 12103 –1), which is available in a range of sizes. Determining the appropriate mixture of sediments, including size distribution of the sediments, was required for a realistic test of ballast water systems.

For the first 40 hours of the screen filtration unit tests, ambient TSS was augmented by adding Arizona Test Dust: ISO 12103-1, A3 Medium Test Dust. (Particle size distribution is shown in Figure 6.) During that time, it was decided to modify the TSS to reflect the size distribution used by Waite et al. (2003) in their filtration and separation study. A 50/50 ratio mixture of Arizona Test Dust: ISO 12103-1, A3 Medium Test Dust and Arizona Test Dust: ISO 122-1, A4 Coarse Test Dust (particle distribution shown in Figure 7) provided that size distribution and was used for the next 60 hours of testing the screen filtration units.

Although the 50/50 mixture produced the particle size distribution similar to that of Waite et al., examination of the size ranges of the mixture showed that the sediment size was predominantly less than 50 microns. Given the design cutoff sizes for the filters used in this study (50 microns for the screen and 55 microns for the disc filter), the 50/50 mixture's size range was thought inappropriate for testing the filters. Thus, at 100 hours of operation of the screen filter unit, the TSS mixture was again altered to provide a 20/20/60 mixture of Arizona Test Dust: ISO 12103-1, A3 Medium Test Dust, Arizona Test Dust: ISO 122-1, A4 Coarse Test Dust, and crushed quartz, respectively. This mixture was used for the final 60 hours of tests of the screen filtration units.

Discussions with sponsors and further consideration of the TSS distribution led to the decision to attempt to mimic actual ballast water sediments prior to further tests. Although little data exists in the open literature on particle size class distribution in ballast water sediments, data on particle size distribution from sediments from No Ballast On Board (NOBOB) ships was obtained from Dr. Frederick Dobbs of Old Dominion University. The size class distribution of the NOBOB sediments (Figure 8) is comparable to the 50/50 mixture used during the 40 – 100 hour timeframe of the screen filtration unit tests. On that basis, the 50/50 mixture of Arizona Test Dust: ISO 12103-1, A3 Medium Test Dust and Arizona Test Dust: ISO 122-1, A4 Coarse Test Dust was used for the full 100 hours of tests of the disc filtration units.

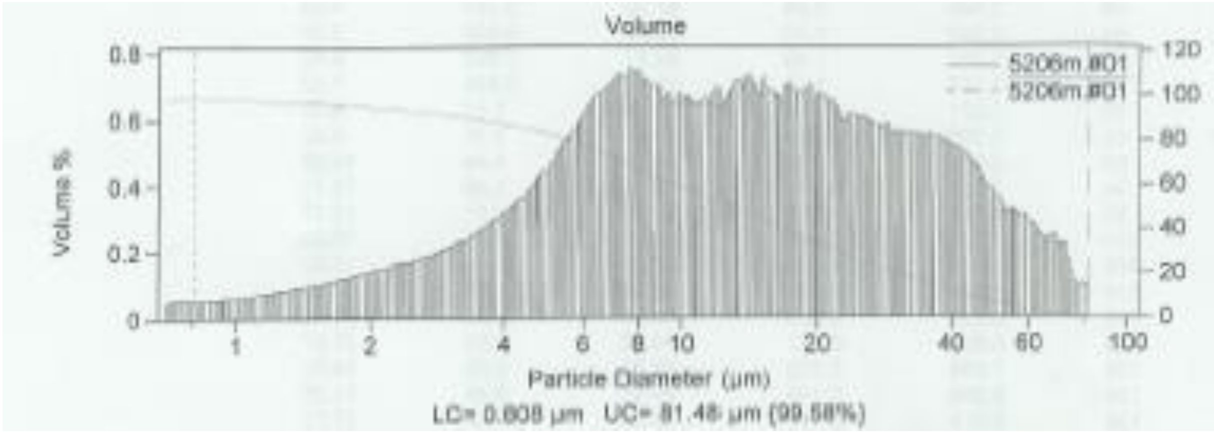


Figure 6. Particle Size Distribution of Arizona Test Dust; ISO 12103 -1, A3 Medium Test Dust.

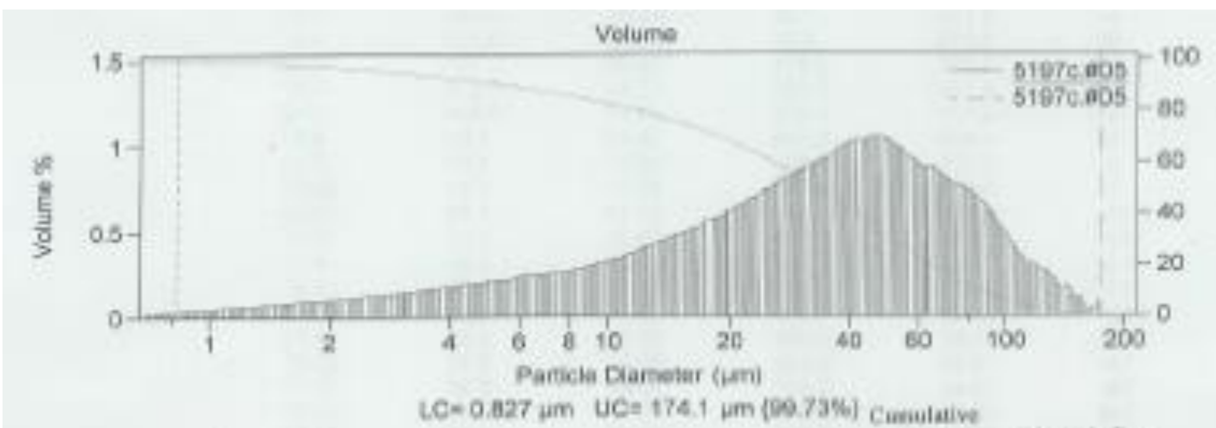


Figure 7. Particle Size Distribution of Arizona Test Dust: ISO 122-1, A4 Coarse Test Dust.

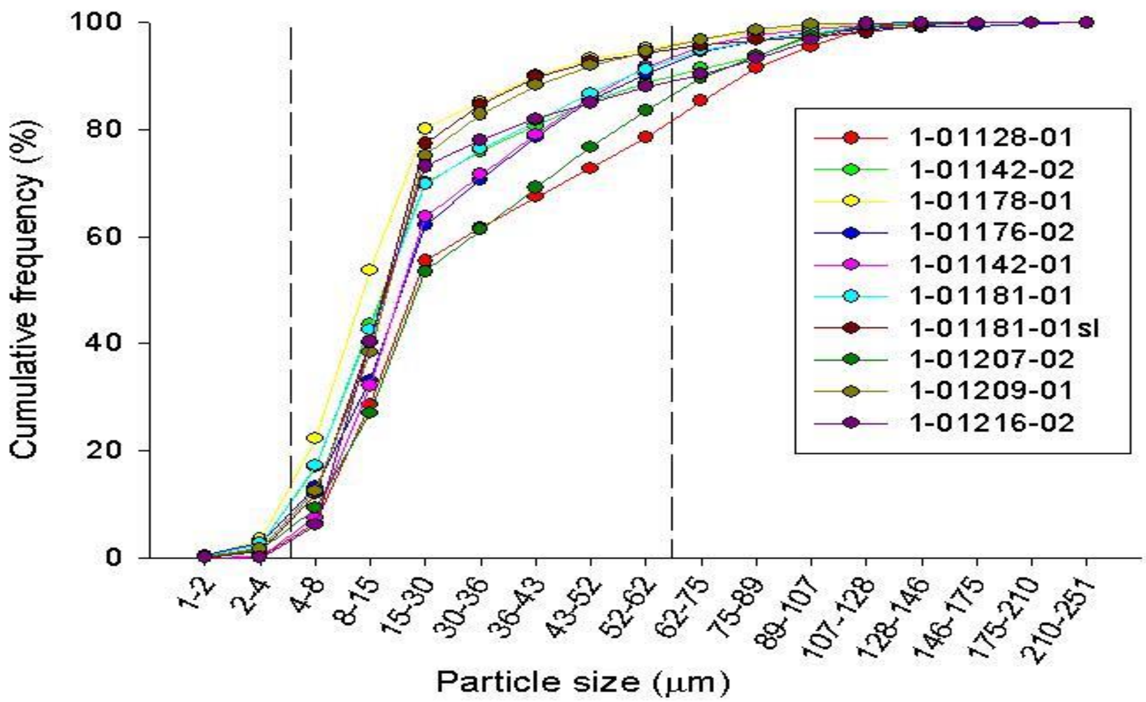


Figure 8. Cumulative Distribution Plot of Ballast Water Sediments for Great Lakes and Chesapeake Bay NOBOB Vessels. Provided by F. Dobbs, Old Dominion University.

2.1.4 System Test Procedure

There were three test phases conducted for each filtration train (screen to media and disc to media). These test phases included an Initial Checkout or System Calibration, Initial Shakedown, and Extended Test Runs in which the sampling and analysis of the three filtration units were conducted. The details of these operational cycles are given below.

2.1.4.1 Initial Checkout

The primary purpose of these tests was to determine the potential of filters as a BW treatment. As mentioned earlier, the 100 gpm flow rate was selected based on recommendations of the basic test plan report. Coincidentally, the nominal feed flow for the media filter unit is 100 gpm. Because filtration is a physical separation, the results of the filtration unit tests can readily be scaled up to 1500 gpm, the nominal flow rate used in ballast water treatment system tests.

During this phase, each filtration train was calibrated to the design flux rate with fresh water and operated at a nominal pressure of 125 psi for a period of one day. Operating flows and pressures were recorded during this phase. The objectives of this phase were to ensure that all systems were operational, gauges and sensors were reading correctly, data acquisition module was operating correctly, and pressures and flow rates could be maintained over the desired ranges. This phase also provided system training**.** Valves were set to regulate the flow through the system to obtain approximately 100 gpm using flow-meters as the guide for balancing flow. Pressure drop across each filter was checked to ensure that it was normal for a clean filter condition. Initial data was recorded using worksheet information that included all pressures and flow rates as given on the flow schematic. In addition to the pressures and flows, the data worksheet included the time and day of startup and shutdown of the system and notes applicable to the system operation.

2.1.4.2 Initial Shakedown Run

A shakedown test of 10-hour duration was conducted to establish how well each filtration train operated with the ambient feed water. The intent was to establish how quickly the filters clogged and required back-washing and to ensure that all systems were capable of meeting the demands of local conditions prior to commencing a long-term test. During this test all data from flow-meters and pressure gauges were recorded. Flow rate was set for a discharge flow rate of 100 gpm.

2.1.4.3 One-Month (100 hours) Extended Test Run

For the extended test, the filter systems were operated with a discharge flow rate of 100 gpm. Test runs were conducted continuously for eight hours each operational day, and the system was shut down on weekends and overnight during the week. The system was not flushed or drained but was allowed to sit in a quiescent state during any non-operational, shutdown period. This process ran continually for 100 hours of operational time over a four-week period for each test of the two filtration trains. During the operating period, pressure and flow data was taken at daily startup, midday and prior to shutdown each day. A plot of pressure drop was also made daily for each filter to assess how quickly the filter clogged and required cleaning or back-flushing. Visual monitoring of the system operation was conducted periodically throughout the day to ensure that the filters were performing satisfactorily and to ensure that no unexpected maintenance was required. When a back-wash or cleaning cycle was performed on any filter, the pressure drop and flow rate were recorded prior to and immediately after the cycle.

2.1.5 Sampling & Approach

The overall experimental sampling and analysis design is described below. The specific manner in which samples were treated to analyze the various organisms of potential interest will also be described. Each filtration system was evaluated for efficacy and efficiency at different sampling points for different stages of the test. Efficacy was evaluated by comparing the concentrations or densities of organisms upstream of the filtration system versus those downstream of the system. Efficiency was assessed by the filtration unit's ability to self-maintain (measured by back-flush frequency) as well as overall system durability.

2.1.5.1 Basic Sampling Series

Samples for biological analysis were obtained four times during each extended test run. Sample times were 25, 50, 75, and 100 percent of the 100 hours for each test run. Triplicate samples for identification and enumeration of marine organisms were collected upstream of the initial filter to characterize the challenge water (ambient water plus added Arizona test dust), and downstream of each filter in the filter train to evaluate the efficacy of each individual filter. All samples for all analyses were taken from these locations (upstream, after screen or disc filter, after media filter). This resulted in a total of 36 biological samples for each extended run or a total of 72 biological samples overall.

Samples for organism identification and enumeration were preserved so that all samples did not have to be analyzed immediately.

Biochemistry and particle size distribution samples were taken daily over the entire month of testing each filter train. Triplicate samples were taken to characterize the challenge water and to determine individual filter efficacy based on percent removal of organic and inorganic suspended solids over the range of sizes that the filters were designed to remove. Thus, three replicate samples were taken five days a week for four weeks at each of three sample sites (feed water with Arizona test dust, after the screen or disc filter, and after the media filter). This resulted in a total of 120 samples for biochemistry and particle size distribution.

2.1.5.2 Data Analyses

The upstream samples represent the concentration or number of organisms of various sizes available to the filters for removal. The sample volumes were selected to provide a sufficient number of organisms to calculate a representative concentration after the filtration systems had removed those size classes for which the filters were rated. Numbers of organisms and particle size-frequency were determined for each sample taken from the flow stream before and after passing through the entire filter system. Filter efficacy was determined for each of the five particle size ranges defined in the following section.

A pre-defined volume (µL) was collected and analyzed for number of organisms, particle size frequency, or concentration. Upstream and downstream results were compared to calculate the percentage removal or reduction of counts for each of the major size ranges. Statistical test results for each paired sample (up and downstream at the same time) of $p < .05$ would indicate rejection of the null hypothesis and indicate that the filter apparatus provided a statistically significant reduction in the measured variable in the size fraction tested.

2.1.5.3 Size Fractions Used for Biological Efficacy Tests

Organisms were sampled prior to filtration and after the screen, disc, and the multi - media filtration system. The upstream samples contained the entire size and shape spectra of organisms and particulates found in the ambient water. Size ranges were determined by evaluating local ambient water prior to the filtration tests. Size ranges are characterized as follows:

1.) Organisms larger than 120 µm (macro-zooplankton including various larval stages of fish, crab, and shrimp)
2.) 80 to120 µm organisms (meso-zooplankton, including the majority of mero-plankton, and larger micro-zooplankton)
3.) 50 to 80 µm organisms (micro-zooplankton)
4.) 25 to 50 µm organisms (micro-zooplankton, larger phytoplankton including those that form chains or have a filamentous body shape)
5.) 5 to 25 µm organisms (phytoplankton)

Organisms smaller than 5 µm (viruses and bacteria) were not counted.

Downstream samples were treated in the same manner as upstream samples to maintain the integrity of the paired-sample model. The size ranges of focus were the 25 to 50 µm and the 50 to 80 µm ranges since the majority of organisms found in the ambient water fell into these ranges. Filter efficacy was determined for these size ranges of organisms as a function of duration of sampling for each combination of filter subsystems tested.

Mean total counts and mean relative counts of identified organisms were conducted to compare the four water streams (challenge water, screen filtrate, disc filtrate, and media filtrate) and to evaluate the efficiency of each filtration system to remove organisms. An analysis of variance test (ANOVA) was performed for this comparison of mean total counts for each water type.

To compare mean total counts of identified organisms of each water type, two hypotheses evaluated were:

- H_o: There is no significant difference in *Mean Total Counts* between the four water types.
- H_a: There is a significant difference in *Mean Total Counts* between the four water types.

2.1.6 Automatically Recorded Data for Test Analysis

Some values were automatically measured and recorded by NRL-KW sensors via a data-logging system and were subsequently transferred to Microsoft Excel. In the following descriptions of measurements, the sensor number corresponds to those in Figure 1.

- Flow Rates were recorded as one point per minute and reported in Tabular and Chart format in terms of Flow Rate (gpm) versus Elapsed Time (hrs (hours)). Flow Rate was measured for Feed Water (Sensor #1), Multi-Media (Sensor #13), and Screen and Disc Filter (Sensor #17).

- Pressure was recorded as one point per minute and reported in Tabular and Chart format in terms of Feed Pressure and Discharge Pressure (psi) versus Elapsed Time (hrs). Pressure was measured for the Feed Water (Sensors # 1, 2), Screen Feed Discharge and Differential Pressure (Sensors # 9, 10), Multi-Media Feed Discharge and Differential Pressure (Senors # 14, 15), and Screen and Disc Feed Discharge and Differential Pressure (Sensors #18, 19).

2.1.7 Manual/Semi-automatic Measurements – Particle Counter

Some data was collected with at least some manual interaction with the instrument during data acquisition. The following sections describe acquisition and presentation of data for particle ranges. As previously noted, for each measurement event (defined as a five-minute data acquisition period) which occurred once a day, the data stream for those five minutes was reported in a MS Excel File. In the following descriptions of measurements, the sensor number corresponds to those in Figure 1.

- Particle Distribution versus Time was recorded in Tabular and Chart format in terms of Particle Count (cts/mL) versus Elapsed Time (hrs). Average Particle Counts were made for the ranges (µm) of 2-5, 5-10, 10-15, 15-25, 25-50, 50-75, 75-100. TSS (cts/mL) was determined for the cumulative range (2-1000 µm). Particle distribution was measured for Feed Water Filtrate (Sensor # 6), Screen Filtrate (Sensor # 12), Disc Filtrate (Sensor # 20) and Multi-Media Filtrate (Sensor # 16).

- Differential Particle Distribution versus Time was recorded in Tabular and Chart format in terms of Particle Count (cts/mL) versus Elapsed Time (hrs). Differential particle distribution was measured at both upstream and downstream sensors for Screen Filtrate (Sensors # 12, 6), Disc Filtrate (Sensors # 12, 20) and Multi-Media Filtrate (Sensors # 12, 16).

- Efficiency versus Time was recorded in Tabular and Chart format in terms of Filtration Efficiency (percent) versus Elapsed Time (hrs). Efficiency was calculated by percent comparison of Particle Counts 2-1000 µm (TSS) upstream to the Particle Counts 2-1000 µm (TSS) downstream. This was conducted for the Screen (Sensors # 12, 6), Multi-Media (Sensors # 12, 16) and the Disc (Sensors # 12, 20).

- Removability versus Time was recorded and reported as Removability (percent) versus Elapsed Time (hrs). Removability was calculated by percent removal of Particle Counts 2-1000 µm (TSS) upstream compared to the Particle Counts 2-1000 µm (TSS) downstream. This was conducted for the Screen (Sensosr # 12, 6), Multi-Media (Sensors # 12, 16) and the Disc (Sensors # 12, 20).

2.1.8 Methods for Sample Collection and Analysis

2.1.8.1 Biological Collection and Concentration

During the four sampling periods, thirty-gallon sample containers were used to collect three replicate samples from each of the three sampling ports: challenge water, screen or disc (50-µm, 55-µm) filtrate, and media filtrate. The screen and disc filtration systems were sampled at different time periods, but all experimental procedures were the same. The samples were collected individually in nine 33-gallon NALGENE tanks, each equipped with a drainage port. Each 30-gallon sample was gravity fed through a 50-µm screen nylon mesh and then a five-µm screen nylon mesh. The 50-µm screen nylon mesh removed the larger particles and therefore accelerated filtration through the five-µm mesh by reducing fouling. Artificial seawater (Instant Ocean®) was used to rinse the 50-µm and then the five-µm captured particulates into a common graduated beaker. The beaker's volume was then recorded. Samples were transferred to amber NALGENE bottles. These bottles were labeled with the tank number, sample date, and volume (mL) and placed in a cooler. For each sampling sequence, the order of this initial sample processing went from cleanest to dirtiest; media filtration (25µm), screen (50 um) and disc (55) filtration, and challenge water. The equipment used was rinsed thoroughly with fresh water between each individual sample. The sample bottles were brought into the lab and treated with Lugols Iodine fixative at a concentration of 0.3 mL of fixative to 100 mL of sample volume. Fixed samples were stored in a refrigerator to await analysis.

2.1.8.2 Biological Sample Preparation

Sample bottles were gently inverted clockwise and counter-clockwise 10 times each to ensure adequately homogenized samples. Homogenized one-mL samples were extracted with Eppendorf micropipettes and placed into a Sedgewick-Rafter counting cell for analysis (50mm X 20mm).

2.1.8.3 Microscopic Analysis for Phytoplankton Identification and Enumeration

The counting cell sample was analyzed using a Nikon E600 Microscope with Phase and Epifluorescence capabilities, a Retiga 1300 Digital CCD camera, and Image-Pro Plus software. The counting cell volume was broken into 1000 squares (one mm X one mm of one-µL capacity). The individual sample squares were analyzed using a 10X objective, Phase one condenser. Phytoplankton total counts and relative counts by shape were obtained for each square. The order in which sample squares were analyzed was determined randomly using an EXEL random number generator. Counting of the randomly selected sample squares continued until phytoplankton total counts reached 400 individuals for screen and 300 for disc. (Note: ETV specifications for adequate total individuals changed during the sampling process resulting in the different numbers counted for the two filters.) In the case of phytoplankton absence, as found in samples from the media filter, the number of counted squares was pre-set to 25 (25 µL) which was determined from analysis of the challenge water. Twenty-five counted squares were needed to obtain 400 (300 for the disc unit) total counted phytoplankton in the challenge water sample. Each Sedgewick-Rafter square (one µL) was saved as a digital image. Chain-forming organisms were measured for length, width, and single setae length if present. Body lengths were obtained using Image Pro Plus software.

2.1.8.4 Sample collection of Total Suspend Solids

Six replicates were obtained in one-L amber NALGENE containers each day. Replicates were filtered on glass fiber filters, oven dried, and weighed to determine TSS concentrations in mg/L. The 47-mm, GF/F, Glass Fiber filters had been pre-rinsed with 300 mL of ASTM (American Society for Testing and Materials) Type 2 water, dried for at least one hour at 105ºC, and weighed prior to use. During the test of the disc filter, pre-rinsed and pre-weighed, PROWEIGH® filters were used. Pre-rinsed filters used for the screen test were weighed two times to establish their pre-weight. The methods for sample preparation and analysis of TSS were preformed as outlined in APHA Standard Method 2540 D (Clesceri, Greenberg, Eaton, 1998).

Problems of mixing the added Arizona Test Dust with the inorganic matter found in the ambient water during the testing of the Screen unit made it necessary to add a static mixer. The static mixer was added less than 80 hours into the test duration of the screen unit, the first unit tested.

3. Results & Discussion

3.1 Differential Pressure versus Time

3.1.1 Differential Pressure of Screen Filter and Media Filter Train

As shown in Figure 9, the feed pressure to the screen filtration unit ranged from 80 to 100 psi. When the differential pressure (DP) of the screen unit reached a maximum of 6 to 6.5 psi, the back-flush cycle was actuated. As indicated in Figure 10, the back flush is denoted by a sudden decrease in DP. For clarity, a plot of a single day's DP cycling is shown in Figure 11. The minimum DP of the media filtration unit, shown in Figure 12**,** was about 4 psi at the beginning of system operation and continued to increase to a final DP of about 11.75 psi. This was below the system's normal back-flush DP of 15 – 20 psi, thus this system did not initiate any back-flush events during the approximate 150 hours of tests. Significantly, there was a distinct increase in differential pressure once the particle loading was changed to the 50/50 mixture of medium test dust and coarse test dust after approximately 40 hours of operation. Note that the intermittent drops to near atmospheric pressure seen in each figure are a result of the nightly and weekend filter shutdowns.

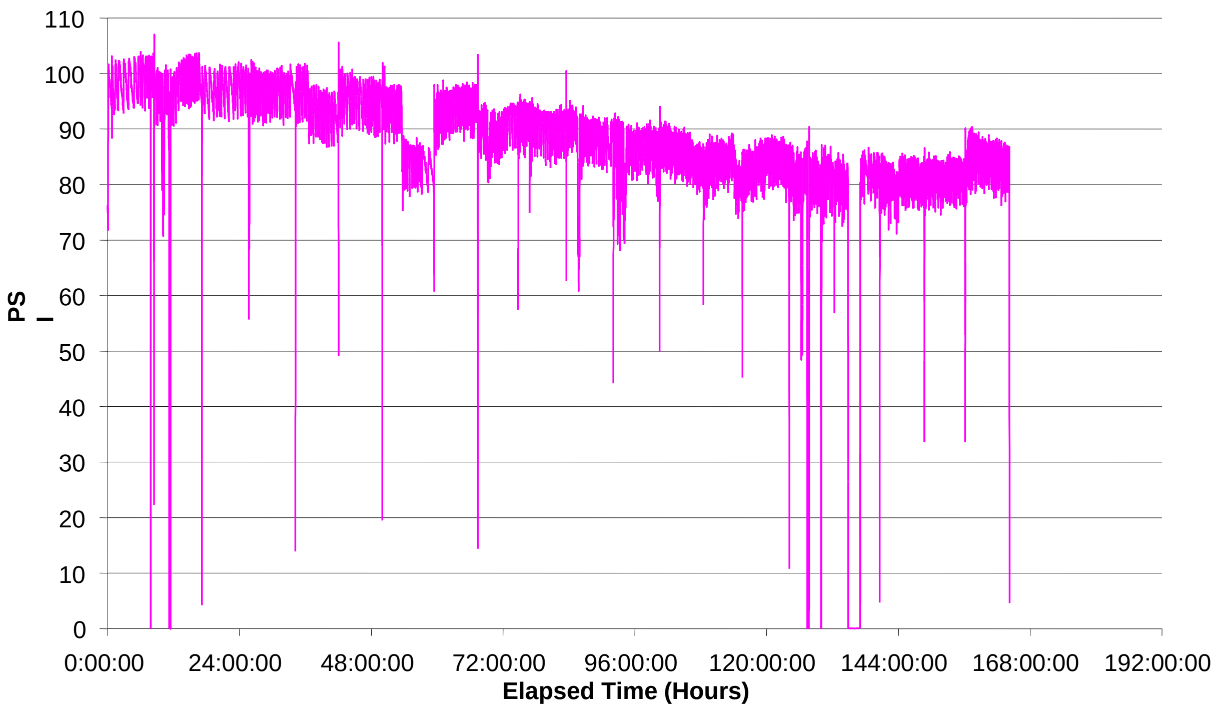


Figure 9. Feed Pressure to the Self-Cleaning Strainer Filter Unit.

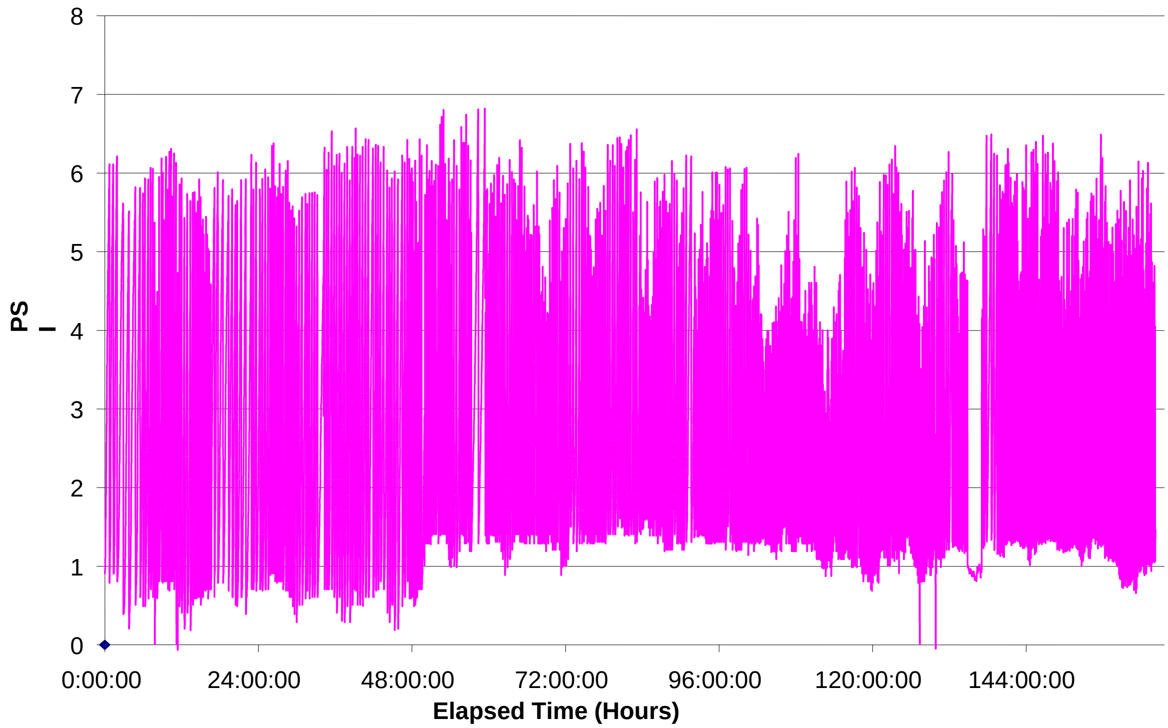


Figure 10. Differential Pressure for Self-Cleaning Strainer Filter Unit.

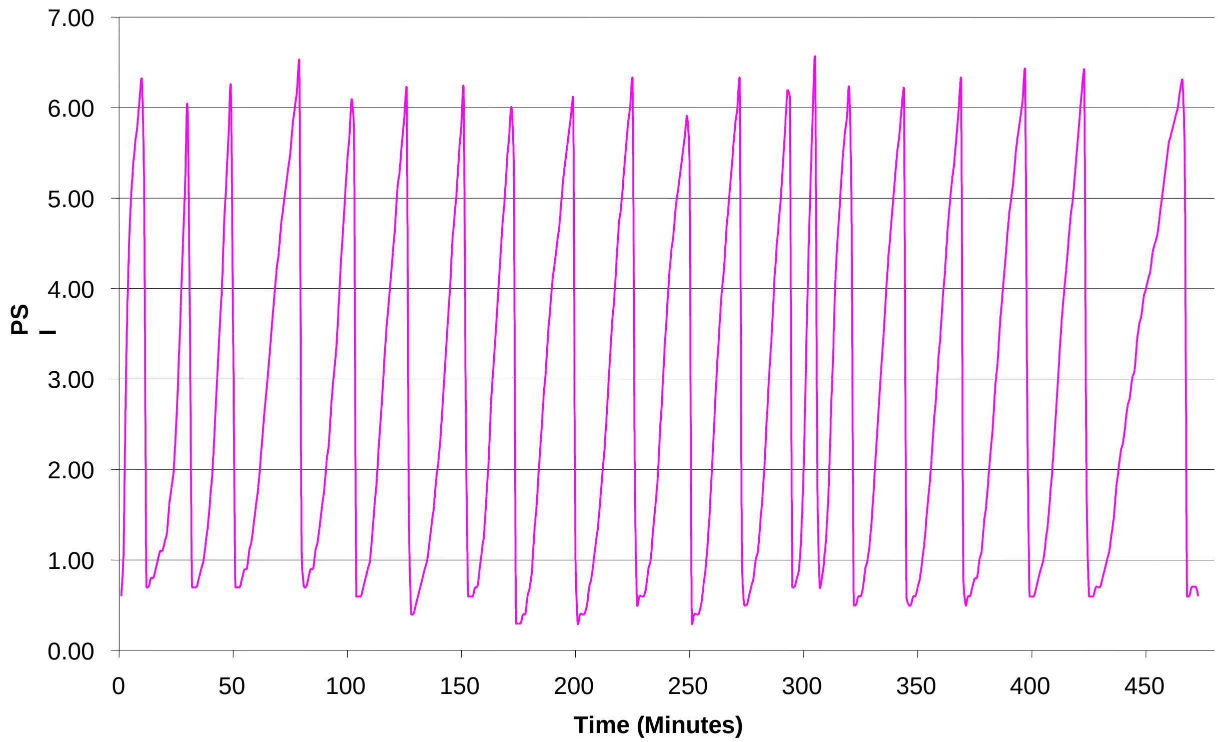


Figure 11. Daily Differential Pressure for Self-Cleaning Strainer Filter Unit.

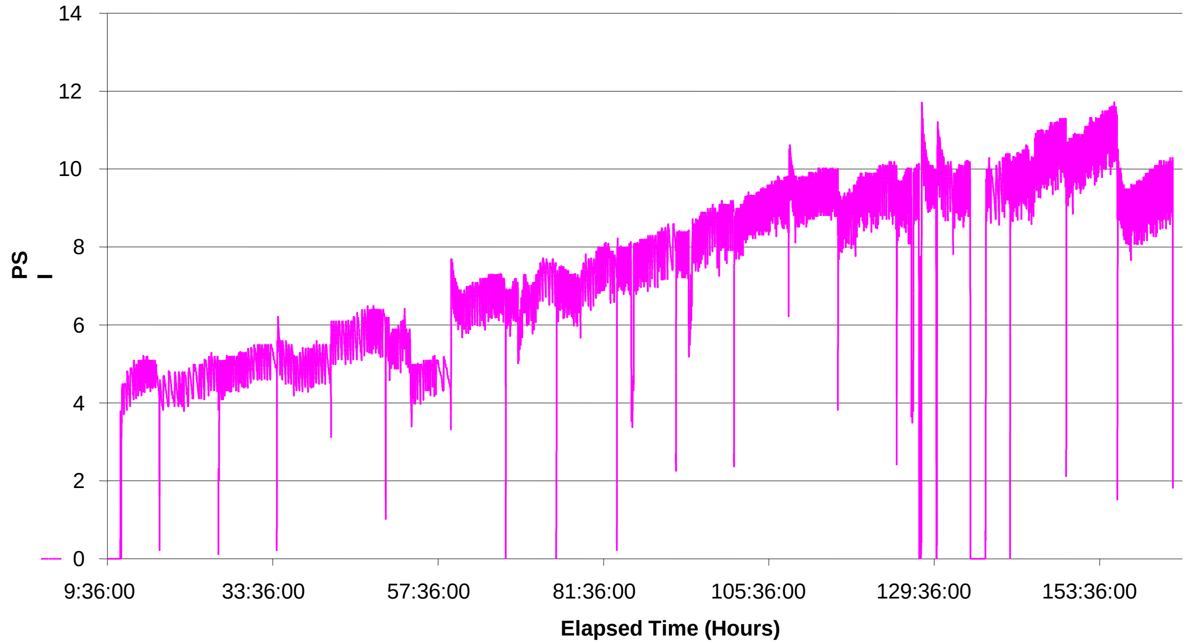


Figure 12. Differential Pressure for Media Filter with Self-Cleaning Screen Filter Filtrate as Feed Water.

3.1.2 Differential Pressure of Disc Filter and Media Filter Train

As seen in Figure 13 the feed pressure to the disc filtration unit ranged from 100 to 125 psi. When the differential pressure of the disc unit reached a maximum of 20 to 25 psi, the back-flush cycle was actuated resulting in the differential pressure drops as seen Figure 14. A daily plot of differential pressure is also shown in Figure 15 for clarity. While the disc filtration system tolerated higher differential pressures than did the screen filtration system at comparable feed pressures, back-flush cycles were considerably more frequent for the disc filtration system as seen by comparing Figure 11 and Figure 15. Furthermore, on three occasions during the 100- hour operational cycle, the disc filtration system ceased to operate due to the back-flush cycle being inadequate which resulted in a drop in differential pressure. At these events, the system was disassembled and thoroughly cleaned manually.

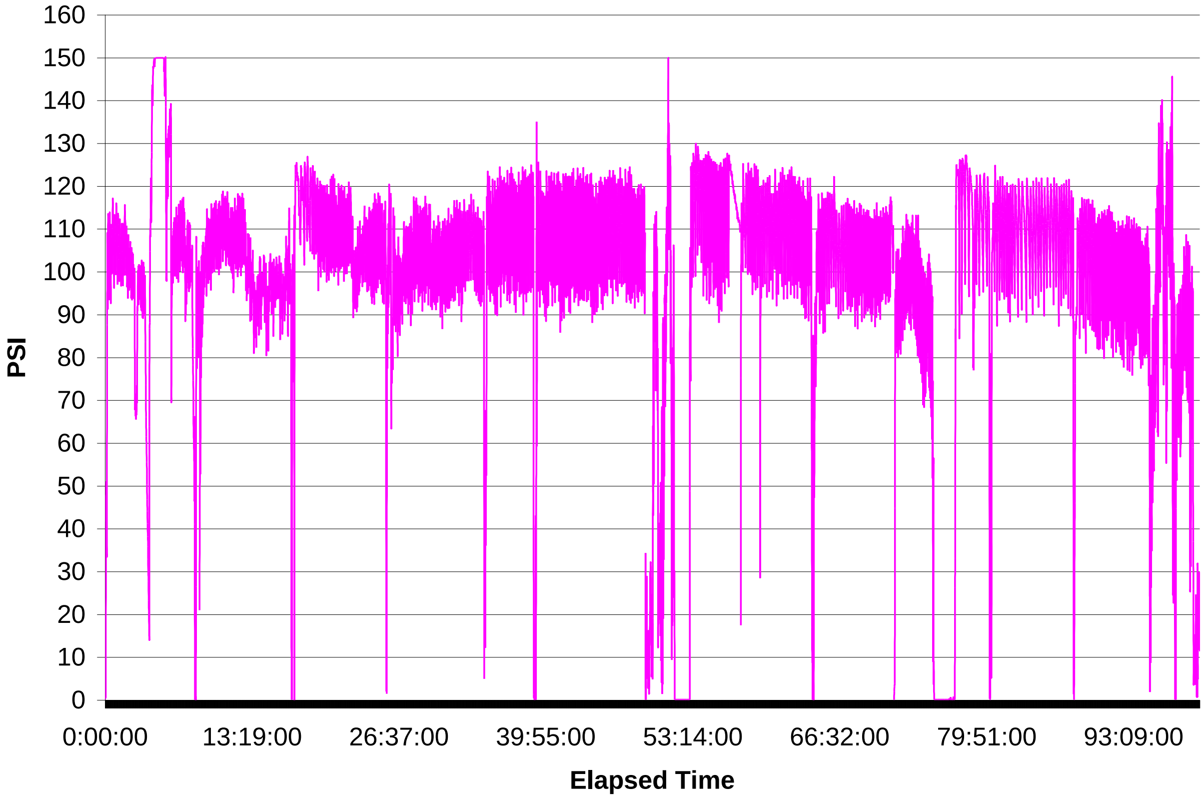


Figure13. Feed Pressure to Disc Filtration Unit. Elapsed time is in hours.

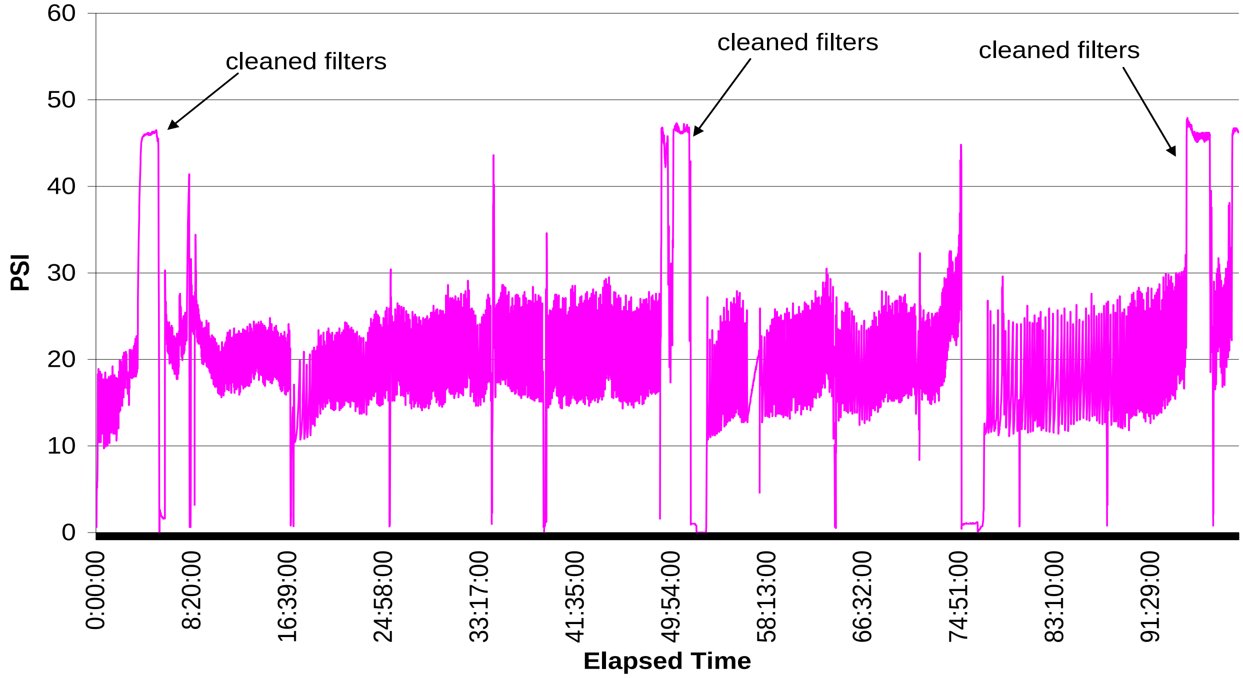


Figure 14. Differential Pressure for Disc Filtration Unit. Elapsed time is in hours.

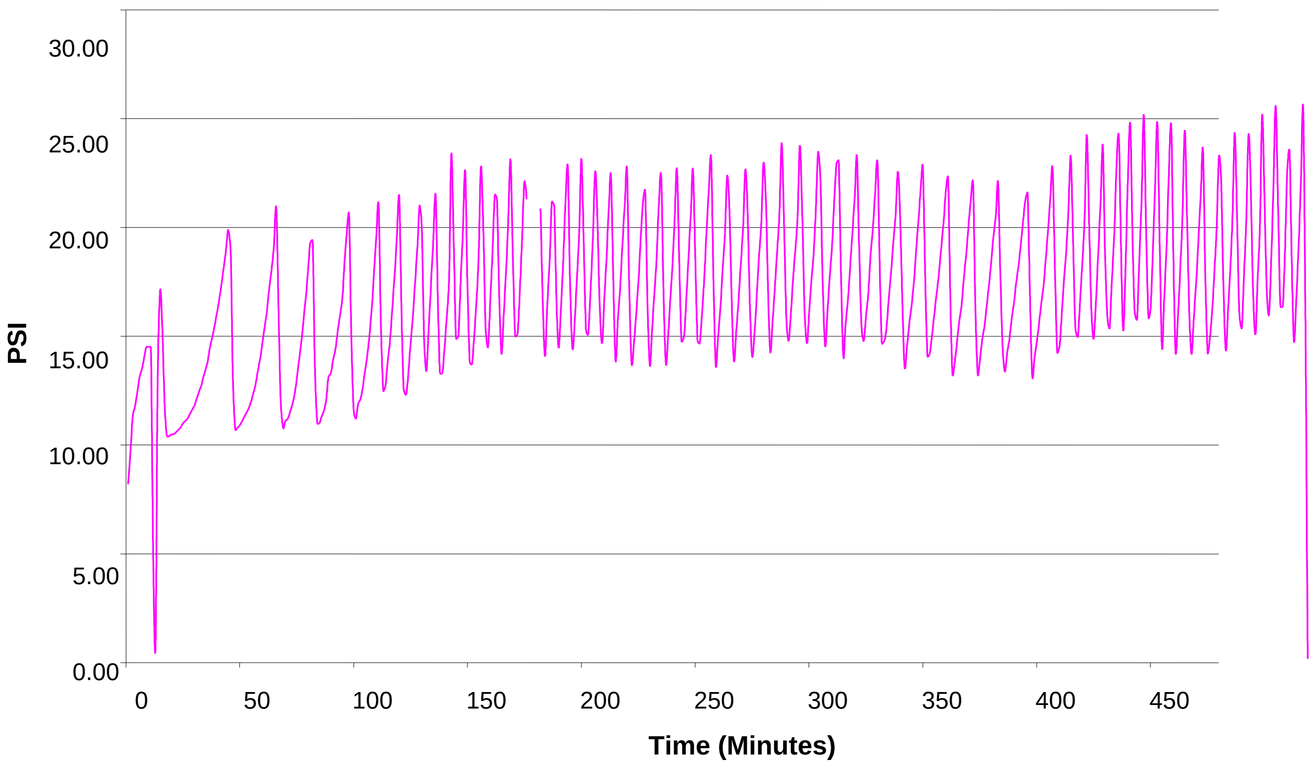


Figure 15. Daily Differential Pressure for Disc Filtration Unit.

3.1.3 Back-flush frequency

Frequency analysis of the differential pressure cycle/back-flush events provides information regarding the overall efficiency of the filtration systems and their relative ability to "self-clean". Back-flush frequency as a function of operational time is plotted in Figure 16 and Figure 17 for the screen and disc filtration systems respectively. Note that the screen filtration unit back flush frequency was consistent until the 40-hour mark when the test dust was altered to 50 percent medium and 50 percent coarse test dust. After that the frequency increased dramatically at a rate of seven cycles/operational hour. Subsequently, back-flush frequency was reduced by 47 percent following the addition of 60 percent crushed quartz. This was likely the result of the screen pores being "cleaned" by the larger/harder entrained particles, thus reducing the overall DP and the resultant back flush frequency.

The disc filtration system, on the other hand, retained a relatively high back-flush frequency of 70 cycles/day with a range of 40-95 cycles/day over the course of the experiment. This does not include the additional manual cleaning events which were needed during operation due to sustained inoperability of the system. Significantly, these cleanings were the only times in which the back-flush frequency was significantly reduced.

Overall, the adequacy and performance of the back-flush operation/mechanism of the screen filtration system was superior to that of the disc filtration system under the experimental conditions. The disc filtration's performance may have been improved by an increase in back-flush feed pressure, though the unit was operated within manufacturer's recommendations.

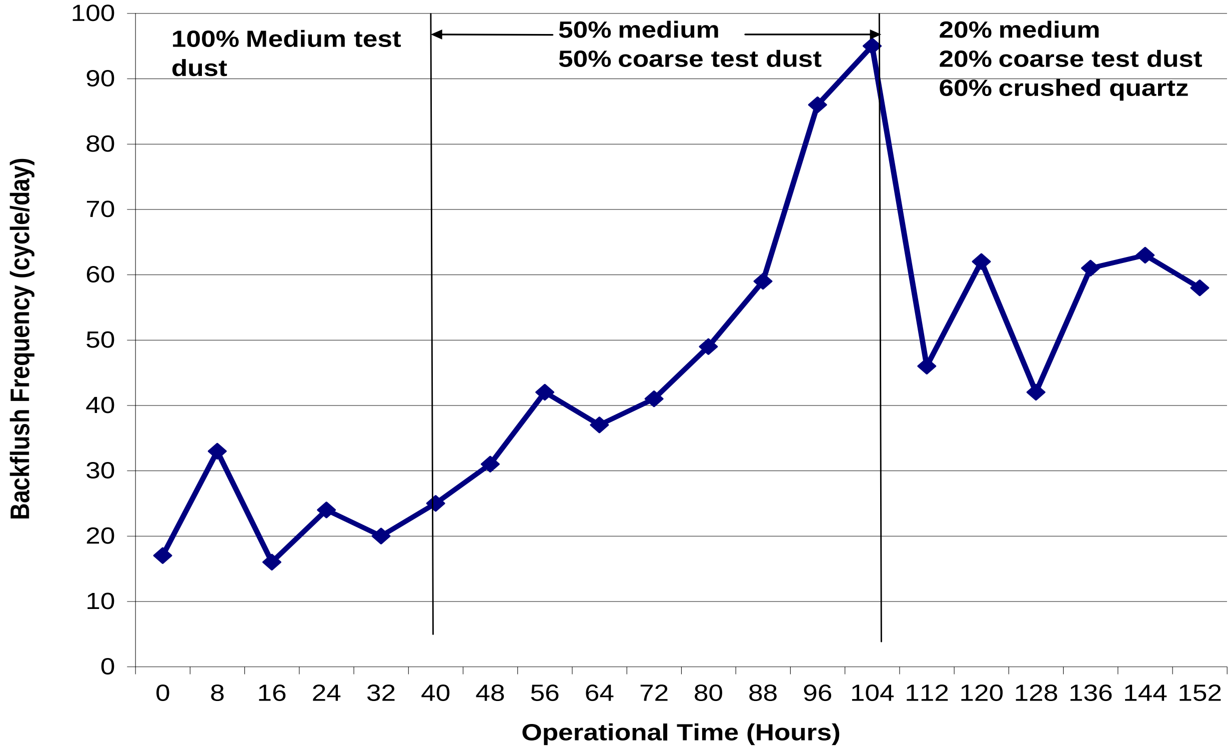


Figure 16. Back-Flush Frequency for Screen Filtration Unit.

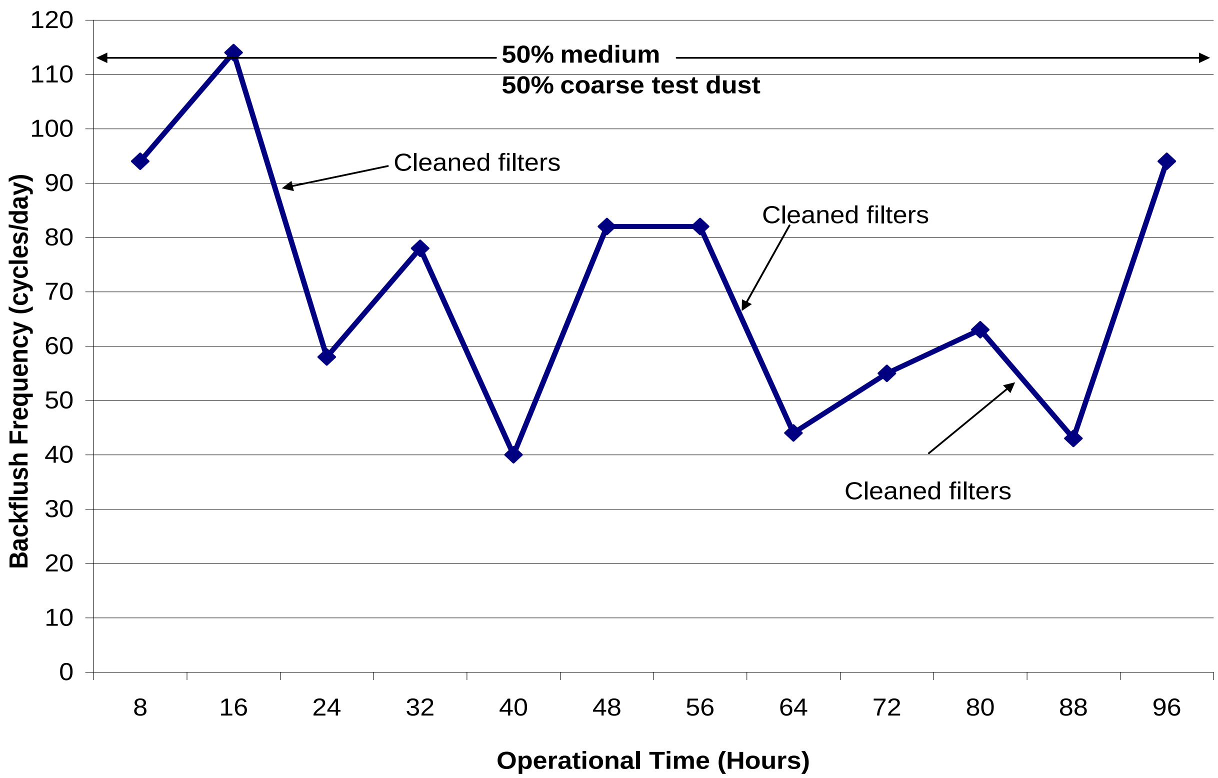


Figure 17. Back-Flush Frequency for Disc Filtration Unit.

3.2 Particle Counting

3.2.1 Particle Size Distribution Versus Time, Self-Cleaning Screen Filter and Media Filter Train

The particle size distribution for the feed water during the testing of the screen and media filter train is shown Figure 18. Clearly and expectedly, the majority of particles were in the 2-10 micron range with the 10-25 microns secondary to those. The particle size distribution for the filtrate from the screen filter unit is shown in Figure 19. Compared to the feed water, there was virtually no change in particle concentrations smaller than 25 microns which is to be expected. The screen's pore size is 50-microns, so the unit was unable to remove the 25 to 50 micron particle range.

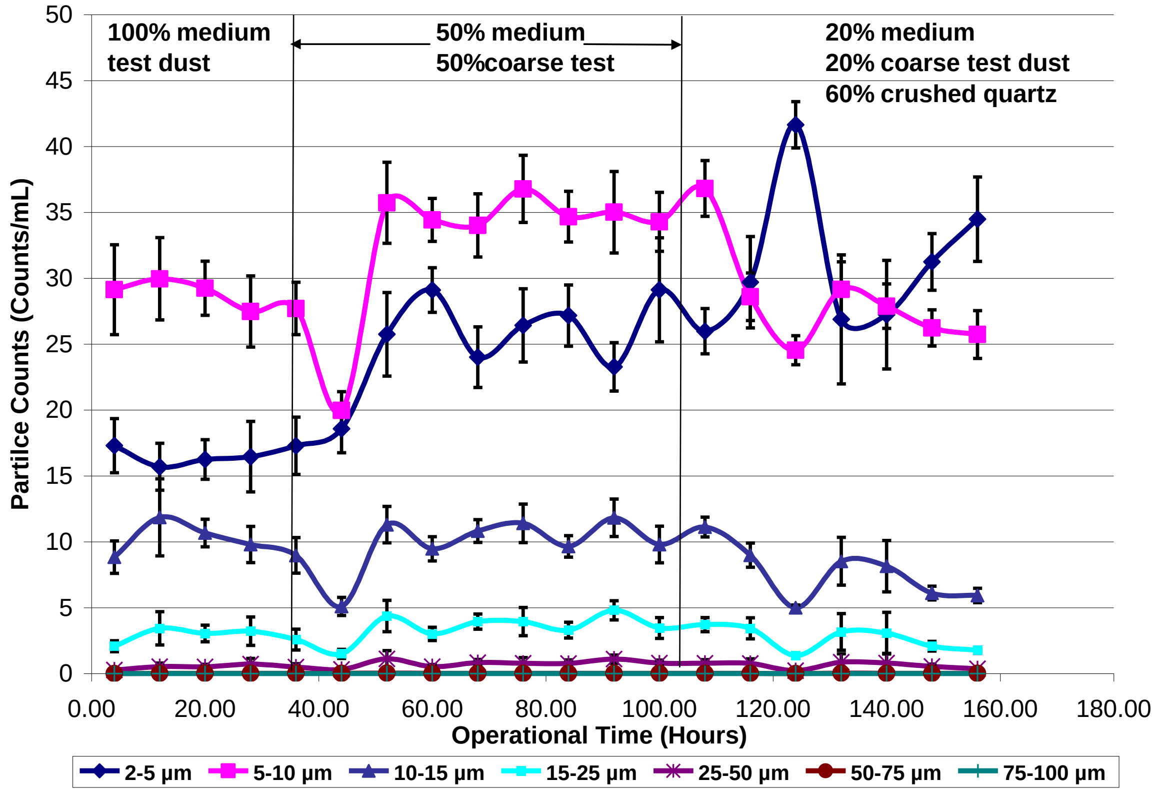


Figure18. Particle Count Results for Feed Water during the Test of the Screen Unit.

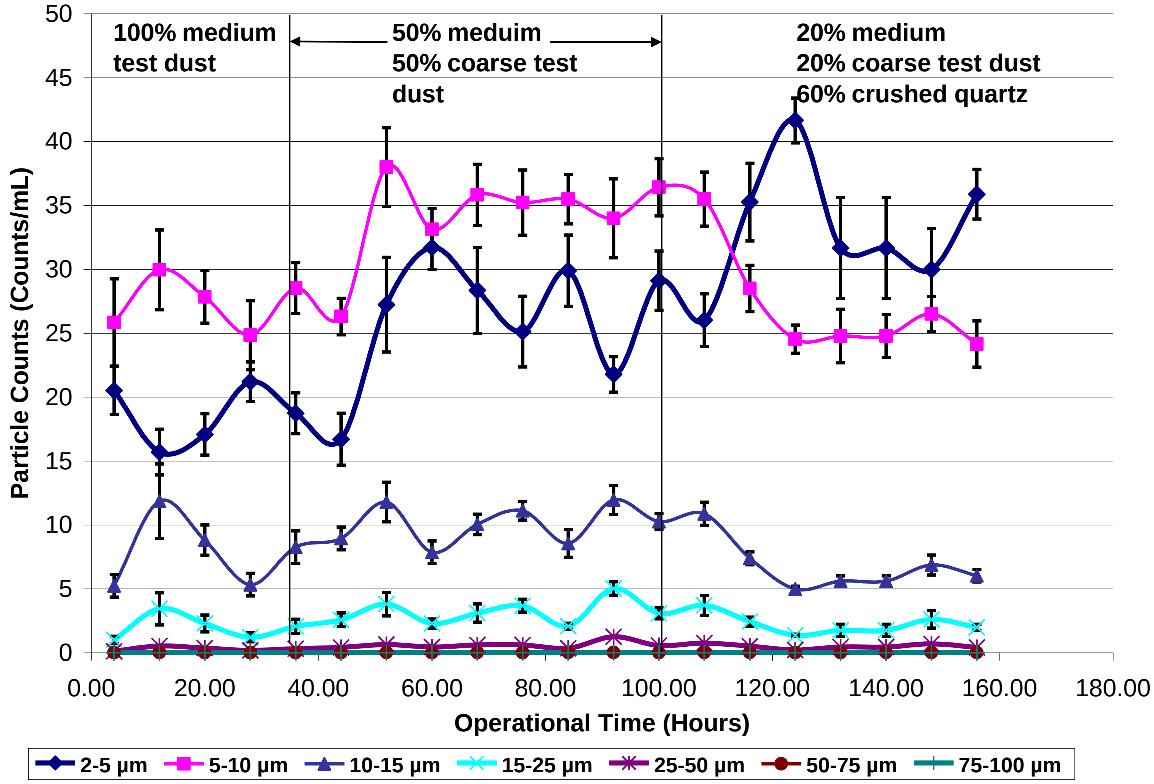


Figure 19. Particle Count Results for the Screen Unit.

The media filter particle counting results are provided in Figure 20. Comparison to those of the feed water indicated that the removal of particles larger than five microns exceeded 80 percent for all size distributions. Also notable from these data was the steady increase in the discharge of particles in the two to five micron size over the course of the experiment despite a relatively constant concentration in the feed water for the first 120 hours. This may have been the result of a loss of efficiency and sediment filtering with increasing particle load in the media bed or the result of media loss from the filtration system.

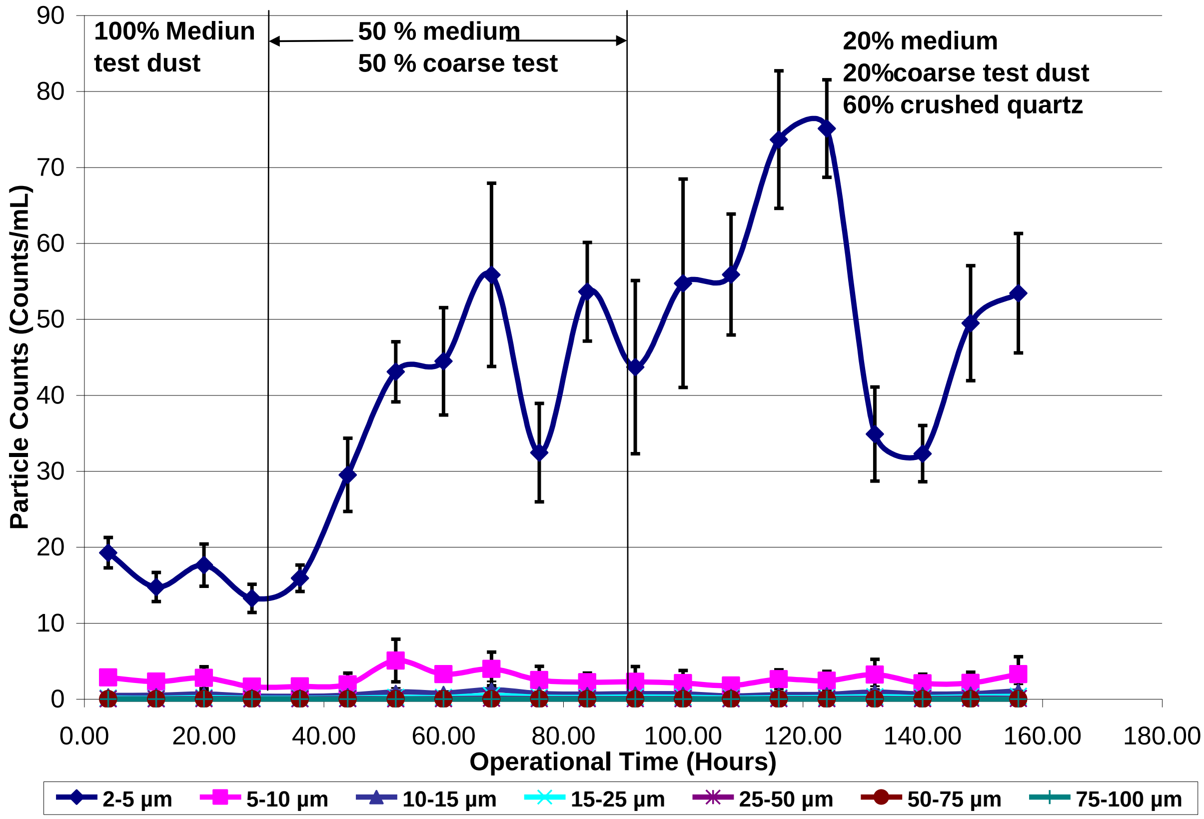


Figure 20. Particle Count Results for Media Filter During the Test of the Screen Unit.

3.2.2 Particle Distribution Versus Time for the Disc Filter and Media Filter Train

The feed water particle size distribution through the course of the experiment with the disc and media filter train is shown in Figure 21. The particle size distribution results for the disc filtration unit as a pre-cursor to the media filter are shown in Figure 22; as expected, there was no change in particle concentrations smaller than 25 microns relative to the feed water over the system operation duration. The 25- to 50-micron range was unaffected by the disc's 55-µm size. This result is identical to that for the screen filtration system under comparable conditions.

The particle size distribution in the media filter's filtrate are shown in Figure 23. As seen during the screen filter test, the media system did not remove any particle concentrations in the two-five micron range, but everything greater than five microns was successfully removed.

3.2.3 Overall Comments on Particle Distributions

Both the screen and disc filtration units (50 µm and 55 µm, respectively) were unable to remove particles less than 25 microns which was a substantial amount of the particles moving through the system. Particles larger than 50 microns were not abundant enough to draw conclusions. Both systems had to increasingly back-flush over the test duration even though the majority of particles were below the rated filter size of the unit. Even with the high back-flush frequency, the disc filtration system was unable to rinse itself of particles and had to be hand rinsed three times.

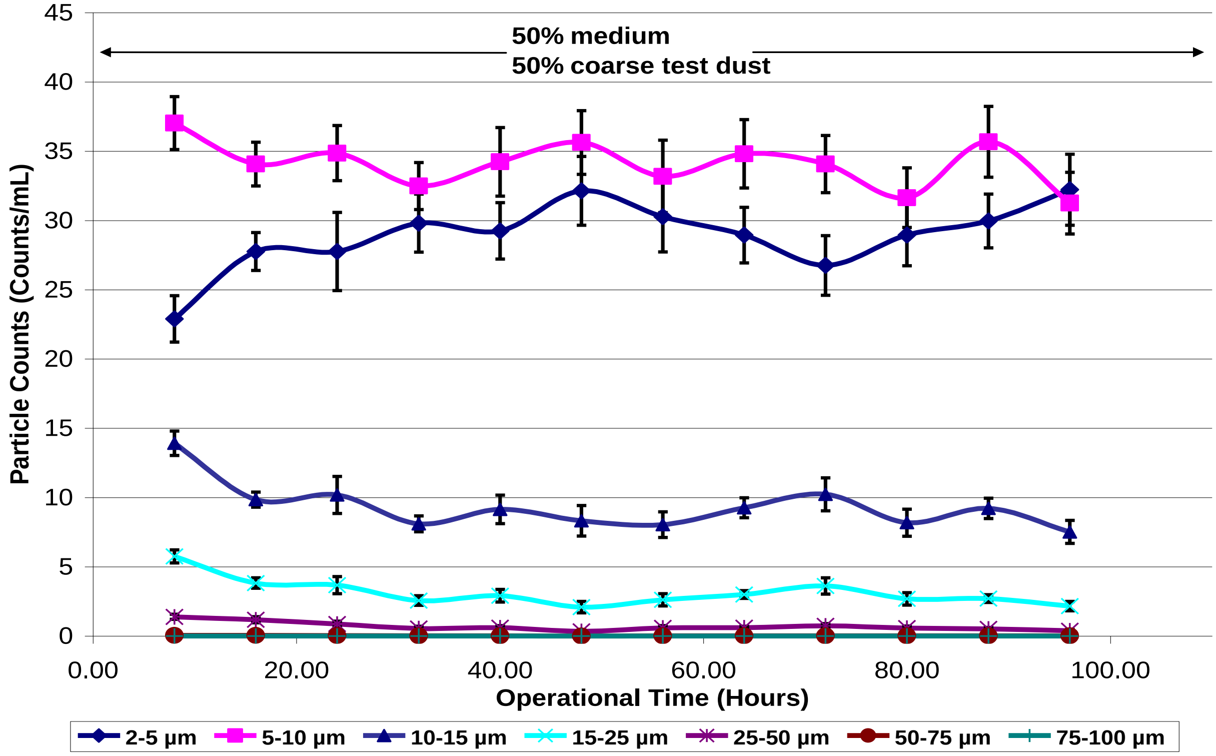


Figure 21 Particle Count Results for Feed Water During the Test of the Disc Unit.

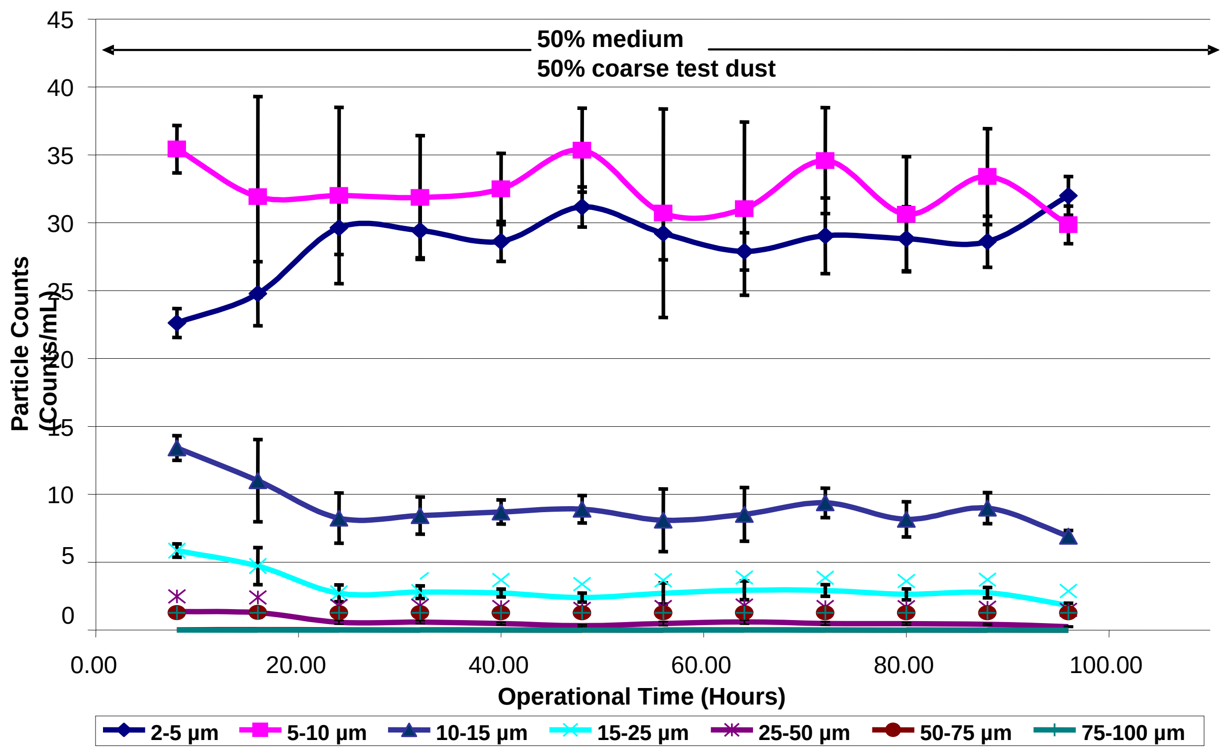


Figure 22. Particle Count Results for the Disc Unit.

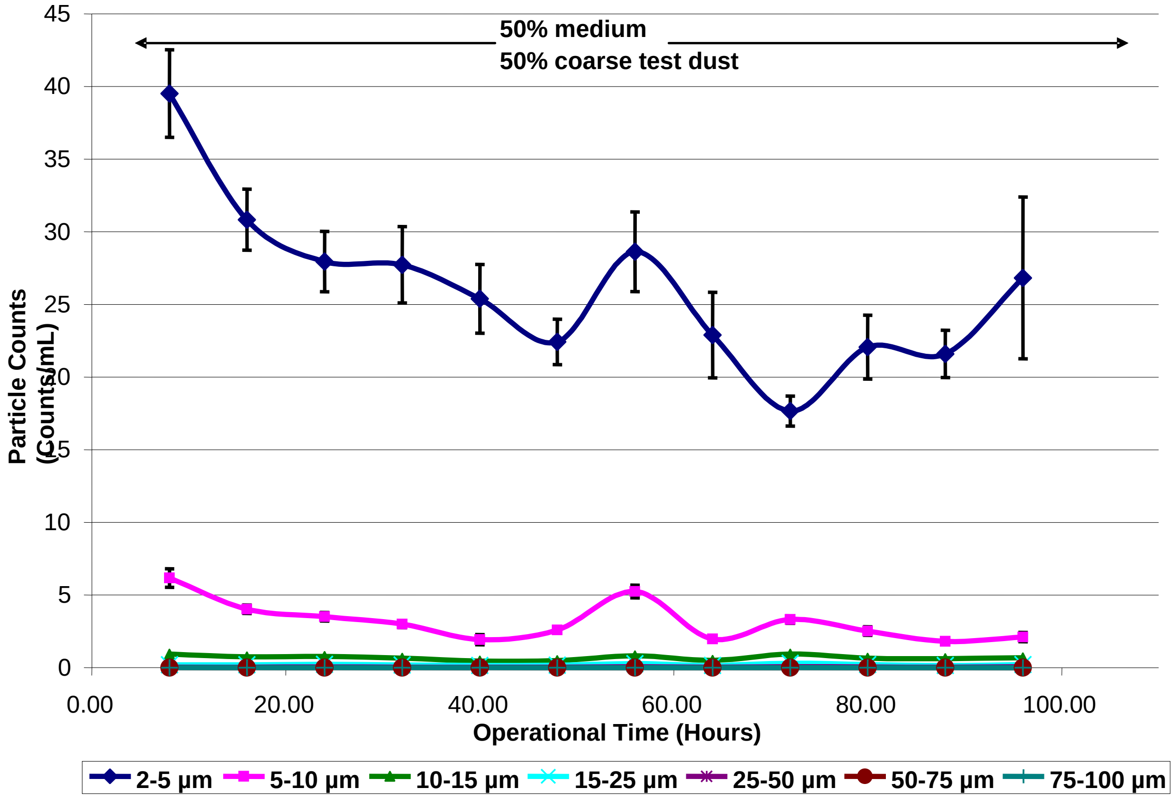


Figure 23. Particle Count Results for Media Filter During the Test of the Disc Unit.

3.3 Total Suspended Solids Determination

3.3.1 Screen Filter and Media Filter Train

The daily mean TSS for the feed (or challenge) water compared to the measurements of the screen and media filtration units is shown in Figure 24. The feed water TSS was variable throughout the course of the experiments and was rather difficult to closely control. Causes for the variability included variable ambient seawater solids loading, lack of a static mixer early in the experiment, and an industrialized injection apparatus for supplementing the suspended solids. With regards to the injection, the major difficulty with the concentrated sediment solution is maintaining the sediment suspension within the container vessel. This was ultimately solved by the addition of multiple oblique mixers and pumping systems.

The bulk of the suspended solids were less than 50 microns, which resulted in a minor reduction of particle concentrations by the screen filter even with the addition of the 50 percent coarse test dust and 60 percent crushed quartz. A comparison between the challenge water and screen system reveals that the mean TSS for the screen unit was generally less than the challenge water due to some removal by the screen filter. The media filter extensively removed TSS relative to the screen filtration system. This is expected since the media filter's pore size was significantly smaller than the screen's.

The relative performance of the screen and media filter systems was also evaluated based on removal efficiency as plotted in Figure 25. The negative removal efficiency prior to 80 hours of operation was actually an artifact from sediments settling in the piping ahead of the filter unit. Notably, after addition of the static mixer the screen filtration system removal efficiency was eight percent on average. Additionally, once the coarser material (Crushed Quartz) was added, the removal efficiency for the screen filter increased appreciably, to approximately 23 percent. This was largely the result of the particle loading being larger than the rated screen filtration size of 50 microns. The media filtration system operated consistently over the course of the experiment with a removal efficiency of 73 percent of TSS on average with a single, unexplained data point below 25 percent.

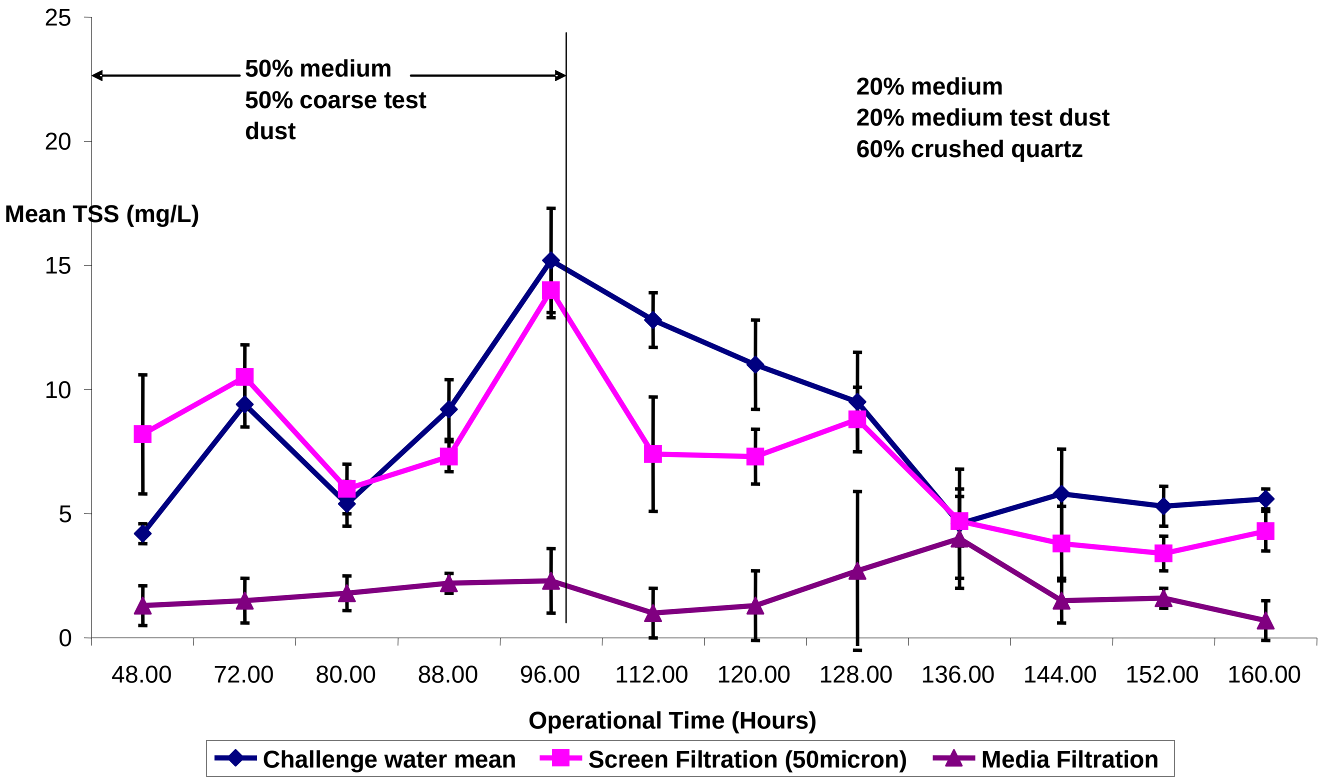


Figure 24. Mean of Total Suspended Solids (mg/L) for the Screen System Tests.

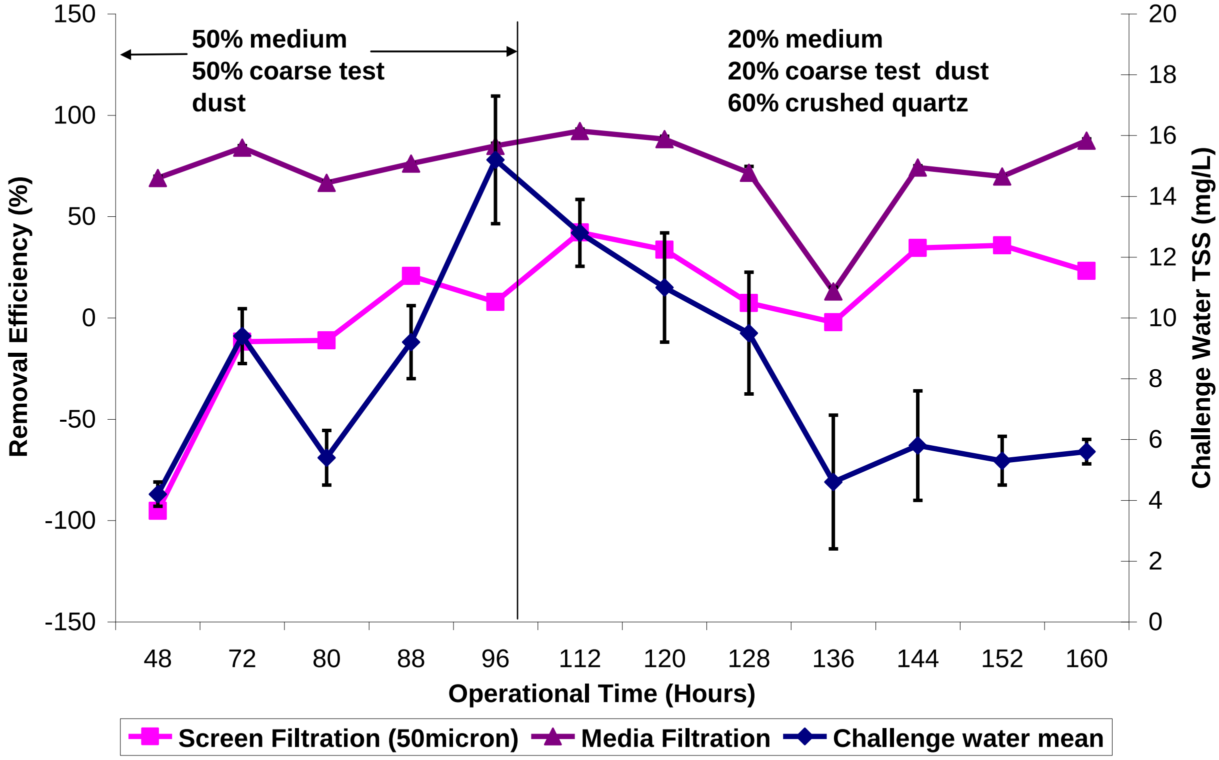


Figure 25. Removal Efficiency of Screen Unit and Media Filter in Comparison to Challenge Water During Screen System Duration.

3.3.2 Disc Filter and Media Filter Train

Daily TSS variations of the challenge water and the disc and media filtration units are shown in Figure 26. These results are similar to the screen filtration test, though the average TSS is somewhat higher as a result of the addition of a static mixer as determined during the previous experiment. Again, the bulk of TSS was less than 50 microns and thus there were only minor reductions of particle concentrations. As with the screen test, the disc unit did remove some particles and thereby its mean TSS was always less than the challenge water mean. TSS after the media filter was significantly less than both the disc system and challenge water due to better removal of total suspended solids.

Removal efficiency of each system is shown in Figure 27. The disc filter was able to remove 15 percent of TSS on average, which is seven percent more TSS on average than the screen unit. However, the disc system needed to be disassembled and rinsed three times during the test period. The media filter removed 61 percent of TSS on average, which is reduced from the previous experiment. This is could potentially be a residual effect from the previous test investigation, though the system was well flushed between experiments.

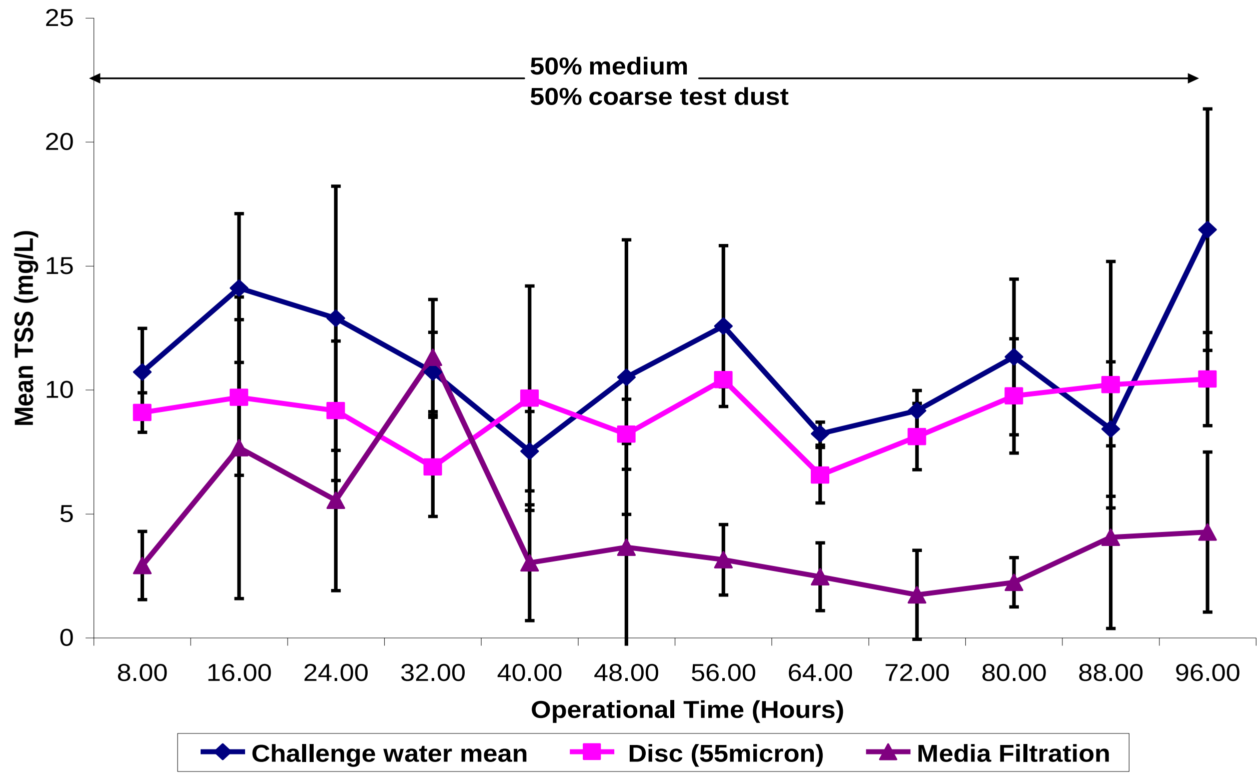


Figure 26. Mean of Total Suspended Solids (mg/L) for the Disc System Duration.

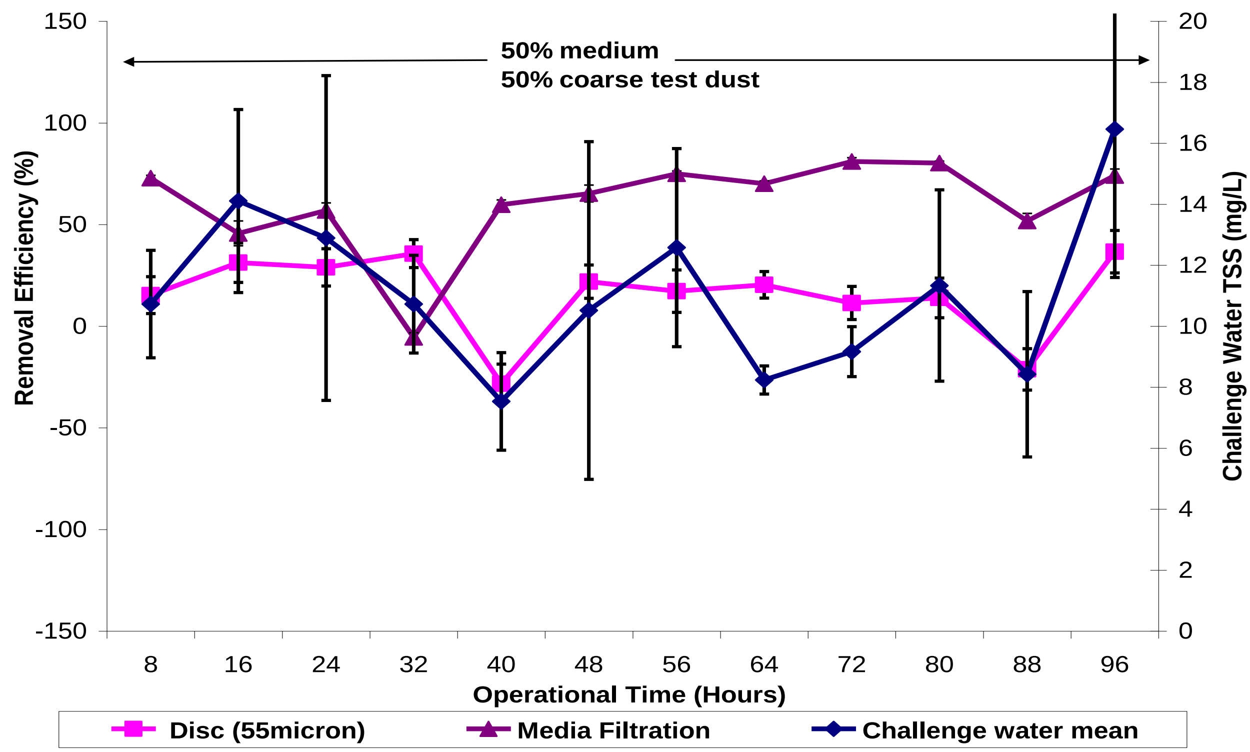
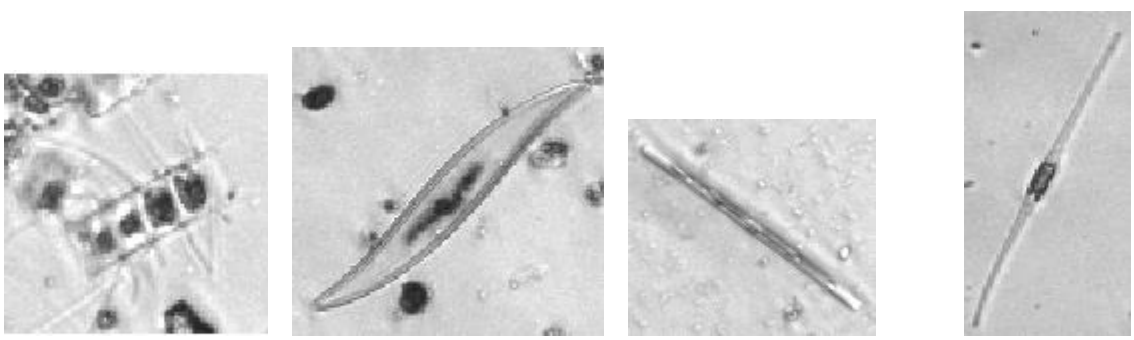


Figure 27. Removal Efficiency of Disc Unit and Media Filter in Comparison to Challenge Water during Disc System Duration.

3.4 Marine Organism Identification & Enumeration

3.4.1 Identification

As stated in Section 2.1.8, "Methods for Sample Collection", the organisms tallied were recorded on Excel data sheets and saved as digital images. Organisms were initially sorted by body configuration described as chain formers or non-chain-formers. The non-chain formers were then categorized by shape. All shapes, including chain formers, were referenced with a letter to further distinguish one from another. The four dominant shapes found in the sample collections throughout the experiments were chain formers (A), pinnate diatoms (D), rectangular diatoms (E), and skinny pinnate diatoms (H). Even though there are numerous micro-organisms characterized by these shapes, particular species found in the sample collections comprised the majority for each shape. The majority of species for each phytoplankton morphology shape consist of: *Chaetoceros spp* - chain former (A) (length: 2–80 µm; width: 6-30 µm; setae length: 10-220 µm); *Gyrosigma spp.* – pinnate diatom (D) (length: 110–175; width: 28-44 µm); *Thalassionema spp*. – rectangular diatom (E) (length: 10-230 µm; width: 2-3 µm); *Nitzschia spp*. – skinny pinnate diatom (H) (length: 125 µm; width: 3-5 µm) (Tomas, Grethe, Syvertesn, Steidinger, Tangen, Throndsen, and Heimdal, 1997). Photographs of these organisms are provided in Figure 28. These species will be referred to by name and letter in the following discussions of total counts for dominant phytoplankton morphologies. These generalized morphologies will also appear in the following figures as indicators of species type.



Chaetoceros spp. (A) *Gyrosigma spp*. (D) *Thalassionema spp*. (E) *Nitzschia spp.* (H)

Figure 28. Morphologies of the Four Most Dominant Phytoplankton Organisms.

3.4.2 Total Biological Counts

For the testing of the screen filtration unit as a pre-cursor to the media filter, total counts of biological organisms larger than five microns were made as previously discussed. Mean total counts of organisms at 72, 104, 112, and 127 hours are provided in Table 2. These data indicate that over the test duration there was no significant removal of organisms by the screen filtration unit. This was determined by comparing the mean total counts of the challenge water to the screen system as shown in Table 2 and Figure 29.

Both the table and figure show there was no removal from the sample acquired after 72 hours of system operation with the mean total counts being 19 per µL for both the challenge water and screen unit. There was minimal removal throughout the rest of the test until 127 hours. At that time more organisms were removed by the screen, but the difference is not significant as indicated by the standard deviation error bars. In comparison, the media filtration unit removed the majority of the dominant organisms from the challenge water at all sampling times. The highest mean total count for the media filtration system was 3 per µL after 72 hours of system operation. All the other sampling times had a mean of one total counted organism. The smaller particle size filtering rating of the media filter (25µm) explains the difference in the removal of the identified and dominant organisms in comparison to the screen system.

Four distinct morphologies dominated the phytoplankton counts. Table 3 provides the actual count (number) of each morphology. Table 4 gives the percent of each dominant morphology relative to all organisms counted, not just the four dominant ones. The discussions that follow are based on the dominant organisms but should be indicative of all. Thus, the total count is provided, and the percentage of all organisms is in brackets for each dominant organism discussed.

Table 2. Mean Total Counts of Organisms after 72 hours, 104 hours, 112 hours, and 127 hours of System Operation.

	Challenge water	Screen	Media Filter
72 Hrs - Mean/µL	19	19	3
72 Hrs - Standard Deviation	4.4	6.6	1.3
104 Hrs - Mean/µL	21	20	1
104 Hrs - Standard Deviation	1.4	1.4	0.2
112 Hrs - Mean/µL	23	21	1
112 Hrs - Standard Deviation	0.5	1.5	0.4
127 Hrs - Mean/µL	19	16	1
127 Hrs - Standard Deviation	2.6	1.1	0.5

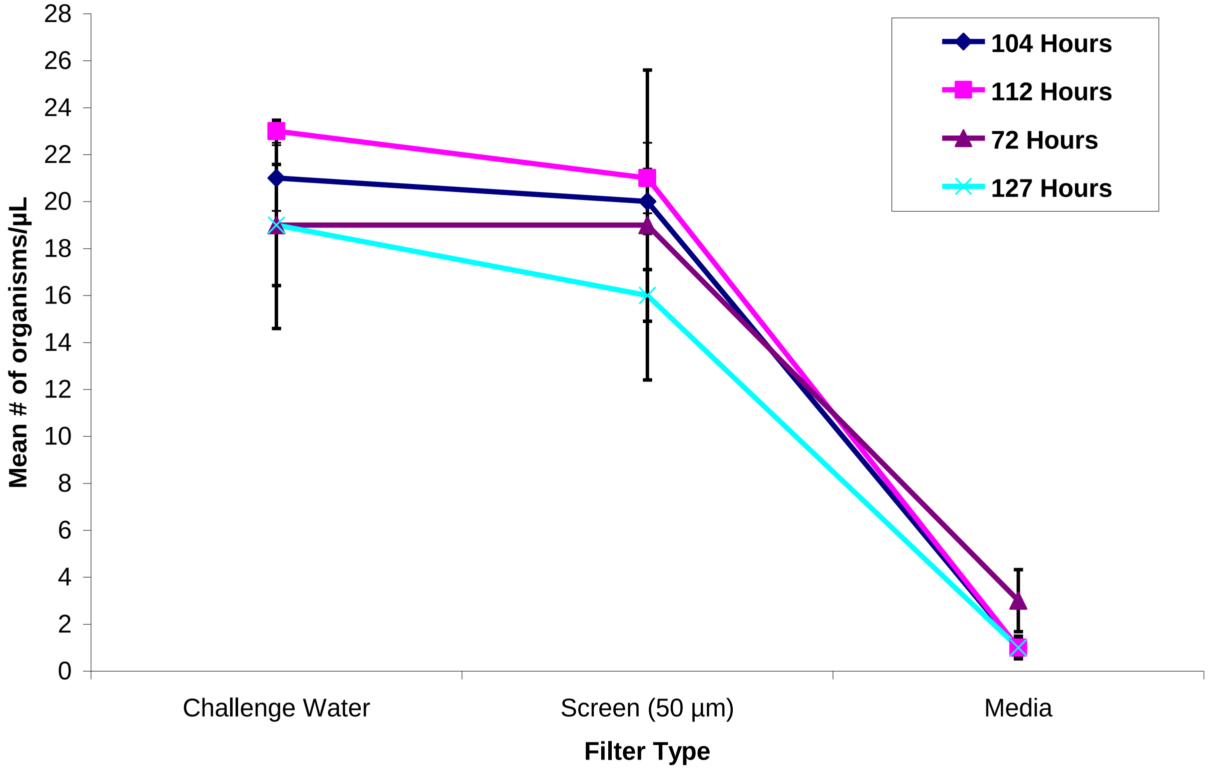


Figure 29. Mean Total Counts of Phytoplankton per (µL) by Filter Type and Duration of System Operation (Hours).

As shown in Figure 30 and Figure 31, the dominant phytoplankton organism after 72 hours of operation was the *Chaetoceros spp.* (A). The challenge water had a mean total count of 10.3 (55 percent) per µL while the screen system had a mean total count of 9.8 (51 percent) for *Chaetoceros spp.* (A). This emphasizes that there was no significant difference between the origins of the two samples and no efficient removal of the *Chaetoceros spp.* (A) by the screen filtration unit. The media filter had complete removal since no *Chaetoceros spp*. (A) were identified in the sample.

Table 3. The Mean Total Counts of the Four Most Dominant Phytoplankton Morphologies for Each System Over Time. (A = *Chaetoceros spp*., D = *Gyrosigma spp.*, E = *Thalassionema spp*., H = *Nitzschia spp*.)

72 Hours		Total Counts/µL		
	A	D	E	H
Challenge Water(mean)	10.3	1.4	1.0	0.0
Challenge Water(std. dev)	2.9	1.2	0.9	0.0
Screen (50µm)(mean)	9.8	1.3	1.2	0.0
Screen (50µm)(std.dev)	4.7	0.5	0.8	0.0
Media (mean)	0.0	0.9	0.4	0.0
Media (std. dev))	0.0	0.3	0.4	0.0
104 Hours		Total Counts/µL		
	A	D	E	H
Challenge Water(mean)	7.5	6.3	2.6	0.0
Challenge Water(std. dev)	1.9	0.9	0.6	0.0
Screen (50µm)(mean)	8.9	4.3	2.6	0.0
Screen (50µm)(std.dev)	1.6	0.8	0.4	0.0
Media (mean)	0.1	0.6	0.2	0.3
Media (std. dev))	0.1	0.2	0.2	0.1
112 Hours		Total Counts/µL		
	A	D	E	H
Challenge Water(mean)	8.4	5.3	3.5	0.0
Challenge Water(std. dev)	0.4	1.1	0.8	0.0
Screen (50µm)(mean)	8.3	5.3	3.3	0.0
Screen (50µm)(std.dev)	0.7	1.3	0.2	0.0
Media (mean)	0.1	0.5	0.2	0.1
Media (std. dev))	0.0	0.2	0.2	0.0
127 Hours		Total Counts/µL		
	A	D	E	H
Challenge Water(mean)	5.8	4.7	0.0	2.7
Challenge Water(std. dev)	1.8	0.7	0.0	1.1
Screen (50µm)(mean)	4.1	4.8	2.0	0.0
Screen (50µm)(std.dev)	1.6	0.0	0.7	0.0
Media (mean)	0.1	0.4	0.0	0.2
Media (std. dev))	0.2	0.1	0.0	0.1

Table 4. Relative Counts (%) of the Four Most Dominant Phytoplankton Morphologies for Each System over Time. (A = *Chaetoceros spp*., D = *Gyrosigma spp.*, E = *Thalassionema spp*., H = *Nitzschia spp*.)

72 Hours		Relative Counts (%)		
	A	D	E	H
Challenge Water	55	7	5	0
Screen	51	7	6	0
Media	0	26	12	13
104 Hours		Relative Counts (%)		
	A	D	E	H
Challenge Water	36	30	12	0
Screen	46	22	13	0
Media	7	41	17	24
112 Hours		Relative Counts (%)		
	A	D	E	H
Challenge Water	37	23	15	0
Screen	39	25	15	0
Media	6	47	21	1
127 Hours		Relative Counts (%)		
	A	D	E	H
Challenge Water	30	25	0	14
Screen	26	30	13	0
Media	13	39	0	19

After *Chaetoceros spp.* (A), the next dominant organism was the *Gyrosigma spp.* (D). The challenge water had a mean total count of 1.4 (seven percent) per µL, and the screen unit had a mean total count of 1.3 (seven percent) per µL. Similar to the *Chaetoceros spp*. (A), there was no significant removal of the *Gyrosigma spp.* (D) by screen filtration system. However, unlike the *Chaetoceros spp*. (A), the *Gyrosigma spp*. (D) was found in the media filter with a mean total count of 0.9 (26 percent) per µL. *Thalassionema spp*. (E) was found in the challenge water and passed through the two filtration units, but very few were counted. There was no distinguishable mean for the total counts of *Nitzschia spp*. (H) for any of the three collected samples. Figure 31 indicates the relative count of *Nitzschia spp.* (H) as 10 percent for the media filter. This appears so because *Nitzschia spp*. (H) was one of the few organism counted during this sample run. The relative counts are lower in the challenge water and screen because the other three phytoplankton groups were counted more often and thus resulted in the relative counts of *Nitzschia spp.* (H) being low or zero.

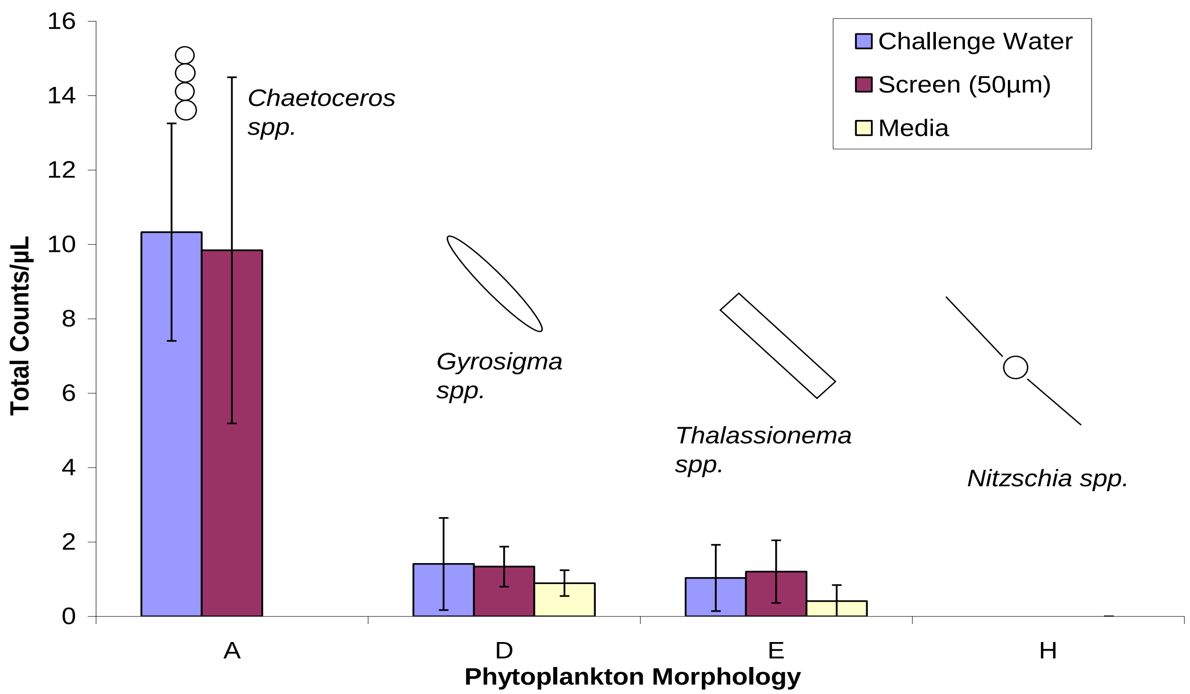


Figure 30. Filter Type Comparison by Total Counts of Dominant Phytoplankton Morphology after 72 Hours of System Operation.

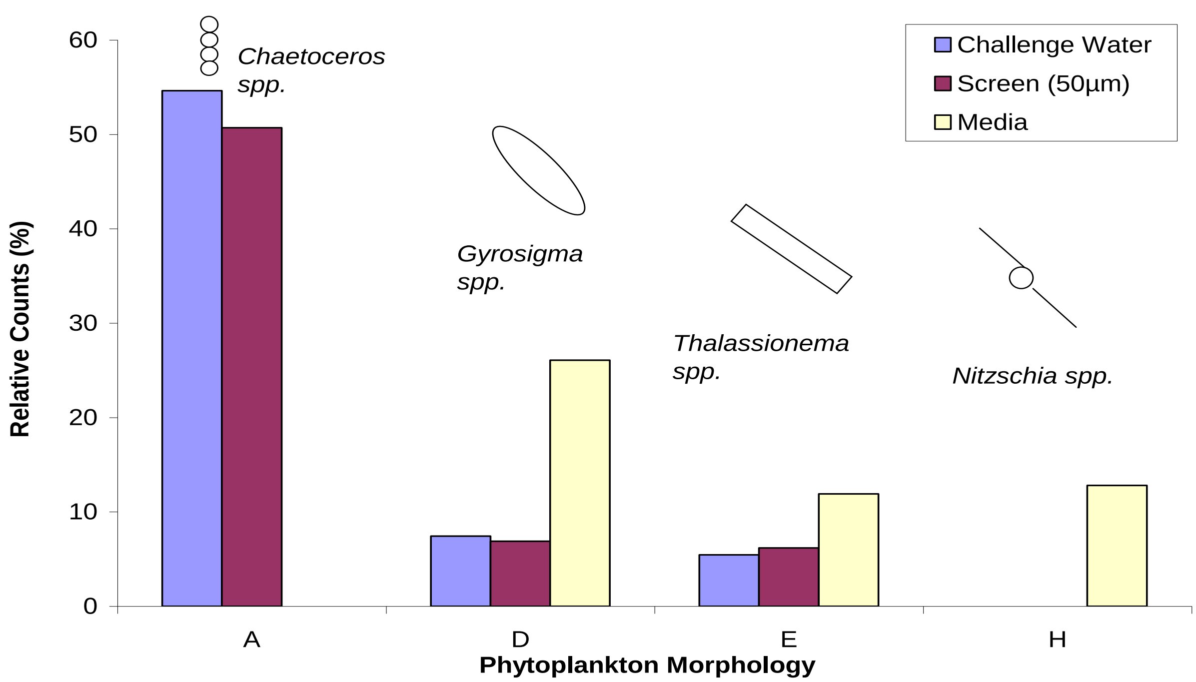


Figure 31. Filter Type Comparison by Relative Counts of Dominant Phytoplankton Morphology after 72 Hours of System Operation.

After 104 hours of system operation, the total number of organisms counted was more dispersed among the four dominant phytoplankton organisms, but *Chaetoceros spp*. (A) still had the greatest mean total counts of the four. Figure 32 and Figure 33 document the unusual scenario that the screen system filtrate had a higher mean total count for *Chaetoceros spp*. (A) than did the challenge water. The challenge water had a mean total count of 7.5 (36 percent) per µL for *Chaetoceros spp.* (A), and the screen unit had a mean total count of 8.9 (46 percent) per µL. It is likely that the screen system broke up the chain-forming phytoplankton causing more of the *Chaetoceros spp*. (A) to be counted in the filtered screen sample than the challenge water sample.

The screen unit was likewise able to capture a greater percentage of incoming *Gyrosigma spp.* (D) after 104 hours of system operation. The challenge water had a mean total count of 6.3 (30 percent) per µL and the screen system had a mean total count of 4.3 (22 percent) per µL. Again, the *Gyrosigma spp.* (D) was counted in the media filter, but in an insignificant amount with a mean total count of only 0.6 per µL. For *Thalassionema spp*. (E), there was no removal by the screen unit, with the mean total count being 2.6 per µL for both the challenge water and screen filtration system (12 percent, 13 percent, respectively). On the other hand, the very low *Thalassionema spp*. (E) counts of the media filter (0.2 per µL) were significantly different from the challenge water.

The long, slender diatom *Nitzschia spp*. (H) was found in extremely low numbers after 104 hours of operation. It was counted only in the media filter sample at a mean total count of 0.3 per µL. As already seen in Table 3 and Table 4, *Nitzschia spp*. (H) is rarer than the other species counted which could account for it not being found in the challenge water. If the organism was positioned with its long axis aligned to the filters, it could have passed through and on to the media filter. The media filter's pore size and orientation are such that the organism would more likely be trapped there than on the other filters.

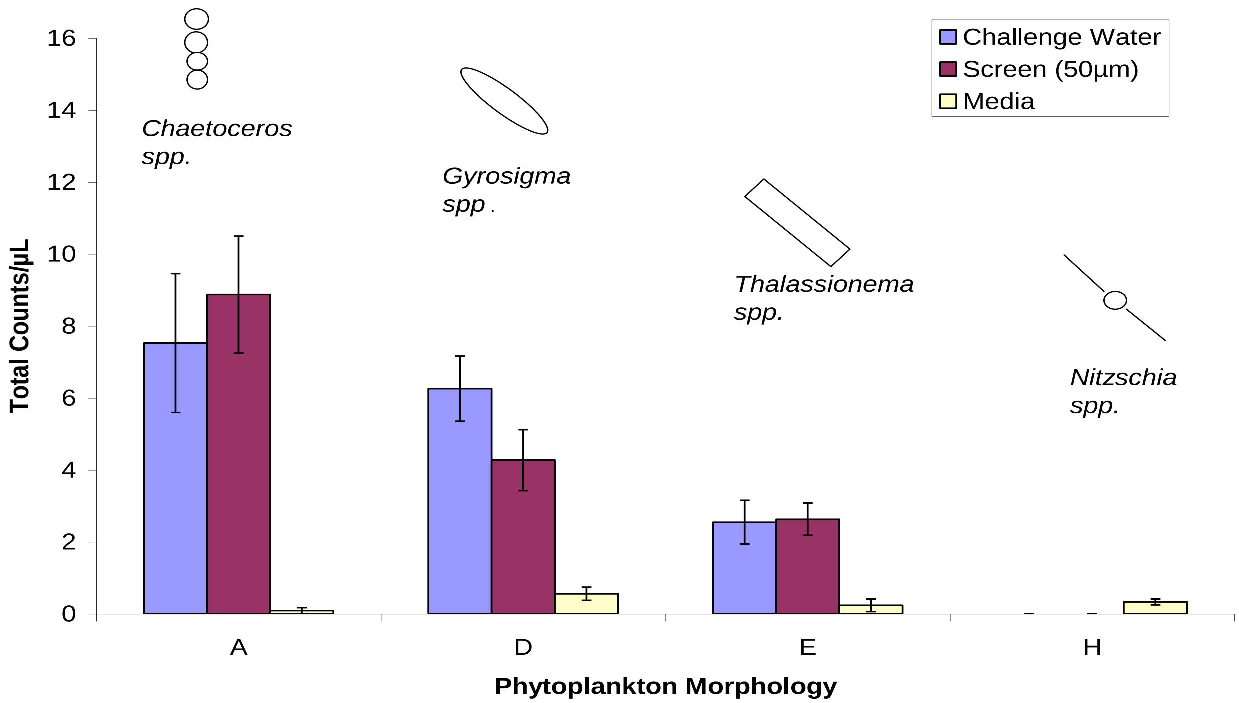


Figure 32. Filter Type Comparison by Total Counts of Dominant Phytoplankton Morphology after 104 Hours of System Operation.

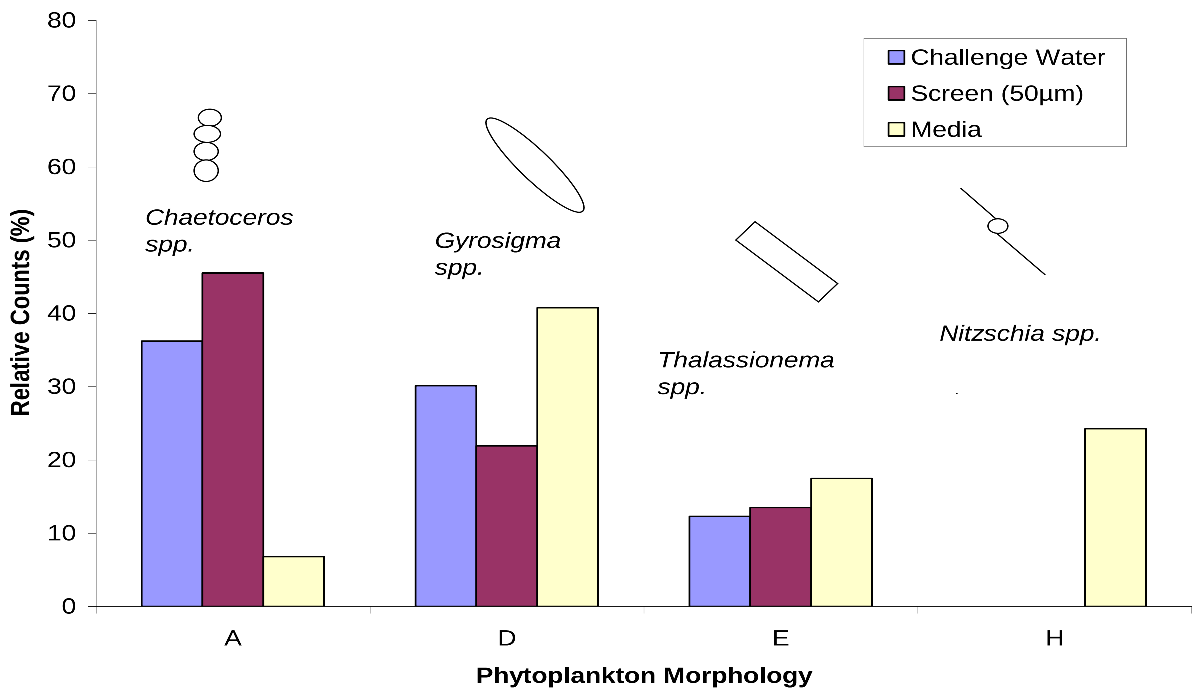


Figure 33. Filter Type Comparison by Relative Counts of Dominant Phytoplankton Morphology after 104 Hours of System Operation.

Examination of the mean total counts for the dominant phytoplankton after 112 hours of system operation, as shown in Figure 34 and Figure 35, reveals there was no removal of organisms by the screen filtration unit. The challenge water and screen unit had almost identical mean total concentrations for each of the phytoplankton organisms. Again, the media filter removed the majority of the four dominant counted species.

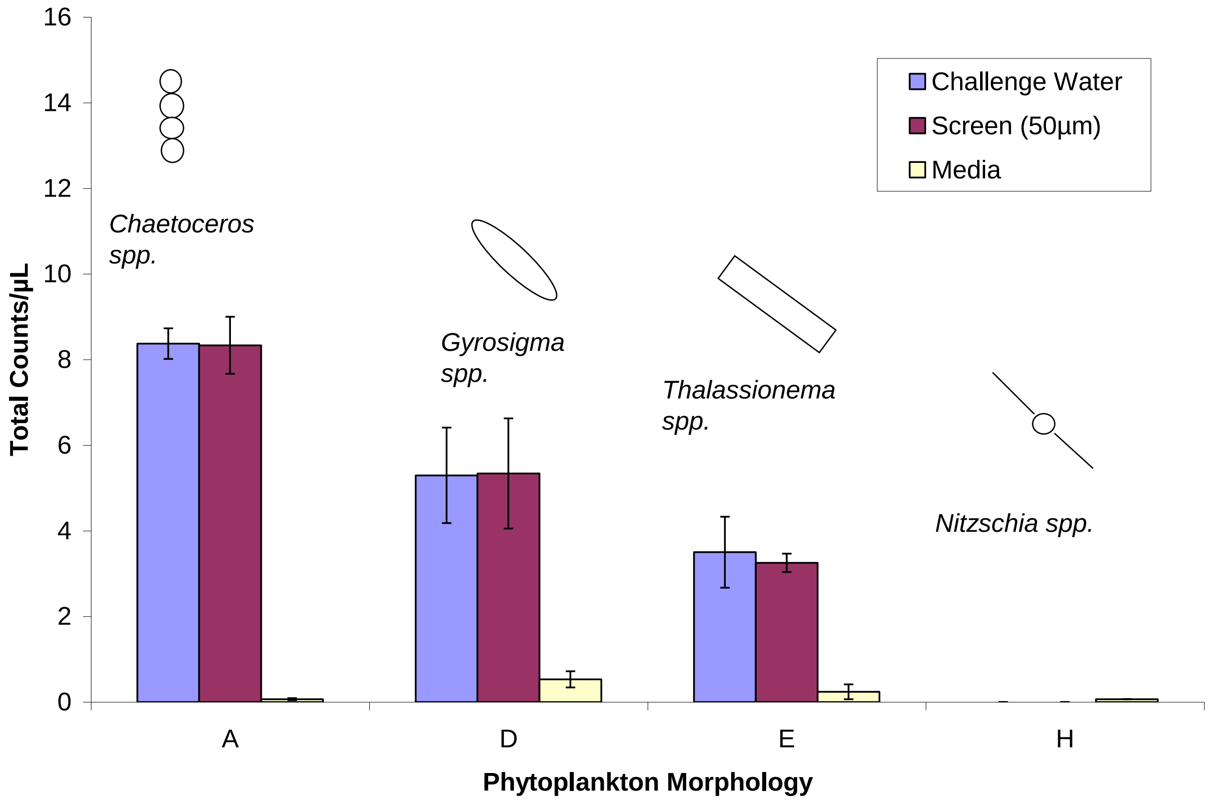


Figure 34. Filter Type Comparison by Total Counts of Dominant Phytoplankton Morphology after 112 Hours of System Operation.

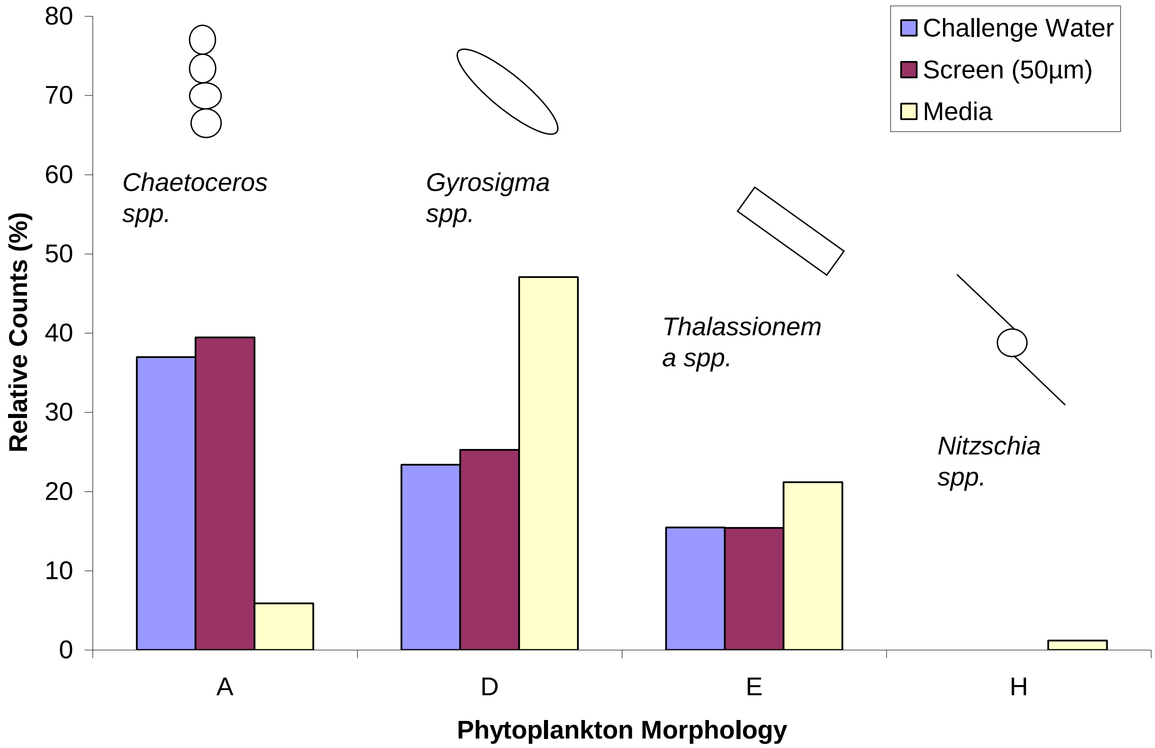


Figure 35. Filter Type Comparison by Relative Counts of Dominant Phytoplankton Morphology after 112 Hours of System Operation.

On the final day of system operation, the results, shown in Figure 36 and Figure 37, were consistent with the prior sampling periods indicating that there was no significant difference between the challenge water and screen system in terms of mean total counts of organisms, but there was a significant difference in relation to the multi-media filter. *Chaetoceros spp*. (A) was again the dominant phytoplankton of the four organisms. The challenge water had a mean total count of 5.8 (30 percent) per µL for *Chaetoceros spp*. (A), and the screen unit had mean total count of 4.1 (26 percent). There was no difference in mean total counts for *Gyrosigma spp.* (D) as well, with the challenge water having a mean total count of 4.7 (25 percent) per µL, and the screen unit having a total mean count 4.8 (30 percent) per µL. The media filter removed a significant portion of both *Chaetoceros spp*. (A) and *Gyrosigma spp.* (D). The other two dominant phytoplankton organisms were not counted in significant enough amounts to make comparisons.

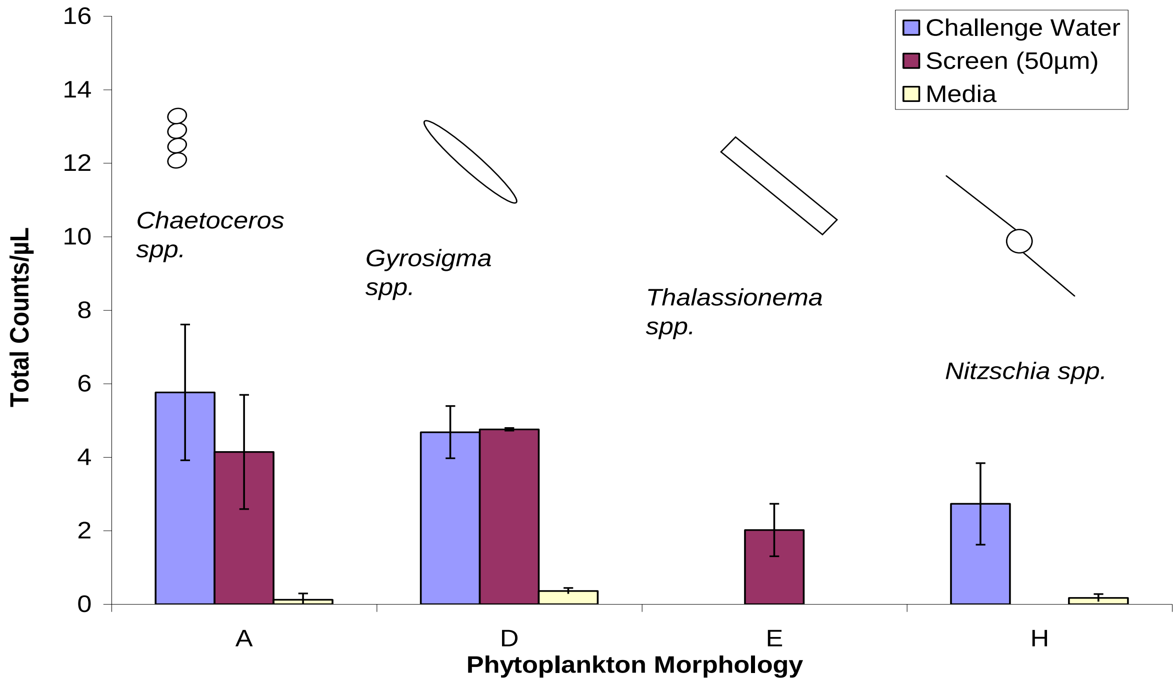


Figure 36. Filter Type Comparison by Total Counts of Dominant Phytoplankton Morphology after 127 Hours of System Operation.

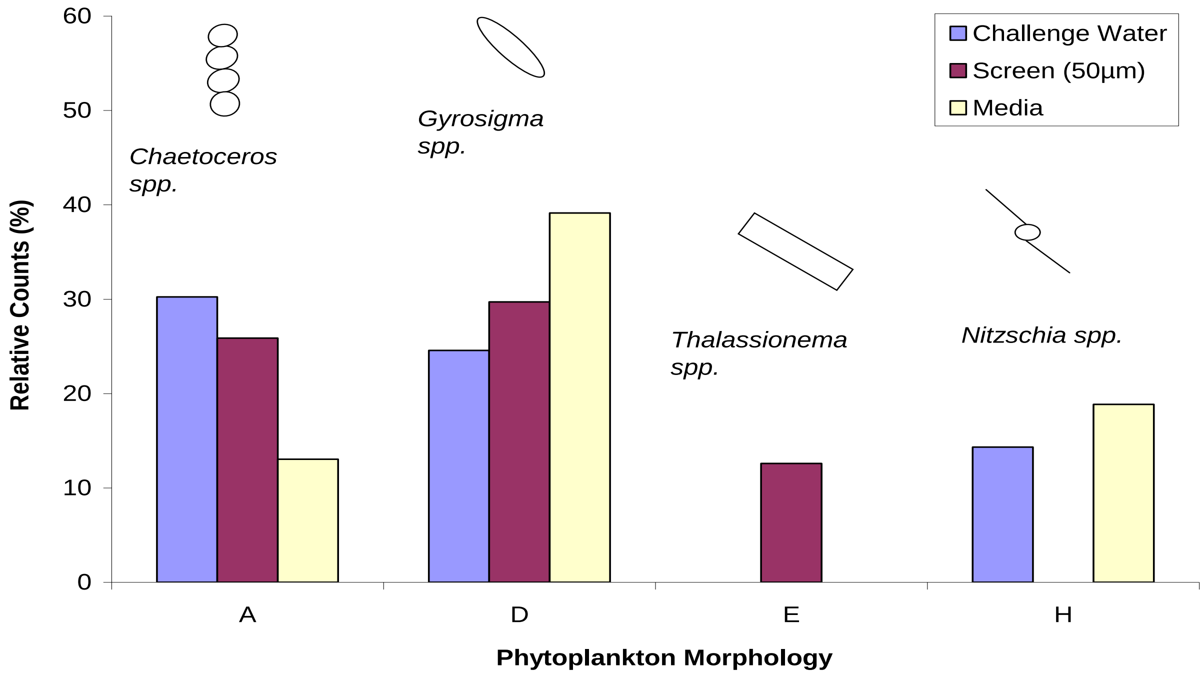


Figure 37. Filter Type Comparison by Relative Counts of Dominant Phytoplankton Morphology after 127 Hours of System Operation.

Overall, in discussing mean total counts of defined organisms for the four sampling periods, there was an inefficient removal of organisms by the screen filtration system and no significant difference between the challenge water and screen unit. In comparison, there was efficient removal of defined organisms by the media filter, and a significant difference in relation of the multi-media filter to the screen unit and challenge water.

Since *Chaetoceros spp*. (A) were so dominant compared to all other phytoplankton organisms in the test duration of the screen filtration system, further analysis was conducted as follows. The mean chain length and mean counts per µL are found in Table 5 for each of the sampling periods during system operation. As *Chaetoceros spp*. (A) moves through the screen filtration unit, the bodies are broken up which causes the lengths to decrease and the total counts to increase. For each of the sampling periods, mean chain length and mean counts per µL are compared by filter type in Figure 38 and Figure 39. These figures also show, as the previous data did, that there was no significant removal of *Chaetoceros spp*. (A) from the challenge water by the screen unit, but there is significant removal by the media filter. Because so few chain formers were counted after the media filter, the following analysis does not include the multi-media filter.

Table 5. The Mean Total Lengths (µm) and Mean Total Counts per µL for Chain Formers (A) for the Screen to Media Filtration Train.

		72 Hours	
	Challenge water	**Screen**	**Media**
mean length (µm)	38.3	42.7	20.0
Std. Dev.	22.4	25.0	2.8
mean counts/µL	10.3	9.8	0.0
Std. Dev.	2.9	4.7	0.0
		104 Hours	
	Challenge water	**Screen**	**Media**
mean length (µm)	41.0	36.2	37.8
Std. Dev.	21.8	18.2	19.6
mean counts/µL	7.50	8.90	0.10
Std. Dev.	1.90	1.60	0.10
		112 Hours	
	Challenge water	**Screen**	**Media**
mean length (µm)	39.1	42.0	25.0
Std. Dev.	18.3	24.0	6.9
mean counts/µL	8.4	8.30	0.10
Std. Dev.	0.4	0.70	0.00
		127 Hours	
	Challenge water	**Screen**	**Media**
mean length (µM)	80.0	27.9	31.1
Std. Dev.	76.6	15.1	10.9
mean counts/µL	5.8	4.1	0.1
Std. Dev.	1.8	1.6	0.2

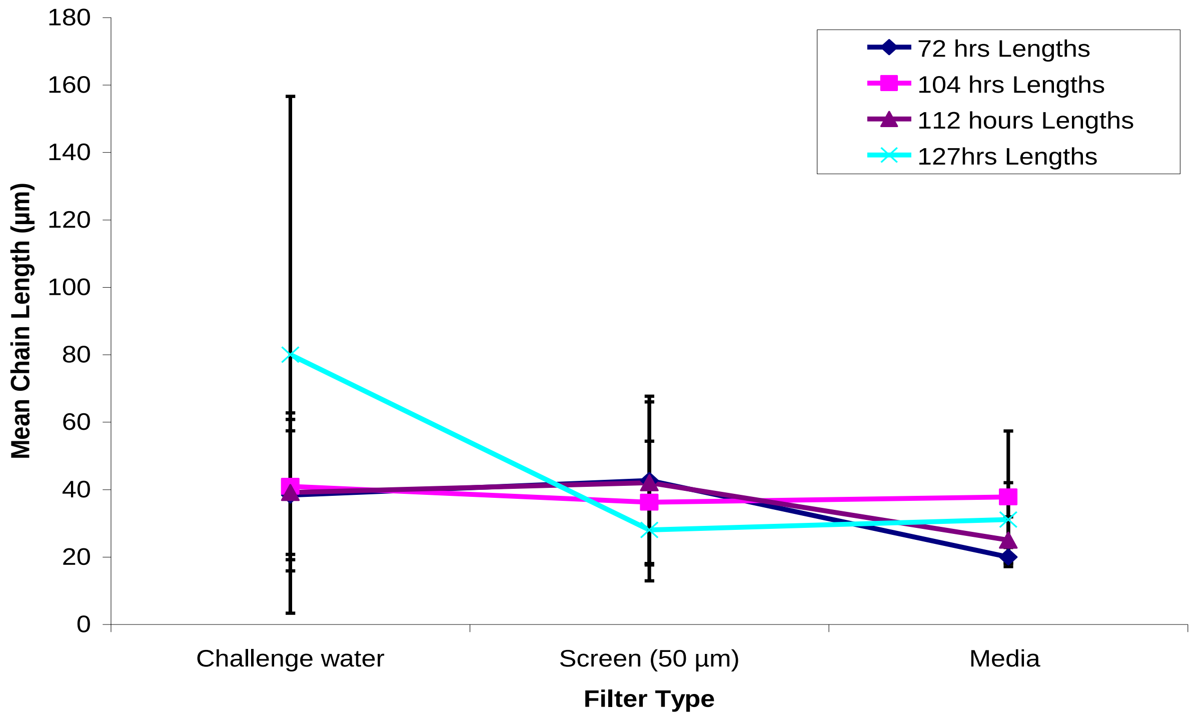


Figure 38. Filter Type Comparison of Length of Chain-Forming Phytoplankton after All Hours of System Operation.

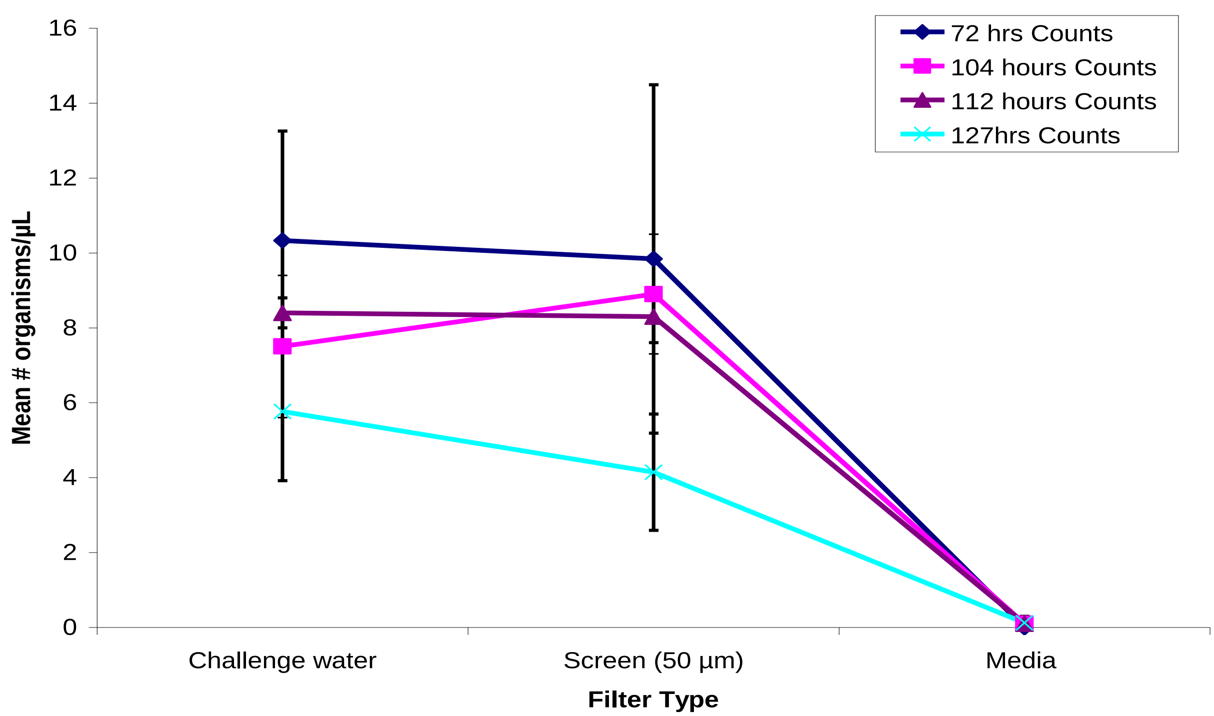


Figure 39. Filter Type Comparison of Mean Total Counts of Chain-Forming Phytoplankton after All Hours of System Operation.

After 72 hours of system operation, the mean length of *Chaetoceros spp.* (A) for the challenge water was 38.3 µm with a standard deviation of 22.4. For the screen system, the mean length was 42.7 with a standard deviation of 25. Figure 40 shows there was a slight increase in length from the challenge water to the screen unit, but the large standard deviations imply that the increase in length was not significant. There is a greater range of size in the screen sample compared to the challenge water sample. This variation implies that many size ranges have filtered through the screen system or have been broken up during the process. The mean total counts are about the same, so there was no removal of *Chaetoceros spp*. (A) from the challenge water to the screen filtration system.

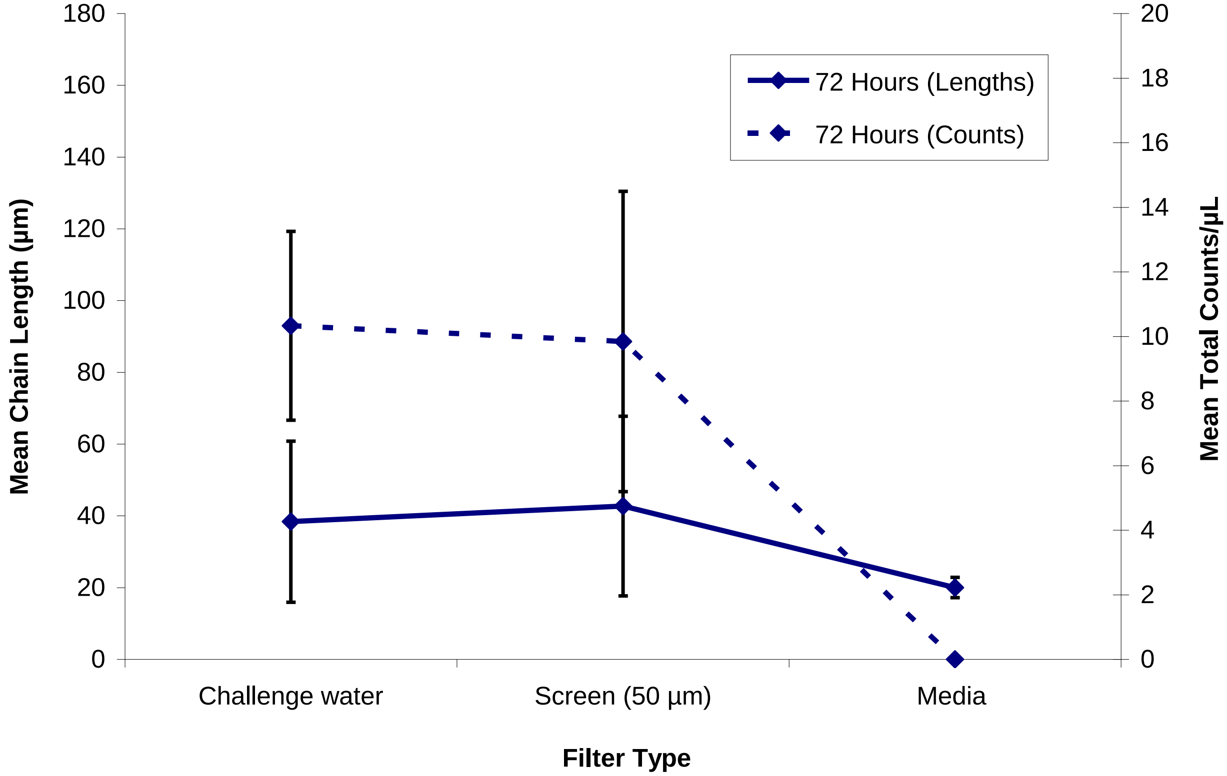


Figure 40. Filter Type Comparison of Mean Total Counts per µL to Mean Chain Lengths (µm) of Chain-Forming Phytoplankton after 72 Hours of System Operation.

From Figure 41, it was evident there was slight increase in the mean total counts and a slight decrease in mean lengths from the challenge water to the screen unit. The challenge water had a mean length of 41 µm with a standard deviation of 21.8 for *Chaetoceros spp*. (A). The screen system had a mean chain length of 36.2 µm with a standard deviation of 18.2. The mean total counts increased from 7.50 with a standard deviation of 1.9 to a mean total count of 8.90 with a standard deviation of 1.6 for the screen unit. The total counts increased as the lengths decreased from the challenge water to the screen system. The standard deviation also decreased from the challenge water to the screen unit. This is indicative of the technology breaking up the chain forming organisms.

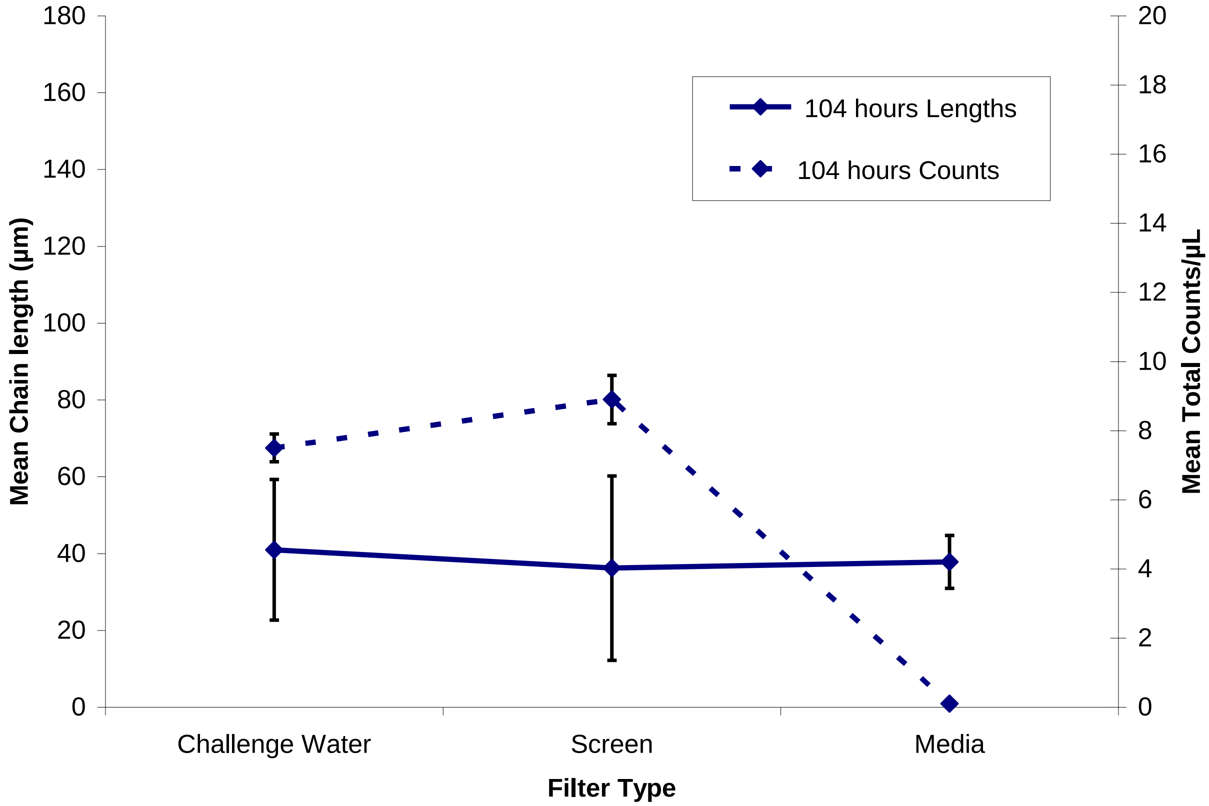


Figure 41. Filter Type Comparison of Mean Total Counts per µL to Mean Chain Lengths (µm) of Chain-Forming Phytoplankton after 104 Hours of System Operation.

The results after 112 hours of system operation (Figure 42) are similar to those found in the first sample collection. The challenge water had a mean length of 39.1 µm with a standard deviation of 18.3, and the screen unit had a mean length of 42 µm with a standard deviation of 24. There was an increase in length, but also an increase in standard deviation. The counts are almost the same, so there was no efficient removal and no significant difference between the challenge water and screen filtration system.

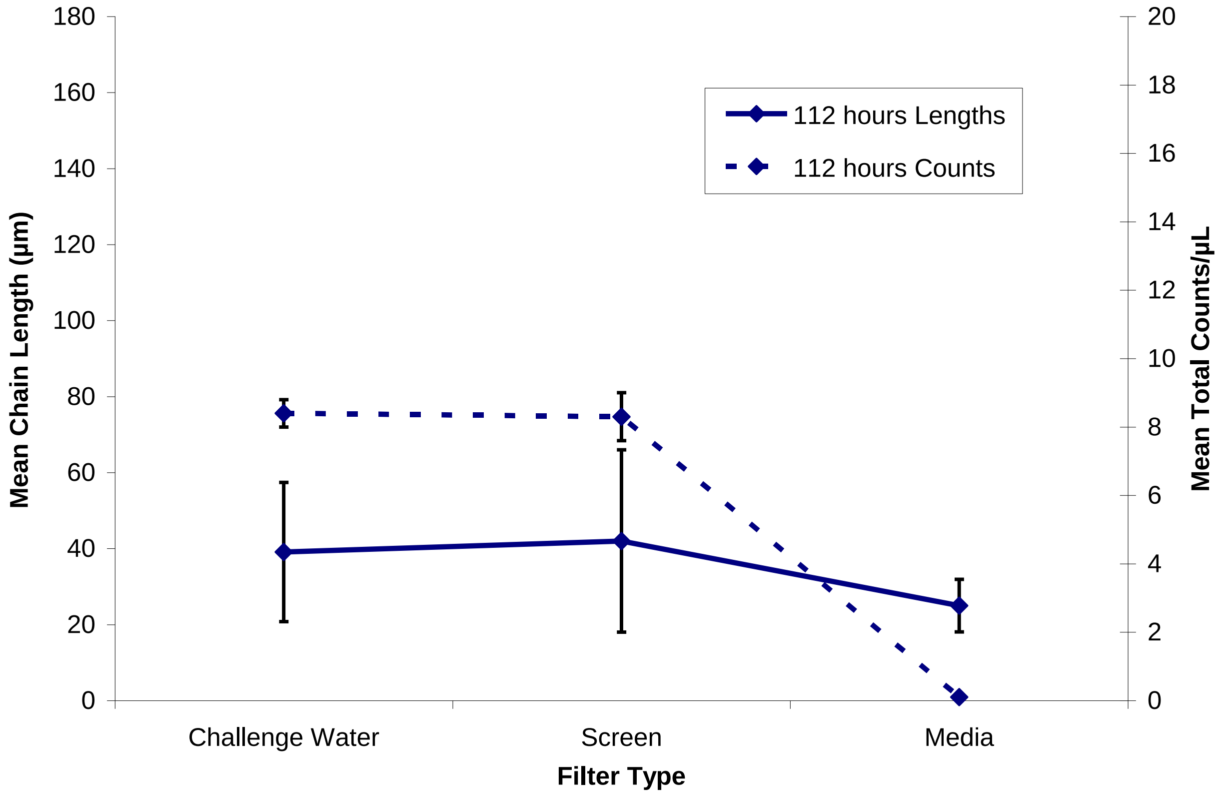


Figure 42. Filter Type Comparison of Mean Total Counts per µL to Mean Chain Lengths (µm) of Chain-Forming Phytoplankton after 112 Hours of System Operation.

Figure 43 shows the final sample collection of system operation was consistent with the prior collections. There was a decrease in the *Chaetoceros spp*. (A) lengths with the challenge water having a mean length of 80 µm with a standard deviation of 76.6, and the screen system having a mean length of 27.9 µm with a standard deviation of 15.1. Again, the standard deviation for both the challenge water and screen unit were so varied that the slight decrease in length is of no significance. There was also a very slight decrease in the mean total counts per µL between the challenge water and screen unit, which once again indicates no significant removal of *Chaetoceros spp*. (A).

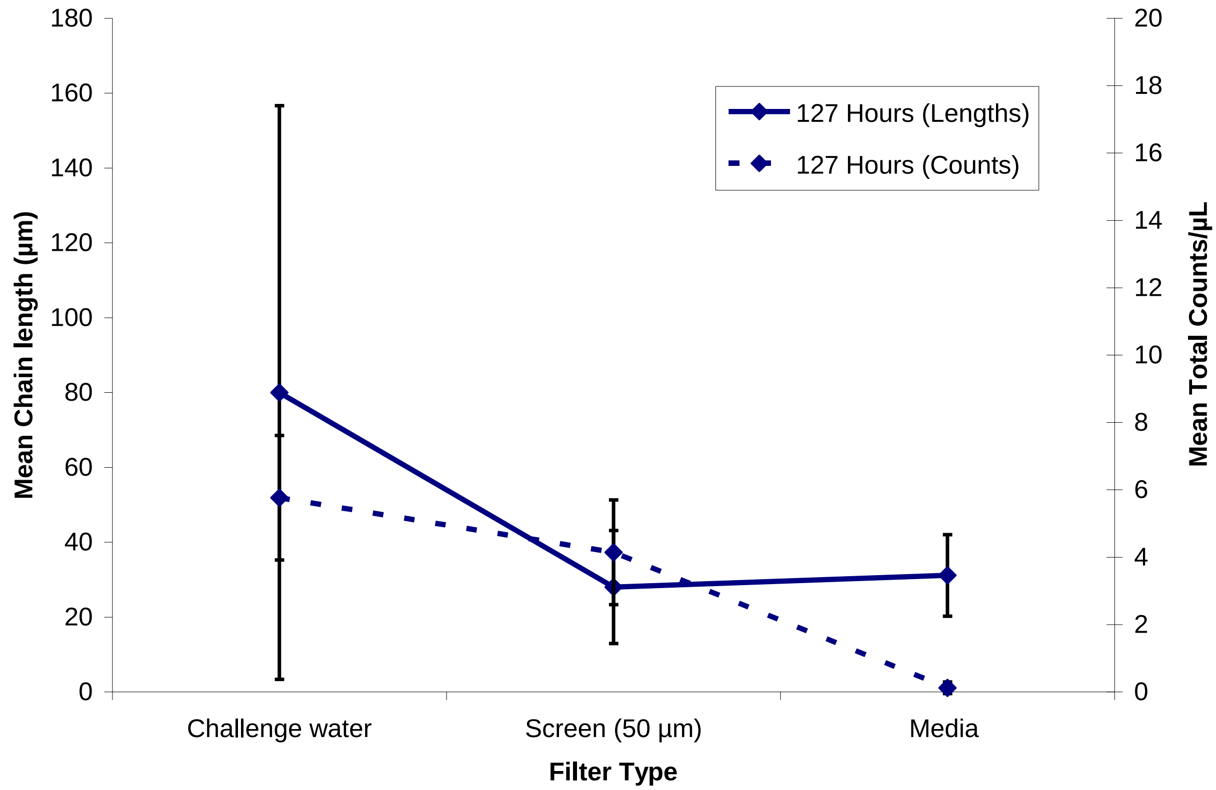


Figure 43. Filter Type Comparison of Mean Total Counts per µL to Mean Chain Lengths (µm) of Chain-Forming Phytoplankton after 127 Hours of System Operation.

The consistency of the four collection periods emphasizes no difference in mean total counts between the challenge water and screen filter. With respect to the length of chain formers, there was no consistent increase or decrease in lengths in comparison to mean total counts because of the variation of sizes measured.

For the testing of the disc filtration unit as a pre-cursor to the media filter, the total counts of biological organisms larger than five microns recorded were nearly identical to that of the screen unit. Mean total counts of organisms at 8, 32, 64, and 80 hours of system operation are provided in Table 6. Evaluation of these results reveals that there was no significant difference in mean total counts between the challenge water and disc system, but there was a significant difference in relation to the media filter. This was determined by comparing the mean total counts of the challenge water to those of the disc unit as shown in Figure 44. This also revealed no efficient removal of organisms by the disc unit, but significant removal of the defined organisms by the media filter similar to the results of the screen system test.

Table 6. Mean Total Counts of Organisms after 8 hours, 32 hours, 64 hours and 80 hours of System Operation.

	Challenge Water	Disc	Media Filter
8 Hrs - Mean /µL	19.5	21.2	1.5
8 Hrs - Standard Deviation	3.8	2.2	0.9
32 Hrs - Mean /µL	20.5	17.3	1.6
32 Hrs - Standard Deviation	5.5	3.3	0.3
64 Hrs - Mean/µL	19.2	17.1	1.8
64 Hrs - Standard Deviation	1.5	2.1	0.1
80 Hrs - Mean/µL	24.1	20.9	1.6
80 Hrs - Standard Deviation	1.2	2.2	0.4

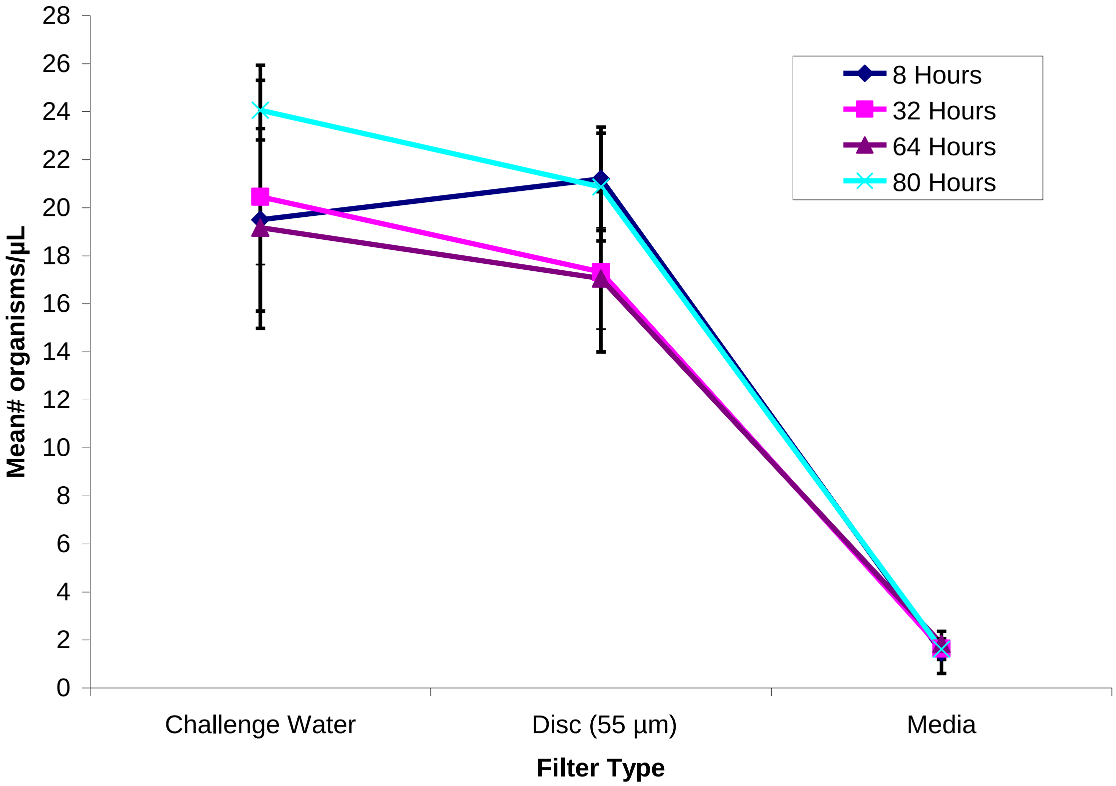


Figure 44. Mean Total Counts of Phytoplankton per (µL) by Filter Type and Duration of System Operation (Hours).

In the first eight hours of system operation there was an increase in mean total counts of organisms from the challenge water to the disc unit with the challenge water having a mean total count of 19.5 organisms per µL and the disc having a mean total count of 21.2 organisms per µL. In this case, there were more counted organisms in the disc unit than challenge water indicating, in conjunction with the large standard deviation, that there was no difference between the two sample collections and no removal of organisms by the disc unit. These results are consistent with the subsequent sample collections. After 32 hours of system operation the challenge water had a mean total count of 20.5 per µL while the disc unit had a mean total count of 17.3 per µL. There was a slight, but not significant, decrease in total counts from the challenge water to disc unit. This was also true after 64 hours of system operation with the challenge water having a mean total count of 19.2 per µL and the disc system having 17.1 per µL as a mean total count of organisms. Similar to results during the screen tests, the media filter removed the majority of organisms with the greatest mean total count being 1.8 organisms per µL after 64 hours of system operation.

As analyzed with the screen system, the total counts of the four dominant phytoplankton organisms are show in Table 7, and the percentage of relative counts for each is given in Table 8. In the explanation below, the percent of relative counts is given in parentheses for each mean total count of the dominant phytoplankton.

Table 7. The Mean Total Counts of the Four Most Dominant Phytoplankton Morphologies for Each System over Time. (A = *Chaetoceros spp*., D = *Gyrosigma spp.*, E = *Thalassionema spp*., H = *Nitzschia spp*.)

8 Hours		Total Counts/µL		
	A	D	E	H
Challenge Water(mean)	6.0	5.4	4.2	0.0
Challenge Water(std. dev)	1.8	2.3	1.2	0.0
Disc (55 µm)(mean)	5.0	6.7	5.2	0.0
Disc (55 µm)(std. dev)	0.3	1.2	1.0	0.0
Media (mean)	0.1	0.5	0.4	0.2
Media (std. dev)	0.1	0.3	0.2	0.2
32 Hours		Total Counts/µL		
	A	D	E	H
Challenge Water(mean)	5.8	6.3	3.9	0.0
Challenge Water(std. dev)	2.3	2.0	1.9	0.0
Disc (55 µm)(mean)	5.9	5.5	2.7	0.0
Disc (55 µm)(std. dev)	1.6	0.8	0.4	0.0
Media (mean)	0.3	0.7	0.2	0.0
Media (std. dev)	0.3	0.3	0.0	0.0
64 Hours		Total Counts/µL		
	A	D	E	H
Challenge Water(mean)	4.9	6.2	3.7	0.0
Challenge Water(std. dev)	0.2	1.3	0.4	0.0
Disc (55 µm)(mean)	5.7	5.1	3.2	0.0
Disc (55 µm)(std. dev)	1.2	0.5	0.1	0.0
Media (mean)	0.2	0.7	0.5	0.0
Media (std. dev)	0.2	0.1	0.2	0.0
80 Hours		Total Counts/µL		
	A	D	E	H
Challenge Water(mean)	6.5	7.0	5.1	0.0
Challenge Water(std. dev)	0.6	1.3	0.3	0.0
Disc (55 µm)(mean)	7.4	6.2	3.1	0.0
Disc (55 µm)(std. dev)	1.5	0.7	0.7	0.0
Media (mean)	0.2	0.4	3.1	0.0
Media (std. dev)	0.0	0.2	0.7	0.0

Table 8. Relative Counts (%) of the Four Most Dominant Phytoplankton Morphologies for Each System over Time. (A = *Chaetoceros spp*., D = *Gyrosigma spp.*, E = *Thalassionema spp*., H = *Nitzschia spp*.)

8 Hours		Relative Counts (%)		
	A	D	E	H
Challenge Water	31	27	21	0
Disc (55 µm)	24	32	24	0
Media	4	37	24	16
32 Hours		Relative Counts (%)		
	A	D	E	H
Challenge Water	28	31	19	0
Disc (55 µm)	34	32	16	0
Media	17	45	13	0
64 Hours		Relative Counts (%)		
	A	D	E	H
Challenge Water	26	32	19	0
Disc (55 µm)	33	30	19	0
Media	9	36	25	1
80 Hours		Relative Counts (%)		
	A	D	E	H
Challenge Water	27	29	21	0
Disc (55 µm)	35	30	15	0
Media	15	27	53	7

After eight hours of operation of the disc and media filter system, the dominant phytoplankton organisms were *Chaetoceros spp*. (A), *Gyrosigma spp.* (D), and *Thalassionema spp*. (E) (Figure 45 and Figure 46). The similar total counts as well as relative percentages for these three phytoplankton morphologies within the challenge water and disc filter filtrate indicate that there was no significant difference between the two samples. This emphasizes the lack removal by the disc filtration unit after eight hours of system operation. On the other hand, the media filter removed the majority of the three dominant phytoplankton. There were a few counts of *Nitzschia spp.* (H) in the media filter's filtrate but none in the other samples, which makes it difficult to draw conclusions.

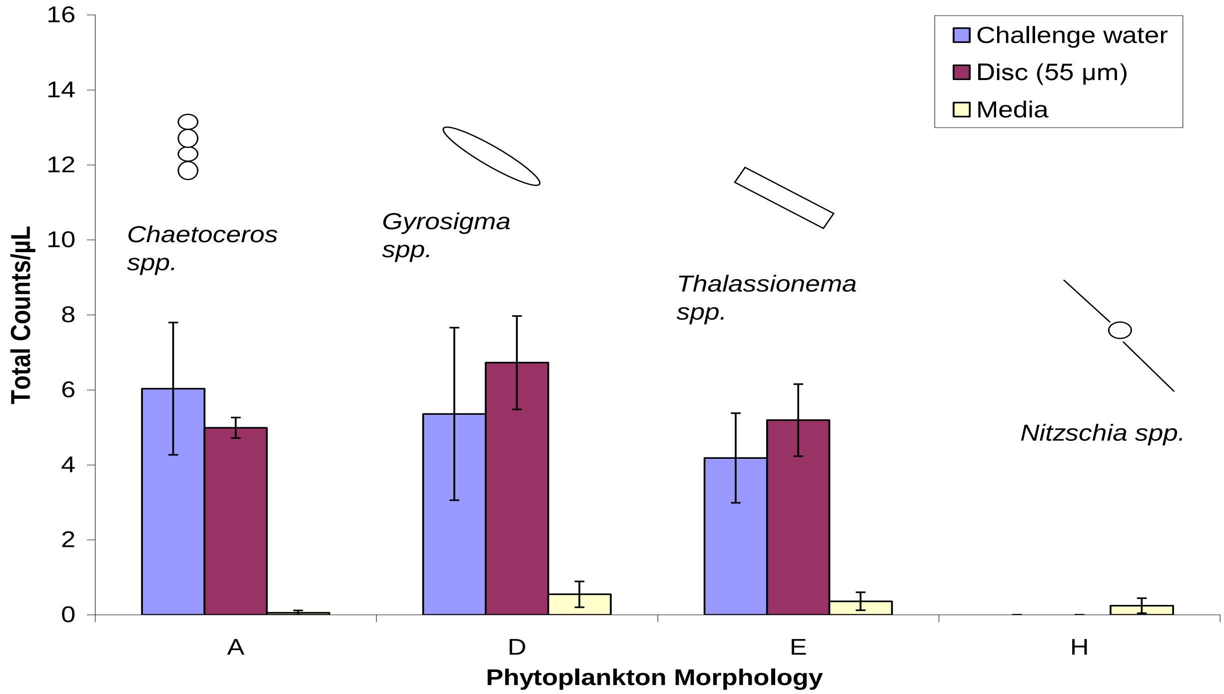


Figure 45. Filter Type Comparison by Total Counts of Dominant Phytoplankton Morphology after Eight Hours of System Operation.

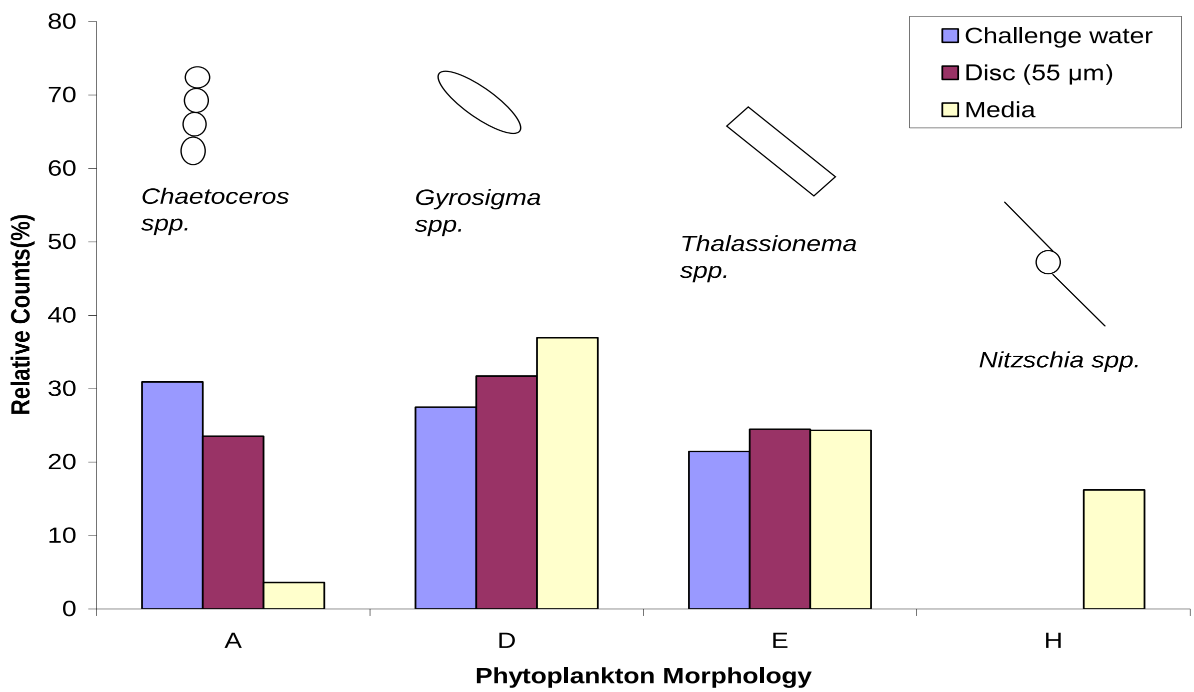


Figure 46. Filter Type Comparison by Relative Counts of Dominant Phytoplankton Morphology after Eight Hours of System Operation.

The results after 32 hours of operation (Figure 47 and Figure 48) were similar to the results after eight hours of system operation. *Chaetoceros spp*. (A) and *Gyrosigma spp.* (D) were the two most dominant organisms. The challenge water had a mean total count of 5.8 (28 percent) per µL for *Chaetoceros spp*. (A) and a mean total of 6.3 (31 percent) for Gyrosigma *spp.* (D). The disc unit had a mean total count of 5.9 (34 percent) per µL for *Chaetoceros spp*. (A) and a mean total count of 5.5 for *Gyrosigma spp.* (D). These two dominant organisms had nearly identical mean total counts for both the challenge water and disc unit indicating no significant removal of organisms by the disc system. The media filter effectively removed the majority of these two organisms with the mean total counts for *Chaetoceros spp*. (A) of 0.3 (17 percent) per µL and *Gyrosigma spp.* (D) of 0.7 (45 percent) per µL. The disc unit was able to remove some of the *Thalassionema spp*. (E) with the mean total count of 3.9 (19 percent) per µL for the challenge water and a mean total count of 2.7 (16 percent) for the disc unit. The media filter showed significantly more removal of the *Thalassionema spp*. (E) organisms but not complete removal. *Nitzschia spp.* (H) was not found at all after 32 hours of operation.

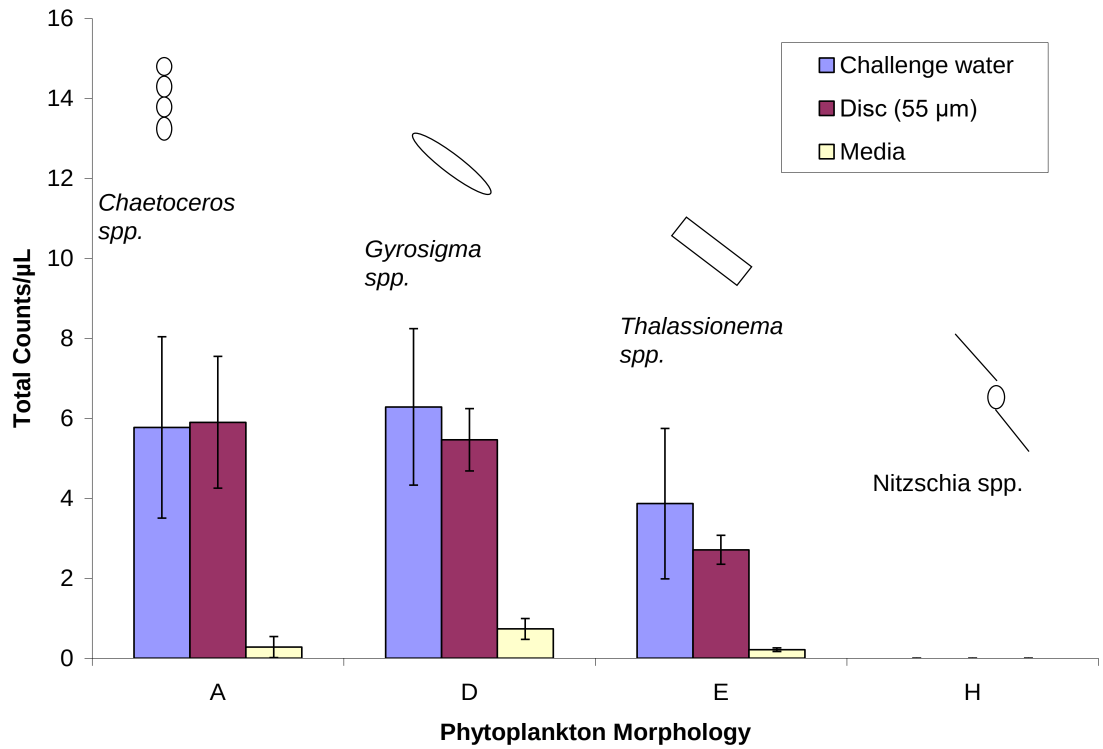


Figure 47. Filter Type Comparison by Total Counts of Dominant Phytoplankton Morphology after 32 Hours of System Operation.

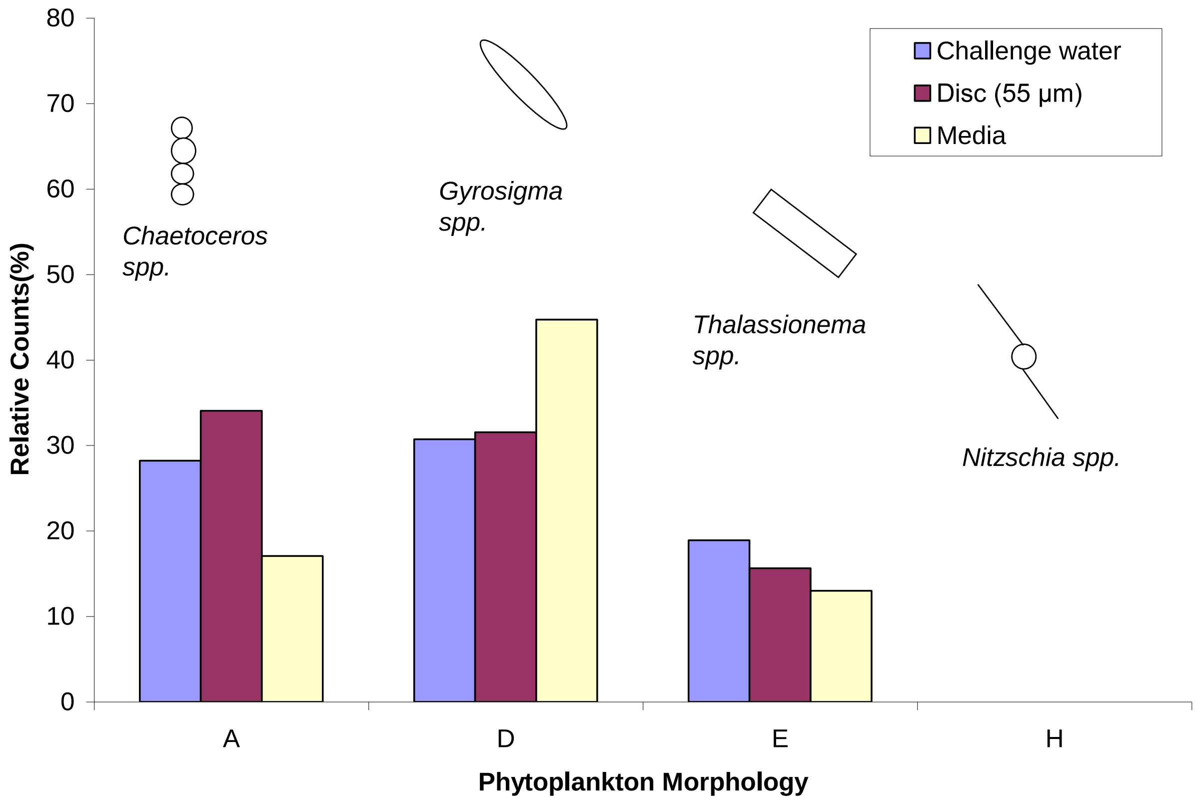


Figure 48. Filter Type Comparison by Relative Counts of Dominant Phytoplankton Morphology after 32 Hours of System Operation.

After 64 hours of system operation there was a higher mean total count of *Chaetoceros spp*. (A) in the disc unit than in the challenge water (Figure 49 and Figure 50). The challenge water had a mean total count of 4.9 (26 percent) per µL of *Chaetoceros spp*. (A), and the disc unit had a mean total count of 5.7 (33 percent) per µL. Some removal occurred with *Gyrosigma spp.* (D) as the challenge water had a mean total count of 6.2 (32 percent) per µL and the disc had a mean total count of 5.1 (30 percent) per µL. There was little difference or removals of Thalassionema spp. (E) by the disc unit since both mean total counts were almost identical. In comparison, the media filter was able to remove the majority of the organisms based on the significant difference in the media filter's mean total counts compared to those of the disc unit and challenge water.

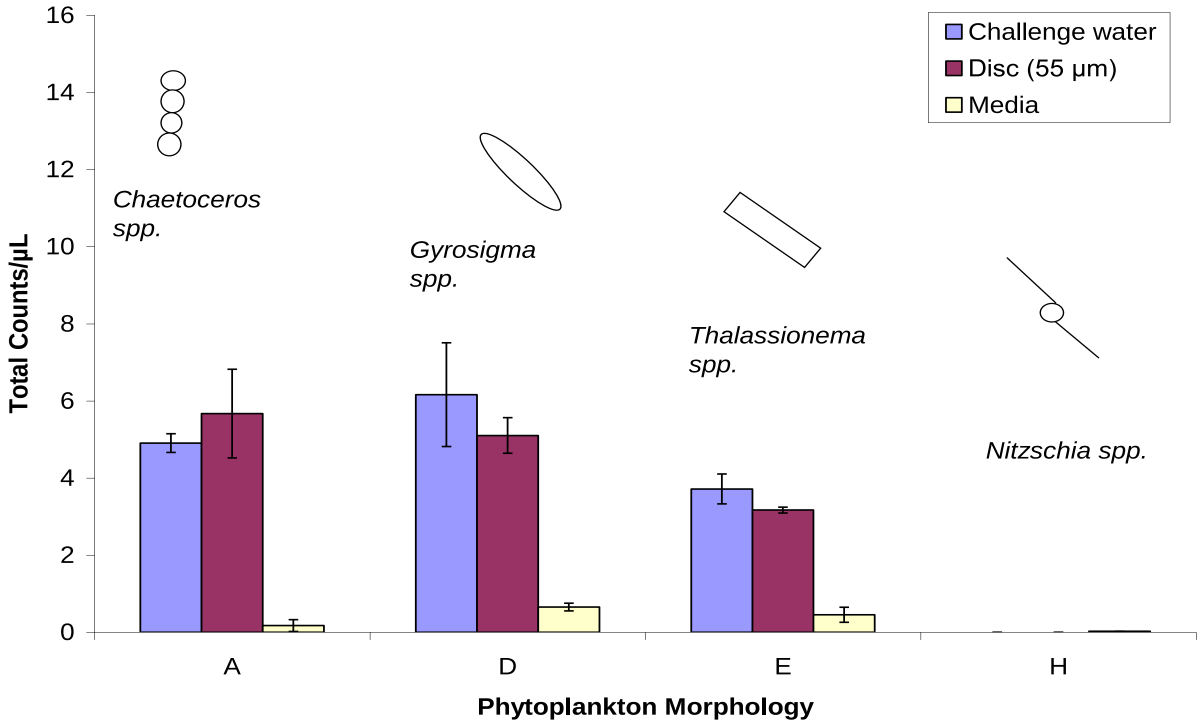


Figure 49. Type Comparison by Total Counts of Dominant Phytoplankton Morphology after 64 Hours of System Operation.

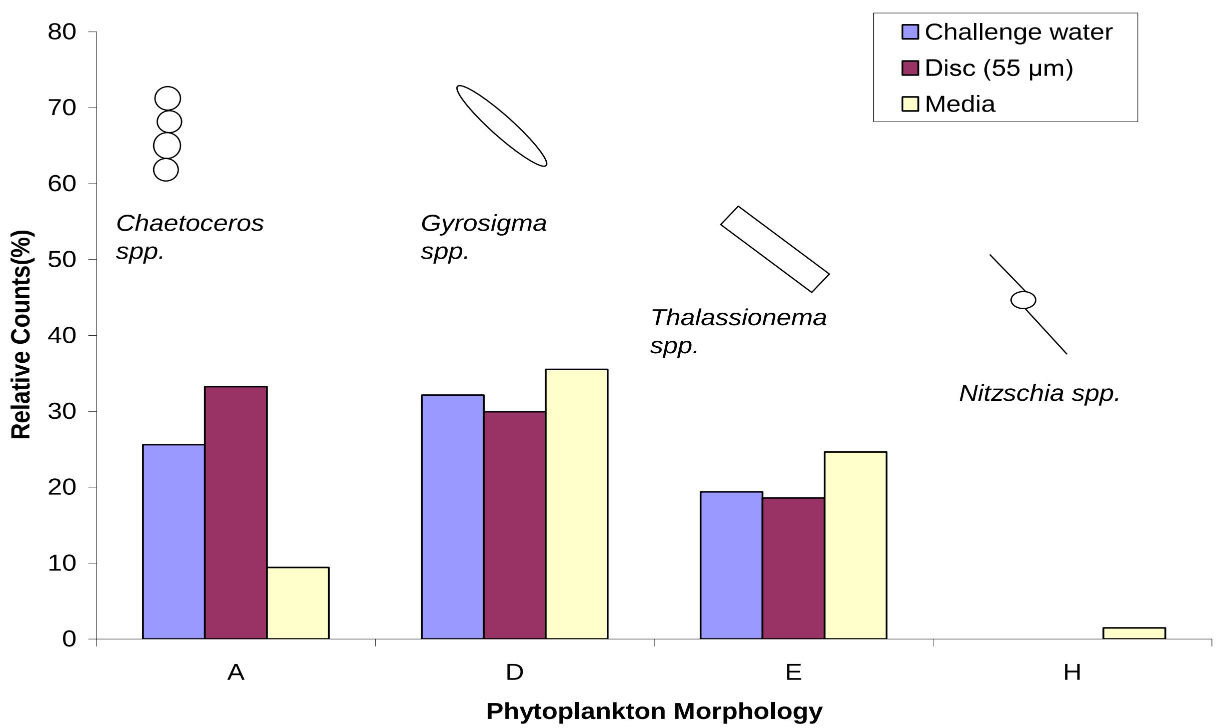


Figure 50. Filter Type Comparison by Relative Counts of Dominant Phytoplankton Morphology after 64 Hours of System Operation.

Again, similar to the previous sample collection, there was a comparable quantity of *Chaetoceros spp*. (A) in the disc system sample collection and the challenge water sample after 80 hours of system operation (Figure 51 and Figure 52). The challenge water had a mean total count of 6.5 (27 percent) per µL of *Chaetoceros spp*. (A), and the disc system had a mean total count of 7.4 (35 percent) per µL. There was only a slight difference in mean total counts of *Gyrosigma spp.* (D) between the challenge water and disc unit, with the challenge water having a mean total count of 7.0 (29 percent) per µL and the disc unit having a mean total count of 6.2 (30 percent). The media filter was able to remove the majority of the *Chaetoceros spp*. (A) and *Gyrosigma spp.* (D). For *Thalassionema spp*. (E), the challenge water had a mean total count of 5.1 (21 percent) per µL and the disc and media filter had mean total counts of 3.1 (15 percent for disc 53 percent for media) per µL. This lack of removal by the media filter from the disc filter's filtrate may be due to the orientation of the elongated organism as it is reaches the media filtration unit.

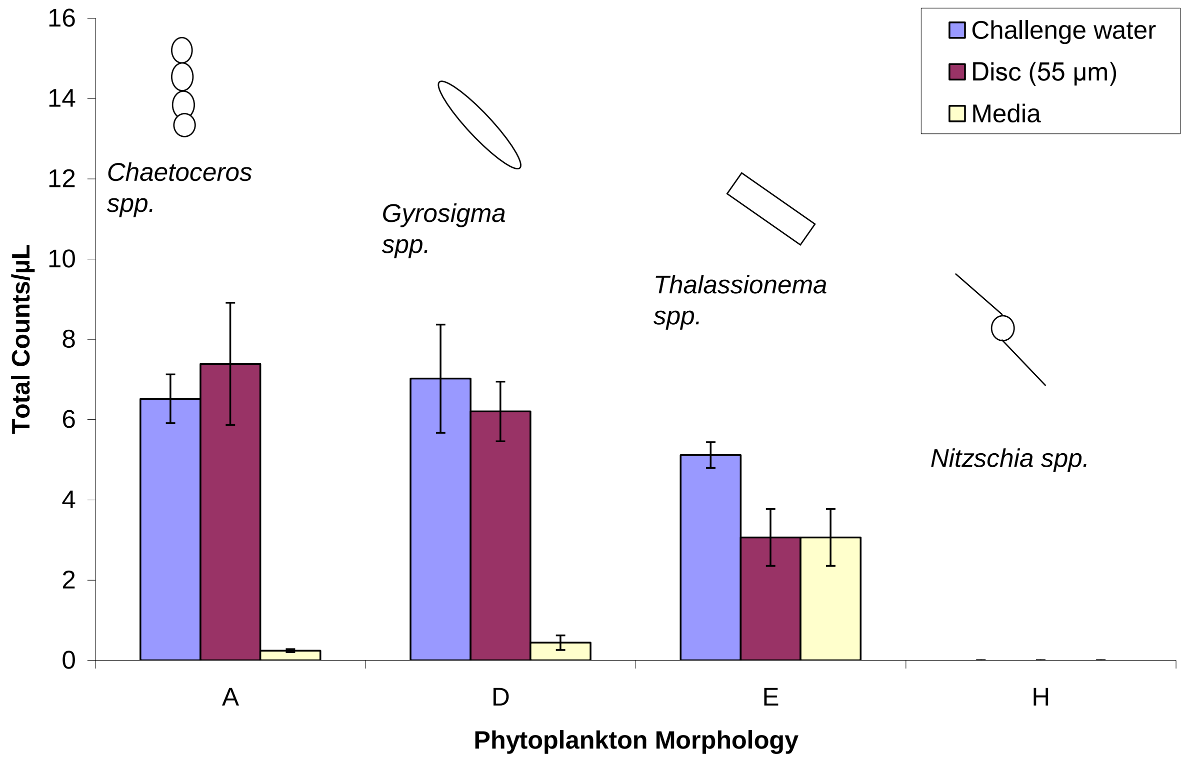


Figure 51. Type Comparison by Total Counts of Dominant Phytoplankton Morphology after 80 Hours of System Operation.

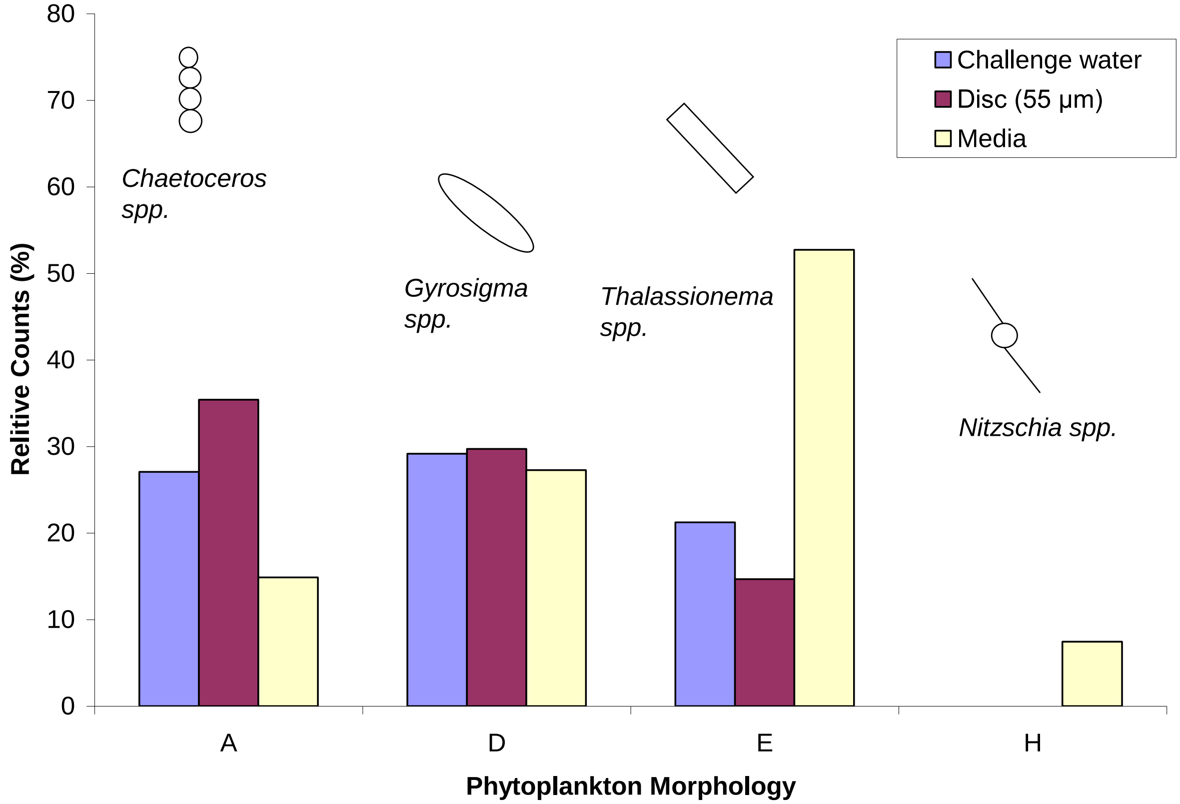


Figure 52. Filter Type Comparison by Relative Counts of Dominant Phytoplankton Morphology after 80 Hours of System Operation.

Considering the overall results of each sample collection, it is evident that there is no significant difference between the challenge water and the disc filtration system. This result is similar to the result for the screen filter in that there was no significant removal of the defined organisms.

Because of the dominance of *Chaetoceros spp*. (A), and because of the greater mean total count for the screen and disc than the challenge water, it is interesting to further analyze this organism. The mean chain length and mean counts per µL are found in Table 9 for each of the sample hours of operation. As shown in Figure 53, the mean total counts for *Chaetoceros spp*. (A) are almost identical for the challenge water and the disc filter except for the very slight increase in the mean count for the disc filter during the last two sample periods. In comparison, there is a significant decrease of mean total counts for the media filter relative to disc unit and challenge water for all sampling periods.

Table 9. Mean Total Lengths (µm) and Mean Total Counts per µL for Chain Formers (A) for the Disc to Media Filtration Train.

		8 Hours	
	Challenge water	**Disc (55 µm)**	**Media**
mean length (µm)	38.1	37.1	36.5
Std. Dev.	26.6	14.3	8.7
mean counts/µL	6.0	5.0	0.1
Std. Dev.	1.8	0.3	0.1
		32 Hours	
	Challenge water	**Disc (55 µm)**	**Media**
mean length (µm)	41.6	34.2	41.9
Std. Dev.	21.8	16.7	19.8
mean counts/µL	5.8	5.9	0.3
Std. Dev.	2.3	1.6	0.3
		64 Hours	
	Challenge water	**Disc (55 µm)**	**Media**
mean length (µm)	35.6	35.8	35.4
Std. Dev.	15.9	21.5	10.5
mean counts/µL	4.9	5.7	0.2
Std. Dev.	0.2	1.2	0.2
		80 Hours	
	Challenge water	**Disc (55 µm)**	**Media**
mean length (µm)	35.3	30.6	37.5
Std. Dev.	17.6	11.8	16.0
mean counts/µL	6.5	7.4	0.2
Std. Dev.	0.6	1.5	0.0

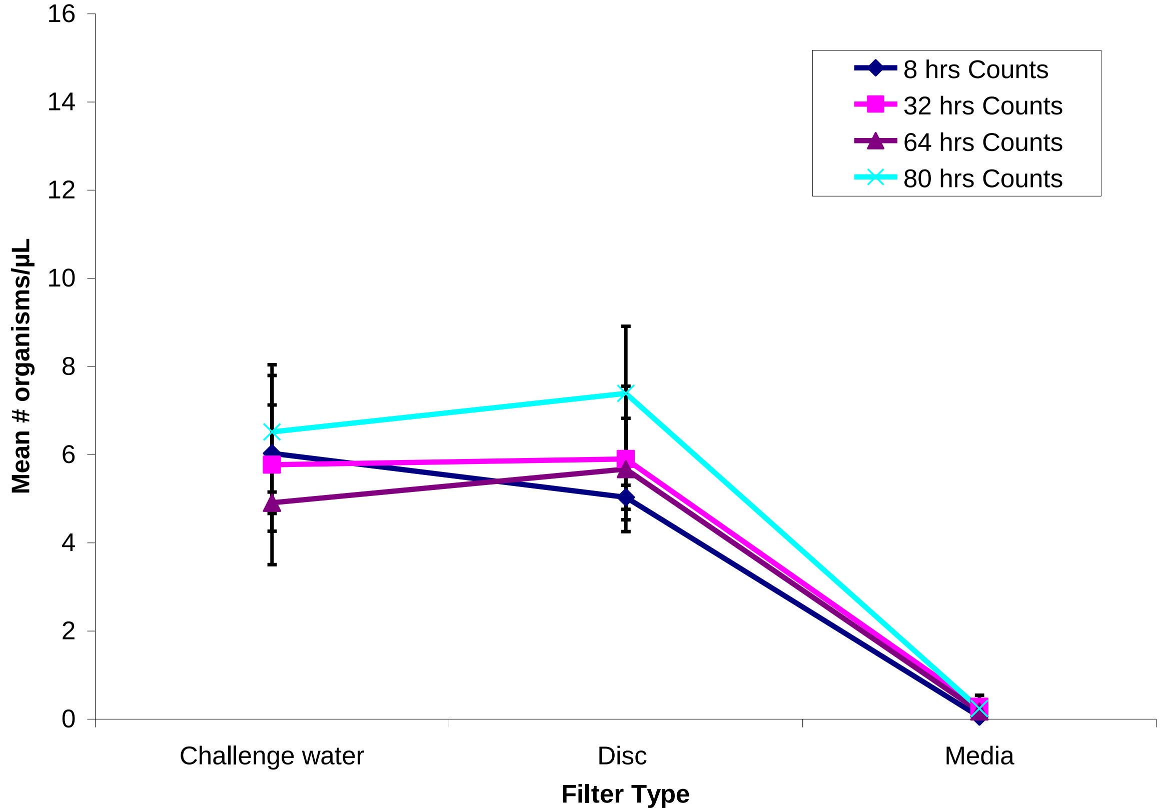


Figure 53. Filter Type Comparison of Mean Total Counts of Chain Forming Phytoplankton after All Hours of System Operation.

Overall lengths of *Chaetoceros spp*. (A) are compared in Figure 54. There is no significant difference in lengths from the challenge water to the disc filtration unit. The similar lengths found in the challenge water and the disc system may imply the disc technology is not breaking the organisms up and chain formers freely filter through the disc filtration system. The overlap in standard deviation for the lengths indicates the many lengths of *Chaetoceros spp*. (A) counted, which relates to the technology actually braking up the organism in the system. Due to the lack of counts found the media filtration filtrate, the following discussion should not be applied to the multi-media system.

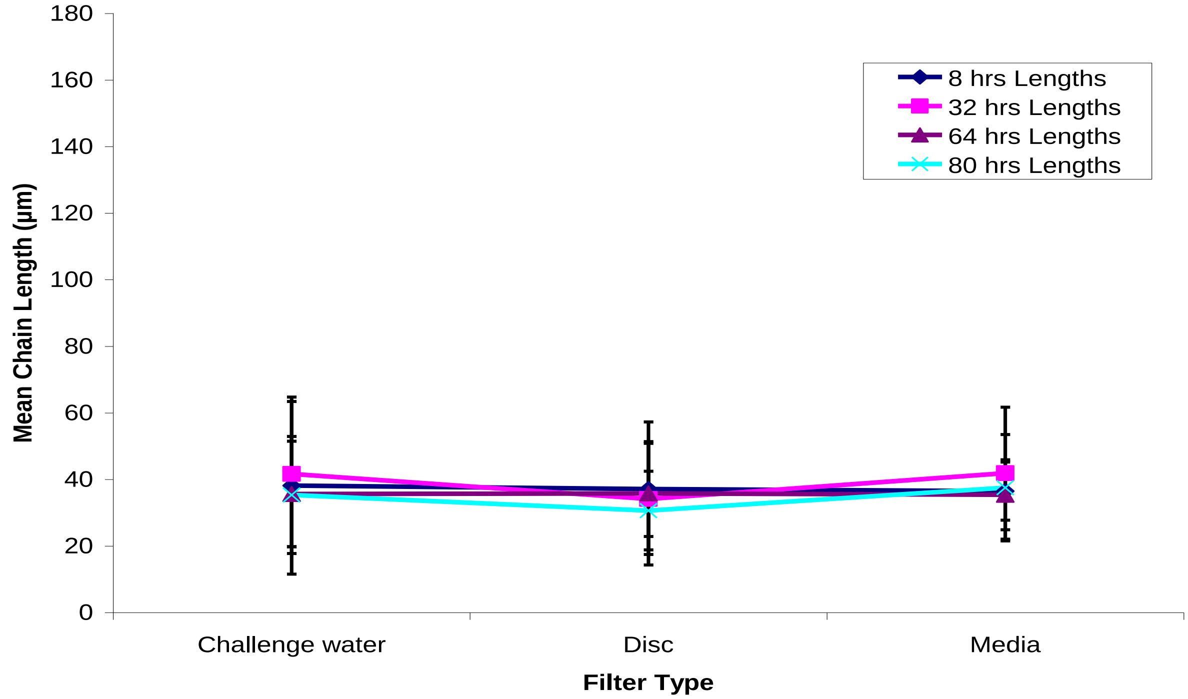


Figure 54. Filter Type Comparison of Length of Chain-Forming Phytoplankton after All Hours of System Operation.

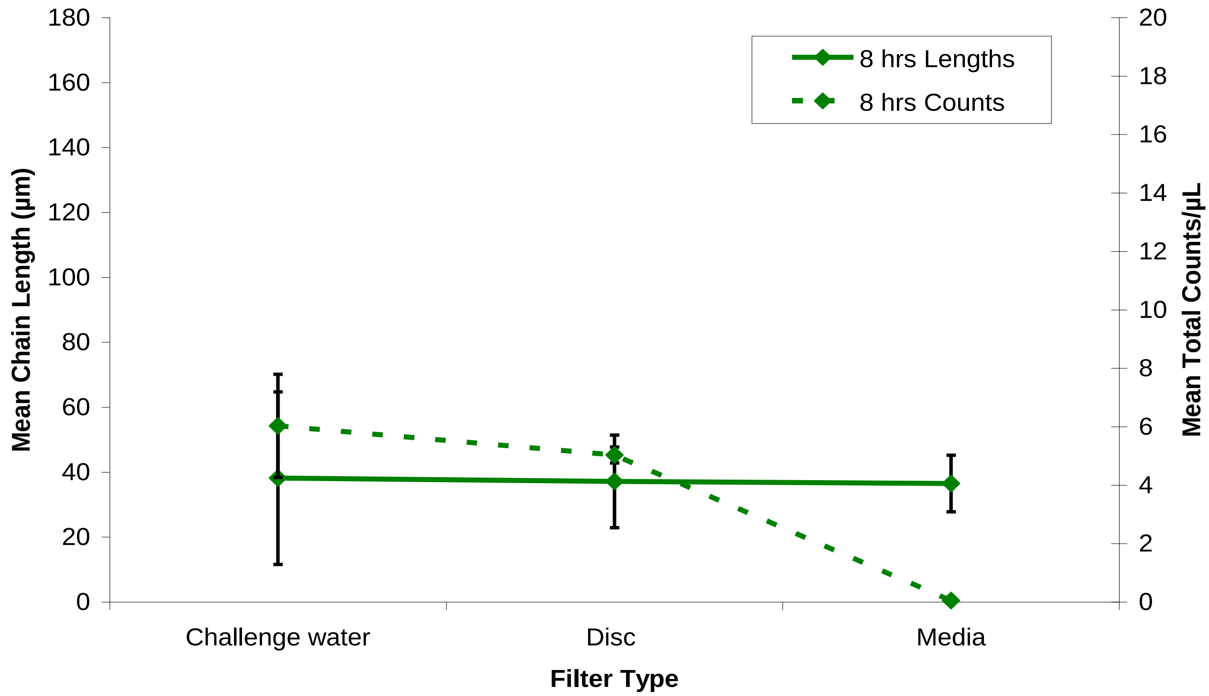


Figure 55. Filter Type Comparison of Mean Total Counts per µL to Mean Chain Lengths (µm) of Chain-Forming Phytoplankton after Eight Hours of System Operation.

From Figure 55, after eight hours of system operation the mean length from the challenge water and disc filtration unit did not differ significantly. Likewise the mean total count changed only slightly after disc filtration. This lack of difference between both aspects of the two samples suggests that there is no difference between the two systems, and that the disc filtration unit performed little to no removal. After 32 hours, the lengths decreased from 41.6 µm for the challenge water to 34.2 µm for the disc unit (Figure 56). Mean total counts were almost identical which suggests that the disc technology is not filtering out *Chaetoceros spp*. (A). There is no significant difference between the challenge water and disc filtration unit. On the other hand, the media filtration unit showed significant removal of *Chaetoceros spp*. (A) at 8 and 32 hours.

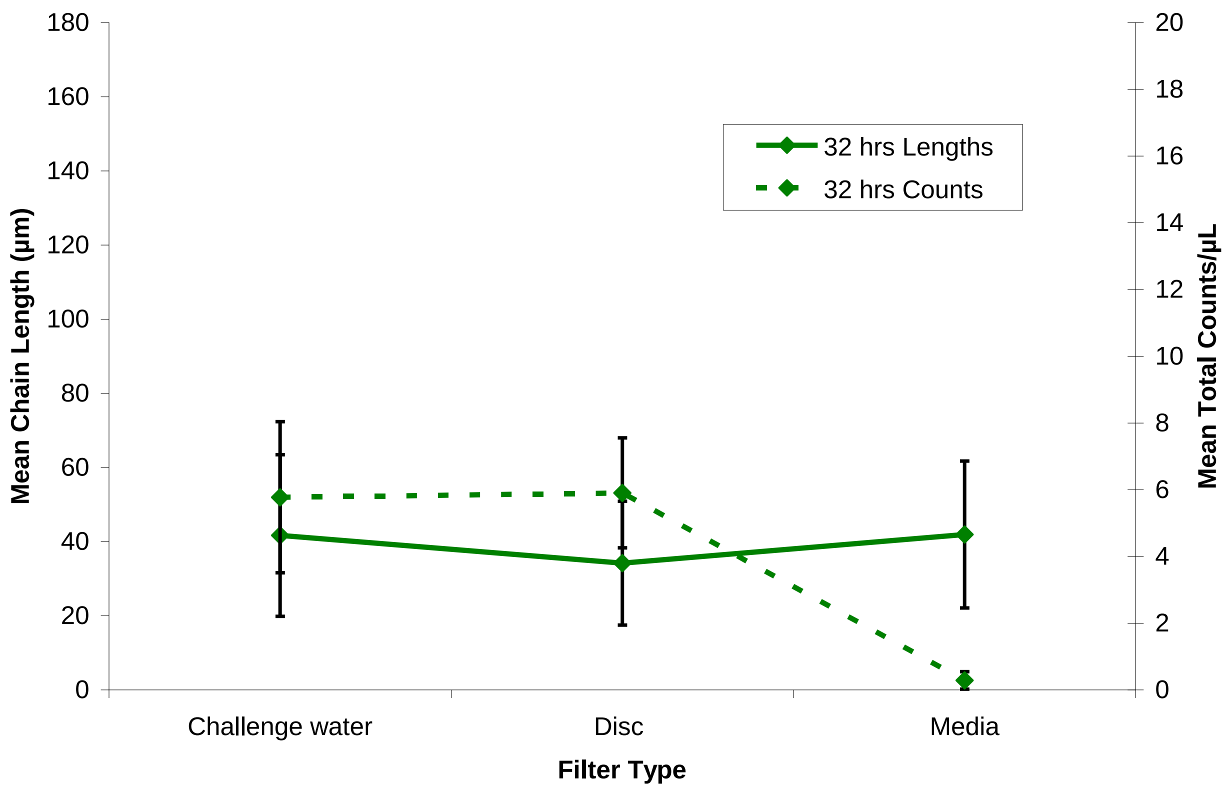


Figure 56. Filter Type Comparison of Mean Total Counts per µL to Mean Chain Lengths (µm) of Chain-Forming Phytoplankton after 32 Hours of System Operation.

Figure 56, Figure 57, and Figure 58 are almost identical with a slight increase in total counts from the challenge water to the disc filtration unit, but with virtually no change in the length of the chain formers. After 64 hours of system operation (Figure 57), the mean chain length of 35 µm is identical with a greater variance (based on the standard deviation) for the disc filtration system. The mean total counts increased slightly from 4.9 per µL for the challenge water to 5.7 per µL for the disc filtration unit. This increase was insignificant, but it suggests the possible break up of *Chaetoceros spp*. (A). At 80 hours of system operation (Figure 58), there was no difference from the challenge water to disc unit for mean counts of *Chaetoceros spp*. (A) or chain length.

Based on the means and the overlapping of the standard deviations, there was no significant difference between the challenge water and disc filtration system relative to mean chain length and mean total counts. The consistency of each sample as well as the overlapping standard deviations indicate there is no difference between the four collected samples in relation to time of operation (8, 32, 64, and 80 hours). On the other hand, for all sampling times, the media filter chain lengths were not significantly different from the challenge water or the disc filter (Figure 55 through Figure 58). In all cases the number of counts was significantly less than the challenge water and the disc filter indicating that the media filter successfully removed *Chaetoceros spp*. (A) from the water.

The ANOVA test output in Table 10, supports the findings and results discussed above that there is no significant difference in mean total counts between the challenge water and screen filtration unit ($\alpha = 0.05$, $p = 0.840$) and challenge water to the disc filtration unit ($\alpha = 0.05$, $p = 0.761$). There is also no significant difference between the screen filtration unit ($\alpha = 0.05$, $p = 1.000$), and the disc filtration unit ($\alpha = 0.05$, $p = 1.000$). Neither filtration unit was able to remove a significant amount of organisms from the challenge water.

The ANOVA test output in Table 11 supports that there is a significant difference between the challenge water and the media filtration unit ($\alpha = 0.05$, $p = 0.001$) in mean total counts. There is also an order of magnitude difference between the screen and disc filtration unit to the media filtration unit as shown in Table 10. Unlike the screen or disc filtration units, the media filtration unit was able to remove a significant amount of the organisms from the challenge water.

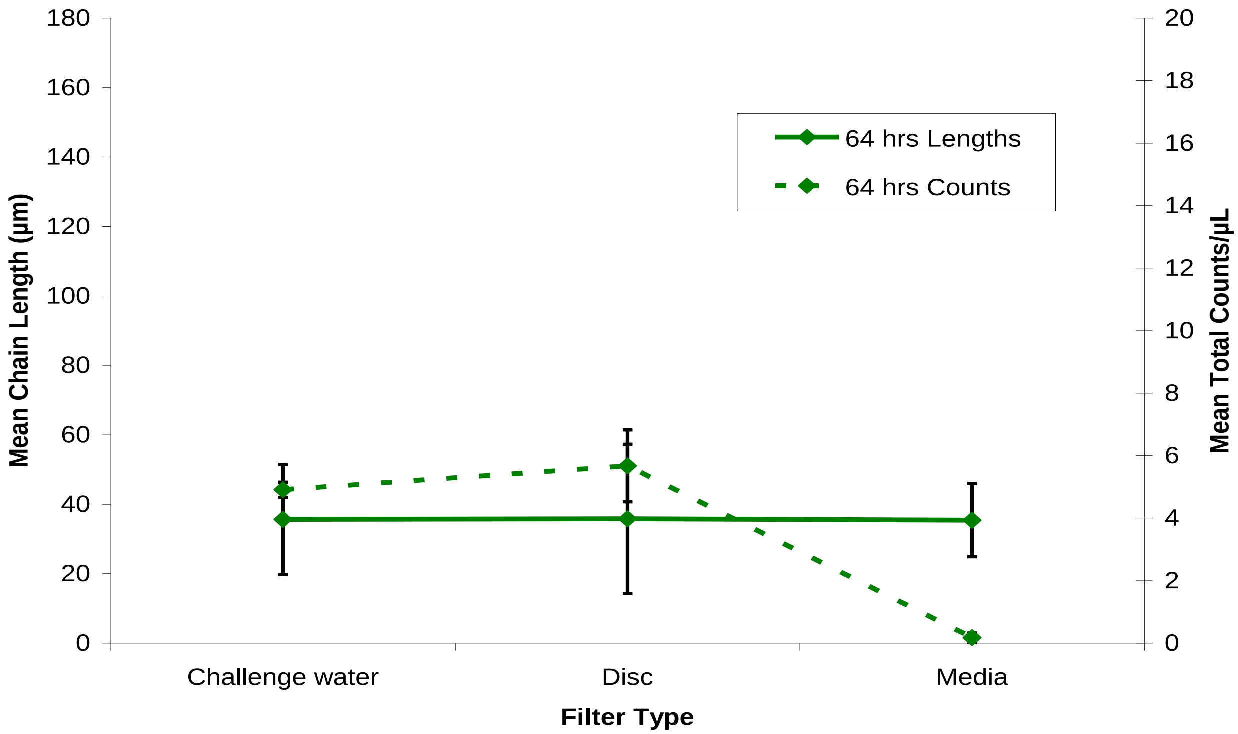


Figure 57. Filter Type Comparison of Mean Total Counts per µL to Mean Chain Lengths (µm) of Chain-Forming Phytoplankton after 64 Hours of System Operation.

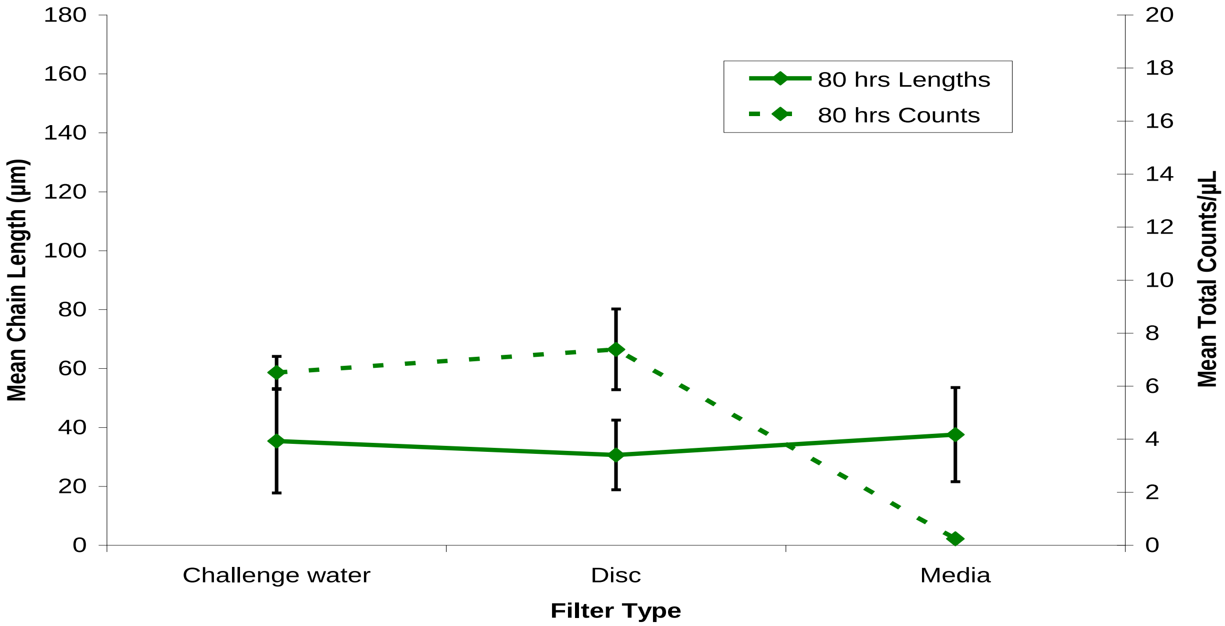


Figure 58. Filter Type Comparison of Mean Total Counts per µL to Mean Chain Lengths (µm) of Chain-Forming Phytoplankton after 80 Hours of System Operation.

Table 10. Tukey Hoc Test of Multiple Comparisons from the Multivariate ANOVA Statistic Test Performed on the Four Water Types.

Tukey Test						
Dependent Variable: Mean Total Counts						
					95% Confidence Interval	
(I) Water Type	(J) Water Type	Mean Difference (I-J)	Std. Error	Significance (Sig.)	Lower Bound	Upper Bound
challenge - screen	screen	1.50	1.27	0.840	-2.54	5.54
	disc	1.38	1.27	0.882	-2.66	5.41
	challenge - disc	-0.33	1.27	1.000	-4.36	3.71
	media - screen	19.00*	1.27	0.001	14.96	23.04
	media - disc	18.88*	1.27	0.001	14.84	22.91
challenge - disc	screen	1.83	1.27	0.706	-2.21	5.86
	disc	1.70	1.27	0.761	-2.34	5.74
	challenge - screen	0.33	1.27	1.000	-3.71	4.36
	media - screen	19.33*	1.27	0.001	15.29	23.36
	media - disc	18.88*	1.27	0.001	15.16	23.24
screen	disc	-0.13	1.27	1.000	-4.16	3.91
	challenge - screen	-1.50	1.27	0.840	-5.54	2.54
	challenge - disc	-1.83	1.27	0.706	-5.86	2.21
	media - screen	17.50*	1.27	0.001	13.46	21.54
	media - disc	17.38*	1.27	0.001	13.34	21.41
disc	screen	0.13	1.27	1.000	-3.91	4.16
	challenge - screen	-1.38	1.27	0.882	-5.41	2.66
	challenge - disc	-1.70	1.27	0.761	-5.74	2.34
	media - screen	17.63*	1.27	0.001	13.59	21.66
	media - disc	17.5*	1.27	0.001	13.46	21.54
Based on observed means						
* The mean difference is significant at the .050 level.						

Table 11. Results From the ANOVA Univariate Statistic Test Performed on the Four Water Types Comparing Mean Total Counts.

Tests of Between-Subject Effects					
Dependent Variable: Mean Total Counts					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1796.594[a]	5	359.319	111.201	0.000
Intercept	4545.754	1	4545.754	1406.81	0.000
Water Type	1796.594	5	359.319	111.201	0.000
Error	58.162	18	3.231		
Total	6400.51	24			
Corrected total	1854.756	23			
a. R Squared = .969 (Adjusted R Squared = .960)					

4. Conclusions

These experiments were designed to test several types of filters under conditions likely to be seen during ballasting operations, i.e., prolonged pumping, frequent shutdown, and moderate sediment loads. The study revealed that standardized efforts for testing filtration-type ballast water treatment equipment should have well-defined sediment loading requirements. These should be characterized not only by TSS, but also by sediment size class distribution.

Test results indicated that a 50/50 mixture of Arizona Test Dust; ISO 12103 -1, A3 Medium Test Dust and Arizona Test Dust: ISO 122-1, A4 Coarse Test Dust adjusted the ambient water supply's suspended solids to a range closely resembling "estuarine water". While every effort was made to provide a feed water characteristic of real ballast water systems, the result was a relatively unchallenging fluid for 50 micron screen and disc filtration systems. More detailed information about the particle distribution of typical estuarine water used for ballasting is required to create a realistic challenge water. If, however, the size characteristics remain skewed towards particles less than 50 microns in size, results similar to those of this study are expected.

No significant removal of particles or organisms was identified from either the disc or screen filtration units for the feed water used for these studies. No effect on mean chain length of *Chaetoceros spp.* as a result of screen or disc filtration was identified. This refutes an early hypothesis that an increase in total counts of *Chaetoceros spp* following the screen filtration unit was the result of a breakup of the chain-forming organisms.

Despite the relatively low particle size of the feed water, both the screen and disc filtration units exhibited a steadily increasing back-flush frequency which was either the result of smaller particles "caking" on the filtration surfaces or bio-fouling due to the nightly shutdown periods.

The media filtration system had a significantly superior performance to either the screen or disc filtration system. This system resulted in a mean removal efficiency of 73 percent for the sediments utilized in the feed water. Furthermore, the media filtration system demonstrated the best filtration of organisms, particularly the four most dominant organisms examined in this study, *Chaetoceros spp.*- chain former (A); *Gyrosigma spp.* – pinnate diatom (D); *Thalassionema spp*. (E) – rectangular diatom; *Nitzschia spp. (H)* – skinny pinnate diatom. The overall size and weight of this filtration system, however, make it an unlikely choice for commercial use aboard most ships.

In summary, within the confines of the sediment loadings of these experiments, neither disc nor screen filters significantly removed sediments or organisms from the challenge water. The media filter successfully removed both sediments and organisms from the flow.

5. Recommendations

For valid tests of ballast water treatment systems, the ETV protocol should include a description of size class distribution in addition to total concentration of TSS. It is expected that the bulk of the distribution will be less than 50 microns.

Filters are not recommended as stand-alone ballast water treatment systems. Filters are not useful for removing organisms or inorganic particles below their threshold pore size – in this study, 50 to 55 microns. Increased back-flushing was required on the units tested. It is expected that filters with smaller pore sizes will require even more flushing making them less useful for shipboard use.

Media filters, while capable of removing smaller particles and organisms than screen or disc filters, are not recommended for shipboard use due to their size and weight.

The use of filtration systems as pretreatment for other active ballast water treatment systems should be carefully weighed in light of the performances seen in this study. Filters could be used to remove large organisms and particles; however, most of the sediments found in ballast tanks were smaller than 50 microns. It is unlikely that filtration systems would remove them, so they would still be available to interfere with other treatments.

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