REMOVAL OF *CRYPTOSPORIDIUM*-SIZED MICROSPHERES FROM SWIMMING POOL WATER WITH REGENERATIVE MEDIA FILTERS

by

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ABSTRACT

GRAHAM LAMB. Removal of *cryptosporidium*-sized microspheres from swimming pool water with regenerative media filters (Under the direction of DR. JAMES E. AMBURGEY)

Cryptosporidium is a chlorine-resistant protozoan parasite that infects an estimated 823,000 Americans annually. The most common mode of transmission for *Cryptosporidium* is ingesting contaminated recreational water from treated (chlorinated) aquatic venues. *Cryptosporidium* oocysts have an approximate diameter of 4.5 microns and easily pass through sand and cartridge filters where the pore sizes in the filter media are typically greater than 50 microns and 30 microns, respectively. A regenerative media filter (RMF), a type of precoat filter using perlite filter media that looks like white powder, was evaluated under a wide range of operating conditions to determine the level of *Cryptosporidium* removal possible.

Cryptosporidium-sized microspheres were used as a surrogate to determine the removal of the RMF connected to a 1500-gallon swim spa. The amount of media added, the grade of filter media, the degree of filter clogging, the steps in the filter regeneration procedure, and the filtration rate were all varied to assess their individual impacts on microsphere removal by a filter that regenerates its media every 24-hours.

The RMF baseline removal of microspheres was found to be 99.6% at 1-hour and 97.1% at 24-hours. The experiments performed determined that all the parameters evaluated significantly impacted RMF removal efficiency, but all of those differences were not large or important. Increasing the filter loading rate by 25% from 1.6 $\frac{gpm}{ft^2}$ to 2.0 $\frac{gpm}{ft^2}$ decreased microsphere removal at 1-hour from 99.6% to 97.7% and at 24-hours from 97.1% to 91.6%. At a constant 1.6 $\frac{gpm}{ft^2}$, increasing the amount of perlite filter media by 50% from 7.5 $\frac{lbs.}{100\,ft^2}$ to 11.25 $\frac{lbs.}{100\,ft^2}$, increased

removals from 99.6% to 99.8% at 1-hour and 97.1% to 98.7% at 24-hours. Overall, RMF's were much more efficient at removing *Cryptosporidium*-sized particles than sand and cartridge filters based on values reported in multiple peer-reviewed publications.

DEDICATION

This thesis is dedicated to my family and Bella for the continued love and support during the process.

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LIST OF ABBREVIATIONS

AIDS	auto immune deficiency syndrome
DI	deionized
DE	diatomaceous earth
GPM	gallons per minute
L	liter
lbs.	pounds (standard US)
m^3	cubic meters
mg/L	milligram per liter
min.	minute
mL	milliliters
mL/min.	milliliters per minute
nm	nanometer
ORP	oxidation reduction potential
PVA	polyvinyl alcohol
PPM	parts per million
PSI	pounds per square inch

PVC	polyvinyl chloride
RMF	regenerative media filter

CHAPTER 1: INTRODUCTION

Cryptosporidium is a protozoan parasite that causes cryptosporidiosis in people. The leading cause of outbreaks in the United States is treated (chlorinated) aquatic venues. Outbreaks due to contaminated swimming pools have been increasing 13% per year (Gharpure 2019). *Cryptosporidium* has a high resistance to disinfection by chlorine requiring a CT of 15,300 $\frac{mg \cdot min.}{L}$ to achieve 3-log disinfection (Shields et al. 2008b). Due to its resistance to chlorine, *Cryptosporidium* removal from recreational water by filtration is critical. The oocysts that cause infection are 4.5-5.5 microns in diameter. The small particle size makes filtration challenging for most filters.

The CDC Model Aquatic Health Code (MAHC) allows for three types of filters to be used for treating public recreation water: sand, cartridge, and precoat filters. Sand and cartridge filters have been shown to achieve removals of *Crypto*-sized microspheres at 31% and 36% respectively, while precoat filters have been shown to achieve removals of 99% and greater (Amburgey et al. 2012).

Precoat filters use media covered elements to remove particles physically by straining. Two filter medias commonly used in precoat filters are diatomaceous earth and perlite. The media is made of small particles that, when packed together, form pores. The pores allow fluids to pass through but not the particles suspended in the fluid. As the fluid is filtered, more particles accumulate on the surface of the media until the media is clogged. The clogged media is normally discarded, and new media is added to the filter.

Regenerative media filters are precoat filters that are designed to remove the clogged media from the elements and then reapply the same media back on the elements. This regeneration process mixes the filtered particles on the surface of the media into the media mixture. After the mixed particles and media are reapplied to the filter elements, the particles that originally clogged the surface are mixed throughout the thickness of the perlite layer to create an unclogged surface so that filtration can continue while using the same media.

The overall objective of this research was to determine how effective regenerative media filters are at the removal of *Cryptosporidium*-sized microspheres. The research further evaluated how the adjustment of filter operation and design parameters affected removal of an 18-inch diameter RMF in a controlled laboratory setting. The filter parameters evaluated include flow distributor version, filtration time, media grade, flowrate, degree of clogging, and the amount of media used. The experiments also included the evaluation of a full-scale RMF on the UNC Charlotte campus pool.

CHAPTER 2: LITERATURE REVIEW

2.1 *Cryptosporidium*

Cryptosporidium is a 4.5 μm – 5.5 μm protozoan parasite that causes cryptosporidiosis, which is an infection that presents as diarrhea and other enteric symptoms including fever, nausea, vomiting, and cramping lasting up to 3 weeks (Gharpure 2019; Hoxie 1997). Groups of people that are at higher risk of infection are people with a weakened immune system including children, older adults, or people with immune deficiencies (Gharpure 2019; DuPont 1995). From 2009 to 2017, 40 states and Puerto Rico reported 444 *Cryptosporidium* outbreaks, leading to 7,465 cases of infection (Gharpure 2019). The largest cause of *Cryptosporidium* outbreaks was treated recreational water, accounting for 156 of the outbreaks, and 4,232 of the infections (Gharpure 2019). Recreational water becomes a source of outbreaks due to *Cryptosporidium* being very chlorine-resistant and due to its transmission by the fecal-oral route. Transmission occurs in recreational water when swimmers accidentally ingest pool water containing *Cryptosporidium* oocysts (CDC 2010; Gregory et al. 2002).

In a study that used 29 healthy people with varying doses of oocysts, the median infective dose of *Cryptosporidium* oocyst was found to be 132 oocysts. While infection rates increased with concentration, some people were infected at doses as low as 30 oocysts (DuPont 1995). People with Acquired Immune Deficiency Syndrome (AIDS) are at a higher risk of infection of Cryptosporidiosis. In a study of AIDS-associated cryptosporidiosis, it was found that infected patients' stools could contain between 5×10^3-9.2×10^5 oocysts per mL (Goodgame 1993). If a child were to have a bowel movement in a typical 450 m^3 municipal pool, the pool's concentration of oocysts was estimated to be as high as 20 per mL after mixing due to swimmers and the recirculation of water, (Gregory et al. 2002). Non-adult swimmers have been shown to swallow 37 mL of pool water during a typical swim (Dufour 2006). If this occurred in a contaminated pool, the ingested number of oocysts is more than 5 times higher than the median infective dose of 132 discussed previously.

In one attempt to determine the prevalence of *Cryptosporidium* in an "average" swimming pool, 160 pool filter backwash samples were tested for *Cryptosporidium*. It that study, 1.2% of the sample were positive for *Cryptosporidium* and about 1% tested positive for *Cryptosporidium* and *Giardia* (Shields 2008). *Cryptosporidium* is found in swimming pools even when maintained in accordance with US pool codes due to its high resistance to chlorine. The CT value needed to achieve 3-log reduction in *Cryptosporidium* oocysts has been determined to be as high at 15,300 $\frac{mg \cdot min.}{L}$ (Shields et al. 2008b). The Center for Disease Control and Prevention (CDC) recommends a chlorine level of 1-3 ppm for swimming pools, which means 3-log inactivation would take 5,100 minutes or 85 hours (Shields & Arrowood 2008).

The experiments discussed later use 4.5 μm diameter microspheres as a surrogate for the *Cryptosporidium* oocysts. Previous research that used *Cryptosporidium* oocysts as well as microspheres concluded that removals were similar and therefore microspheres were a good surrogate in recreational water (Amburgey et al. 2012).

2.2 Diatomaceous Earth Filters in Water Treatment

One of the biggest cryptosporidiosis outbreaks was the Milwaukee outbreak of 1993. This disaster was caused by contaminated drinking water and affected an estimated 403,000 people (William 1994). While ultraviolet disinfection is an efficient method of inactivating

Cryptosporidium in drinking water, most treatment facilities rely on chlorine disinfection. The use of chlorine disinfection alone leaves *Cryptosporidium* removal dependent on the physical removal of oocysts; typically, by filtration (Lorenzo-Lorenzo 1993; Ongerth 1997). Diatomaceous Earth (DE) filters are a type of precoat filter that utilize the skeletal remain of single-cell organisms as filter media and is an efficient method of removing *Cryptosporidium* oocysts in drinking water treatment (Bhardwaj 2001). DE filters have been shown to have a 3 to 6-log (99.9% - 99.9999%) removal of *Cryptosporidium* oocysts in drinking water (Ongerth 1997; Ongerth 2001, Schuler 1991).

2.3 Precoat Filter in Recreational Water

Precoat filters are an approved method of filtration for public pools, however they are not as prevalent as sand filters (CDC 2016). A Precoat filter at a full-scale public swimming pool in Finland was found to have an average removal efficiency of 90% at 180 GPM and 80% at 326 GPM when measuring particle sizes ranging from 3 – 100 μm (Christensen 2018). Studies that used *Cryptosporidium*-sized microspheres found DE filters as well as Perlite precoat filters to be able to achieve 2-log (99%) removal and higher (Amburgey & Walsh 2012, Lu & Amburgey 2017). No reports of regenerative media filter removals of *Cryptosporidium*-sized particles were found in the literature.

CHAPTER 3: EXPERIMENTAL METHODS AND PROCEDURE

3.1 Seeding Suspension

Microspheres were used as surrogate for *Cryptosporidium* oocysts. The microspheres used were YG-fluorescent carboxylate-modified polystyrene microspheres (Polysciences, Inc, Cat. #16592, 4.5 µm). A 1000 mL seeding suspension was made with microspheres and DI water. The seeding solution was continuously stirred in a 1000 mL Erlenmeyer flask with a magnetic stir plate (IKA, Color Squid) and Teflon-coated stir bar prior to and during the experiments. The microsphere seeding suspension was pumped into the filter system before the filters pump using a peristaltic pump (Watson Marlow, Model 505Di). The microspheres were fed before the filter pump to help ensure the seeding solution would be well mixed with the influent water before reaching the sample locations.

The volume of spheres added to the 1000 mL of DI water was calculated using the equation below.

$$C_1 \times Q_1 = C_2 \times Q_2 \tag{3.1}$$

Where: C_1= Concentration of spheres in seeding solution.
Q_1= Flowrate of peristaltic pump.
C_2=Concentration of spheres in the influent of filter.
Q_2=Flowrate of the filter.

A concentration of spheres in the influent of the filter was selected to be approximately 12 spheres per mL. The peristaltic pumps flowrate was set to 67 mL per minute. This flowrate was used to dose the 1000 mL of microsphere seeding solution in 15 minutes, the time of an experiment. The flowrate was calculated using the equation below.

$$\frac{V}{t} = Q \tag{3.2}$$

Where: V=Volume of seeding suspension
t=Time of experiment
Q=Flowrate of peristaltic pump

The flowrate of the filter was dependent on the experiment being conducted and was between 140 and 200 GPM. With all parameters of equation 3.1 known or selected, the concentration of the microsphere seeding suspension (C_1) was calculated. The microspheres came from the manufacture with a concentration of 5.58×10^8 microspheres per mL. The concentration was used to calculate the volume of sphere solution to be added to the seeding suspension used in the experiment. The equation used was equation 3.3 seen below.

$$\frac{C_1 \times V}{C_m} = V_s \tag{3.3}$$

Where: C_1= Concentration of spheres in seeding solution used in experiment.
V= Volume of seeding suspension used in experiment.
C_m=Concentration of microspheres from manufacture solution.
V_s= Volume of manufacture sphere solution to be added to the seeding suspension used in experiment.

3.2 Filter Media Particle Size Analysis

Particle size analysis was performed on the three grades of media (Harborlite, Perlite) particle analysis was conducted using a laser diffraction particle size analyzer (LS 13320, Beckman Coulter) equipped with an Aqueous Liquid Module (ALM, Beckman Coulter). The tests were performed using DI water. The extended optical model was used to allow for the detection or particle down to .04 micron. The sample was added into the instrument until the obscuration read "ok," and the sample was analyzed. The optical model used was the Mie theory. A fluid refractive index of 1.332 was used. A sample refractive index of 1.6 was used for the real part and 0 for the imaginary. The results were plotted and can be seen in Appendix B.

3.3 Lab-Scale

3.3.1 Lab-Scale Configuration

3.3.1.1 Regenerative Media Filter

The regenerative media filter used in the lab-scale experiments had an 18-inch diameter and 72-inch tall filter body. The filter contained 128 flexible cylindrical filter elements. The filter elements were 0.5-inches in diameter and 48-inches long. The RMF was controlled using a personal computer with LabVIEW software (National Instruments). The program used to control the filter had programmed filter operation sequences as well as the ability to record data.

The programmed filter operation sequences were for loading media, removing air from the filter, regenerating media, and discarding media. The parameters that were measured continuously by the filter were turbidity, pressure, and flowrate. The flowrate was measured using a flowmeter (GF, Signet Magmeter). Turbidity and pressure were measured on both the influent and effluent side of the filter. Turbidity was measured using two turbidity meters (Hach, Filter Track 660sc, Laser Nephelometer). The turbidity meters were controlled using a head unit (Hach, sc100). Pressure was measured using two pressure transducers (Honeywell, MLH). Other values that were calculated by the program were the media age, time since last regeneration, filtration time, and differential pressure. A 3-D rendering of the filter system can be seen below in Figure 3.1

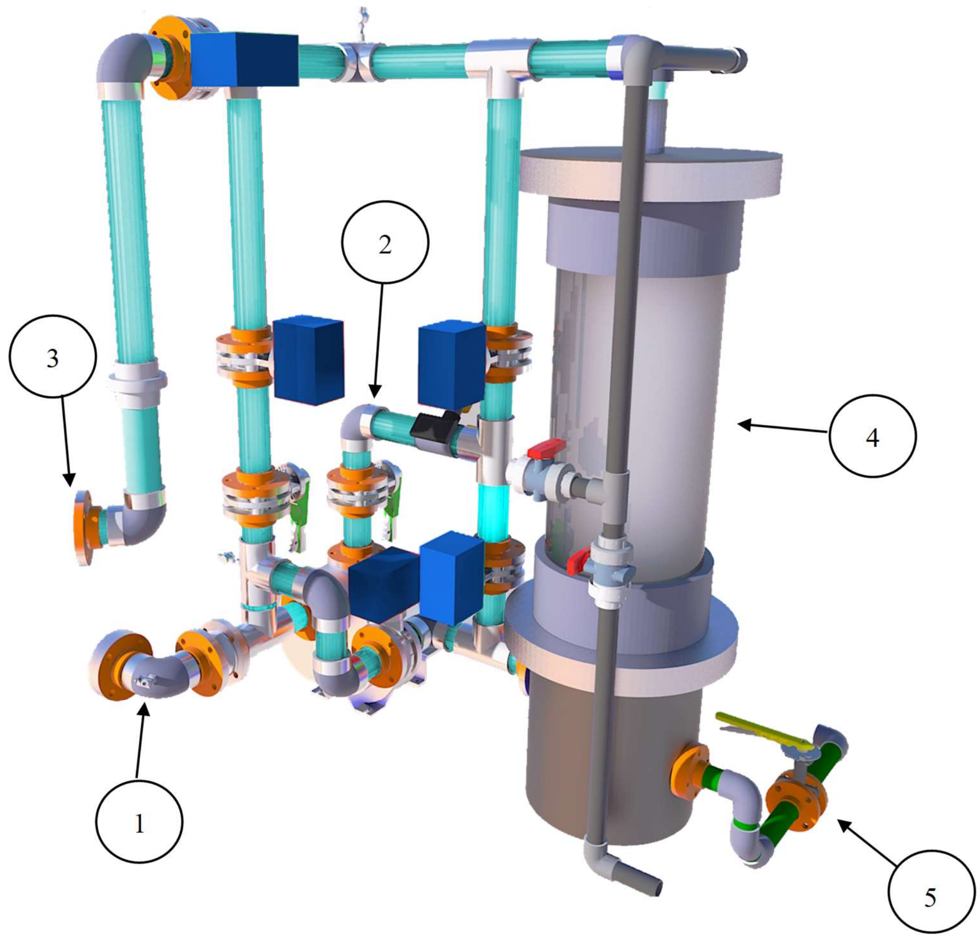

Figure 3.1: Lab-scale regenerative media filter (after: Alansari, 2022).

1: Seeding solution/dust port	4: Filter body
2: Influent sample location	5: Drain valve
3: Effluent sample Location	

3.3.1.2 Swim-Spa

The swim spa used in the lab scale experiments held 1,500-gallons (5,500 liters) of water. The pool water was continuously monitored with a water quality controller (Hayward, Poolcomm, CAT5000). The controller was connected to a pH probe (Hayward, CAT PRO-15), and an oxidation reduction potential (ORP) probe (Hayward, CAT PRO-25). The controller also measured water temperature. The controller dosed acid and chlorine when the pool waters parameters changed from a setpoint value. When the pH was above 7.5 a peristaltic pump (Pulsafeeder, Chemtech XPV, Punta Gorda, FL) would feed a 1:10 muriatic acid (Jasco, Memphis, TN) dilution into the pool until the pH measured 7.5 or less. When the ORP was measured to be below 770 mV the controller would start a peristaltic pump (Stenner, SVP4) feeding a 1:10 bleach dilution until the measured value was at least 770 mV.

The measured water parameters were also confirmed using a separate probe (Yokogawa, FU20). This probe was connected to a head unit (Yokogawa, EXAXT450) to display the measured value. This probe measured ORP and water temperature. Before each experiment, the water quality was tested using a Taylor pool testing kit (Taylor, K-2005). The parameters measured were pH, free chlorine, alkalinity, and hardness. The pool waters typical parameters during experiments are shown below (Table 3.1).

Table 3.1: Model water parameters

	Free Chlorine ($\frac{mg}{L}$ $as\ Cl$)	pH	Alkalinity ($\frac{mg}{L}$ $as\ CaCO_3$)	Hardness ($\frac{mg}{L}$ $as\ CaCO_3$)	ORP mV	Temperature (°F)
Min	0.5	7.5	20	90	730	70
Typical	1	7.7	85	165	750	85
Max	2	8	130	220	865	89

3.3.2 Tracer Study

A tracer study was performed using salt (NaCl) to determine the detention time of the filter. Two conductivity meters (Hach, D3422D3) were installed onto the influent and effluent of the filter. The conductivity meters were submerged in a section of polyvinyl chloride (PVC) pipe that the water from the filter was continuously flowing into at the top and then flowing out the bottom of the of the PVC section. The data being measured by the conductivity meters was recorded into a spreadsheet using LabVIEW and plotted.

The experiment was conducted with the filter flowing at 140 GPM. The salt mixture used was 500 grams of salt dissolved in 15 liters of water. The salt was pumped into the filter at a rate of 1900 mL per minute using a peristaltic pump. The peristaltic pump used was the same as used for seeding solution mentioned previously. The figures from the tracer study showing the measured conductivity can be seen in Appendix C. Origin 2022b (OriginLab, Northampton, MA) was used to create the figures and to calculate the time needed for the effluent to reach equilibrium. This value was found to be 67.4-seconds.

3.3.3 Filter Operation

3.3.3.1 Loading Media

Media was loaded into the RMF by filling the filter approximately 25% with water from the swim spa. A vacuum (Vacmaster, VK811PH, Greer SC) attached to the pipe exiting the top of the filter was used to pull the media out of a bag and through the water inside the filter. A valve at the bottom of the filter body was opened approximately 50%. With the vacuum on, the water could not exit the top of the filter due to an air gap, and the filter media could be vacuumed into the filter and mixed with the water. The correct amount of media was added to the filter by first weighing the bag of media using a scale (Mettler-Toledo, SB12001) and then subtracting the desired weight of the added media. The valve on the filter was closed once the scale read the original weight of the media with the desired amount of media subtracted. With the correct amount of media added to the filter, an air relief valve at the top of the filter was opened and water was pumped in the filter until almost completely full. The filter could not be filled completely at this point to avoid clogging the air relief valve with filter media. To remove the remaining air from the system, an air out procedure was started.

During an air out procedure, the water and suspended media was pumped through the filter elements in the forward direction. The water in the filter however did not return to the spa, but instead the water was recirculated in a loop through the filter. The effluent pipe was the highest point in the loop and therefore air accumulated in the effluent as the water recirculated for 10 minutes through the filter. After 10 minutes, the effluent valve to the pool was opened allowing water along with the accumulated air to be pumped in the spa and released from the system. This air out procedure was repeated twice after media was loaded.

3.3.3.2 Regenerating Media

When a media regeneration procedure was started, the first step was the pump being turned off. Next, the effluent valve would be closed to prevent contaminants from reaching the pool. The direction of flow would be reversed so that pumped water would flow from the top of the filter through the inside of the filter elements and then out the sides of the filter elements. The pump would be started before the valve configuration was completely open. The pump starting before the valves were opened caused pressure to build in the filter. The extra pressure build-up and sudden release as the valve was opened helped separate the media from the filter elements. The flow of the water being pumped carried the filter media from the outsides of the filter elements to the insides of the element tubes. As the media accumulated within the filter elements, water was continuously recycled through the filter. The stage of the media regeneration lasted 3 minutes. After this part of the regeneration process was completed, the precoat stage began. During this phase of the regeneration process, the direction of flow would return to the forward direction. The media was then reapplied to the outside of the filter elements. This stage was varied during experimentation. Some experiments used multiple stages of flowrate and some lasted for different amounts of time. The specific regeneration procedure used for each experiment is discussed more later. The Regeneration process in summarized in the Table below (Table 3.2).

Table 3.2: Stages of regeneration procedure

Step in Regeneration Procedure	**Time (minutes)**
Filtration in the forward direction	-
Media regeneration begins and filter is closed off from pool	-
Direction of flow is reversed (opposite of filtration direction), media goes inside of elements	3
Precoat: direction reverses back to forward direction, media returns to outside of elements	10-12
filtration is continued	-

3.3.3.3 Discarding Media

Media was discarded by opening the drain valve at the bottom of the filter body and reversing the direction of flow (opposite of the filtration direction). The flow would go through the center of the flow tubes and out the sides pushing the media off the septum, into the filter body, and out of the opened drain valve of the filter. The first stage of discarding media was power draining. When the filter was power draining, the filter effluent valve would be closed to prevent water from returning to the pool. The water and filter media would be pumped out of the drain together. This stage allowed for media to be removed from the filter but prevented the filter body from filling with air.

In the next stage of draining the filter, the pump was not used. Instead, a valve was opened on the influent pipe network of the filter that allowed air into the bottom of the filter. Because the drain valve at the bottom of the filter was open, water was flowing out of the filter creating a vacuum on the filter body. The vacuum on the filter pulled the air bubbles into the filter from the valve on the influent. The air bubbles moved upwards to further remove media particles from membranes and the inner wall of the filter. The air coming into the bottom of the filter disrupted the filter elements causing them to contact each other removing media from the sides. The drain and air valves were left open until the filter was completely drained.

3.3.4 Cleaning and Spa Filling Procedure

After the RMF was drained, the 1500-gallon swim spa was drained. Once drained, any remaining water in the swim spa was vacuumed out. If any media had escaped from the filter into the pool during the prior experiment, it was vacuumed out.

The spa was refilled with Charlotte, North Carolina tap water that was additionally filtered with two 20-inch sediment filters (Hydronix, Chino Hills, CA) in series. To create pool water, chemicals were added to the water in the spa. Before adding chemicals, the spa jets were turned on to ensure mixing of the chemicals. First 105 ml of muriatic acid was added to the spa, and the target pH of the spa was 7.5. Chlorine was added to the pool as 75 mL of bleach (Clorox), and the free chlorine target of the pool was 1 ppm. Hardness was added as 2 lbs. of calcium chloride (Poolife Calcium Plus), and the target hardness of the water was 180 mg per L as $CaCO_3$. Alkalinity was added to the spa as 2 lbs. of baking soda (Arm & Hammer, Pure Baking Soda). The target alkalinity of the pool was 80 mg per L as $CaCO_3$. The Spa had a programmable heater with the ability to regulate temperature, and the temperature was set to 85 degrees Fahrenheit.

Glassware that was used during experiment included eleven 500 mL bottles (Wheaton) and a 1000 mL Erlenmeyer flask. These were washed prior to each experiment using a Lancer 1400 LX washer. The cycle used included a prewash with detergent, wash with detergent, rinse with purified water, drying and cooling.

3.3.5 Experimental Procedures

To start the experiment the RMF was regenerated with the regeneration procedure required for the experiment. A summary of regeneration procedure and the experiments can be seen in Appendix A. After the media regeneration procedure was complete, the computer program timed when the filter began filtration. This value was used to calculate the filter run time or time since the most recent regeneration. Filter run time changed between experiments, and a summary of experiments and filter run times can be seen in Appendix A as well.

When the filter run time required for the experiment was reached, a 500 mL sample was taken from the influent and effluent sample lines. These carryover samples were used to measure any microspheres that were remaining in the spa or filter from the prior experiments and hence any potential accumulation of spheres over multiple experiments. The seeding peristaltic pump was primed with the microsphere seeding solution that was being continuously stirred. The peristaltic pump was turned on, the seeding valve to the filter was opened, and a timer was started. Samples were taken at 3 times and in triplicate. The Influent samples were collected in 15 mL conical bottom centrifuge tubes (Corning, CentriStar) and the effluent were collected in 500 mL glass bottles (Wheaton). Influent and effluent samples were staggered by one minute with influent first so that the water sampled in the influent had time to travel through the filter and out the effluent. After the last sample was taken at nine minutes, the experiment was concluded. Sample times relative to the seeding being started can be seen in Table 3.1 below.

Table 3.3: Sample collection times in minutes

Influent	Effluent
2	3
5	6
8	9

In the case that another microsphere seeding was to be done after a longer filtration time in the same conditions, the filter would be left running until the next seeding time. When the time came for the next seeding, carryover samples would be taken to ensure that carryover from the 1-hour seeding did not influence results with high background counts or contamination of the sample lines. For 8- or 24-hour experiments, after the carryover samples were taken, a second seeding solution that was prepared the same as the first was started. Samples were taken in the same manner at the same times.

3.3.6 Clogging Experiments

Clogging experiments were performed in two ways. The first method of clogging used was test dust (Wateropolis INC, Pool Test Dust), the second method of clogging was a valve installed on the filter effluent that simulated clogging by increasing the pressure on the media inside the filter without adding particles. Both methods of clogging were tested to determine what the effects the changes in pressure would have on the RMF removal efficiency. Three levels of contamination were tested by using 72, 1100, and 2200 grams of test dust. The 72 grams of dust experiment represented realistic conditions of a daily bather load. The clogging recorded with 2200 grams of dust was approximately equal to 1 month of pressure change experienced by the filter in real world conditions. This ratio of dust to change in pressure was used to calculate the loading that would be added to the filter per day, 72 grams. The 72 grams of dust was used in two experiments and added over an 8- or 2-hour period. The 1100 and 2200 grams of dust experiments tested the effects of the filter removals in more extreme conditions, and the dust was added over shorter times. In the extreme condition experiments, the dust was added in less than an hour. In all the dust experiments, the dust was added to water to create a slurry, the slurry was continuously mixed using a mixer (Caframo, Compact Digital). A peristaltic pump (Watson Marlow, 504U) was primed with the slurry and pumped into the filter at the influent pipe before the filter pump.

3.3.6.1 Extreme Conditions Dust Experiments

The seeding experiments using 1100 and 2200 grams of test dust were performed with all the same preparation as the previously described lab-scale experiments. After the RMF was regenerated, the peristaltic pump was used to pump the slurry into the filter at a flowrate of 1800 mL per minute. The purpose of the experiment was to clog the filter using dust an additional 4 PSI. The initial pressure measured at the influent of the filter was 5.0 PSI. Because the amount of dust required was initially unknown, the dust was added in steps until the target pressure was reached. The first slurry was 700 grams of dust in 10 L of water. The filter influent pressure reached equilibrium in 10 minutes at 6.5 PSI. The next slurry of dust prepared was 200 grams of dust in 2 L of pool water. After the pressure stabilized, the influent pressure was 7.4 PSI. Another slurry was fed into the filter with 200 grams of dust and 2 L of pool water. After the pressure reached equilibrium, the pressure was 8.4 PSI. After the pressure of 8.4 PSI was reached in the filter, the valve used to feed the slurry was closed before air was pumped into the filter. One hour after the dust was added, the peristaltic pump for the microsphere seeding suspension was started. Samples were taken in the same way as previously described. After the samples were collected, the RMF was regenerated again, this time with 1100 grams of dust mixed with the perlite media. One hour after the dust was added, the peristaltic pump for the microsphere seeding suspension was started and samples were collected.

The experiment using 2200 grams of dust was performed 6 days after the 1100 gram experiment. The filter and swim spa were not drained, and the filter was left running continuously and set to regenerate the media automatically every 24-hours. With the 1100 grams of dust mixed in the filter media, another 1100 grams of dust was added to the filter. The 1100 grams of dust was added to 14 L of water and fed into the filter at the same rate. With a flowrate of 1800 mL per minute, the time to add the dust was approximately 8 minutes. The total amount of dust in the filter was now 2200 grams. One hour after the dust was added to the filter, a microsphere seeding experiment was started and sampled. After the first seeding, the filter was regenerated, and a seconding seeding was started and sampled.

A third experiment was conducted later in which the dust was fed slower than in the previous two experiments. This experiment fed the dust continuously over 45 minutes and used a flow rate of 420 mL per minute. This was so 19 L of dust slurry could be added to the filter over the 45 minutes. Fifteen minutes after the dust was added to the filter, the microsphere seeding pump was started, and samples were collected. The procedure allowed for the filter to be evaluated exactly 1-hour after the most recent media regeneration. After the samples were collected, the filter was regenerated with the 1100 grams of dust still inside. After 1-hour, another microsphere seeding was started, and samples were collected.

3.3.6.2 Realistic Conditions Dust Experiments

The realistic condition experiments used 72 grams of test dust that was added to the filter over 2- or 8-hour time periods. The standard experimental preparation procedure was followed to clean the filter and swim spa prior to each experiment.

After the RMF was regenerated, the peristaltic pump began pumping a 19 L slurry into the filter. The rate of the peristaltic pump was set to add the slurry over a 2-hour time. After the slurry was added to the filter, the seeding solution was started, and samples were taken in the same manner as previously described. The 8-hour experiment was performed in the same way as the 2-hour experiment except for the rate that the slurry was added.

3.3.6.3 Manual Valve

A manual valve was installed onto the filters effluent pipe. The filter and spa were drained and refilled following the cleaning procedure. After the filter was regenerated, the influent and effluent pressures were given 5 minutes to stabilize. After the pressure was stabilized, the effluent valve was closed until the pressures increased by 4 PSI. One hour after the media had been regenerated, the seeding suspension was fed into the filter, and samples were collected.

3.3.7 Regeneration Experiment

The media regeneration experiment was used to determine the potential impact of precoat duration on pathogens returning to the pool from the filter. The precoat phase of media regeneration is when media is returned to the outside of the filter elements (or flex tubes). For this experiment, 7.5 lbs. of 900-grade media per 100 square feet was used in the filter. These experiments were both performed after 2.0×10^8 spheres had been added to the filter. The concentration of microspheres based on the filter volume (of approximately 140 gallons) was calculated to be 390 spheres per mL. The influent and effluent were not sampled for this experiment because there was no flow between the swim spa and the filter. The filter was recirculating, so only one sample at each time was taken. This experiment measured the concentration of microspheres instead of the removal of the filter. The filter was set to use a modified media regeneration program. The media regeneration was started, and the media was moved to the inside of the filter elements. This stage of the regeneration process lasted for 3 minutes. The modification to the regeneration cycle was the next phase. The direction of flow switched, and the media began to return to the outside of the filter elements. In other experiments this precoat phase lasted for 10-12 minutes depending on the number of phases. In this experiment the precoat phase was set to last 30 minutes. The precoat was single phase, and the flow rate was 140 GPM.

Samples were taken from a sample port located at the top of the filter. Samples were taken throughout the 30 minutes of the experiment. The experiment was performed twice using the same procedure. The times that samples were taken for each experiment can be seen in Table 3.2 below. In the table, the first time the experiment is performed is shown as A, and the second is shown as B.

Table 3.4: Regeneration experiment sample times in minutes

A (min.)	1	2	4	5	7	9	11	13	15	17	19	23	-	27	29
B (min.)	-	-	4	5	7	9	11	13	15	17	19	-	25	-	-

The two samples that were collected prior to 4 minutes in experiment-A contained a large amount of media. This media was captured during sample processing. The media was mixed with the microspheres that were being counted so the spheres could not be seen to be counted. These samples were removed from the results due to not being able to accurately count them.

3.4 Full-Scale

The full-scale experiments were conducted at the UNC Charlotte campus pool that was equipped with a regenerative media filter. The pool was approximately 130,000 gallons. While the swimming pool was open for use, there were no bathers during the experiment. The filter used was an automatic regenerative media filter model (Defender, SP-41-1038). The filter had a filter surface area of 812 square feet. The media was changed in the filter before the experiment following manufacture instructions. The media added to the filter was 900-grade Harborlite perlite media, the same used in lab-scale experiments. The filter operated at 1,080 GPM during the experiment.

The seeding solution used in the full-scale experiment was made the same way using the same equipment and materials as the lab-scale experiment. The calculations for the lab-scale experiment were adjusted for the seeding solution dilution. The seeding solution had to account for the higher flowrate of the full-scale experiments. To make the dilution, 1,100 mL of microspheres were added to 10 L of DI water. The seeding solution was mixed in a 10 L polyethylene container (Cubitainer). The seeding solution was added to the RMF using the same peristaltic pump used in the lab-scale experiments. The seeding pump pumped the seeding solution in at 700 mL per minute.

Samples were taken in the same way as the lab-scale experiment. Influent and effluent samples were taken with a 1-mintue delay. The same sample times were used with the effluent samples taken at 3-, 6-, and 9-minutes. The same sample containers were used for the effluent samples as the lab-scale experiment. Influent samples were taken in 50 mL sample containers (Corning, CentriStar).

The method of regenerating the filter was different for the full-scale and lab-scale filters. The lab-scale filter used hydraulics to remove the media from filter elements. The full-scale filter used a pneumatic bumping system the raised the elements and then dropped them to remove the media. After the media was removed from the filter elements, the precoat stage of the media regeneration started. During precoat the media was added back to the filter elements. The precoat stage lasted 10-minutes, and then the filter returned to filtration mode.

An important distinction between most lab-scale experiments is that the precoat stage only added media at one flow rate. Typical lab-scale experiment regeneration sequence was multi-staged. For this reason, an experiment was done using the lab-scale filter using single stage media regeneration. The comparison of the full-scale filter to the single-stage media regeneration is a more accurate comparison.

Two experiments were done using the full-scale RMF, an experiment at 1-hour and another at 24-hours after media regeneration. After the media was changed in the RMF, the media was regenerated. One hour after the media was regenerated, the seeding suspension was pumped into the filter and samples were collected. The 24-hour experiment was conducted in the same way 24-hours after the media regeneration.

3.5 Sample Processing

When processing samples, all samples were shaken for at least 30 seconds by hand, and the 15- or 50-mL centrifuge containers were mixed with a vortex mixer (Fisher Scientific) for 30-seconds as well. After being mixed, in cases when the 500 mL bottles were overfilled, the sample water was removed to the 500 mL mark. In the cases when the 15 mL samples had slightly more or less than 10 mL, the variance was adjusted for in the calculation of the concentration. Influent samples were processed last because of their high concentration of spheres. Spillage contaminating the workspace or carryover from equipment could have otherwise impacted the results.

All equipment used for processing samples was cleaned using DI water, including 3 sets of tweezers (Millipore), 3 glass 15 mL microanalysis filter funnels (EMD Millipore), and 3 funnel spring clamps (Millipore). The regulated 3-place vacuum manifold was rinsed with DI water as well. The filters used were 3-µm polycarbonate track etched (PCTE) (Isopore, 25mm), and these filters were placed on each of the three filter locations of the manifold with one of the tweezers designated to that sample. Each of the funnels were placed and clamped on to the filters. The first samples filtered were the carryover samples and then the effluent samples. The manifold had a constant suction while each of the three sample places had a valve to control the suction. As the sample was being poured the sample place valve was opened to pull the sample through the filter. The clamp and the filter funnel were removed from the sample place. The filter was then removed from the manifold using the tweezers designated to that sample place. The filter was transferred to a sample slide (Corning 2948-75x25) by being slid (and not picked up vertically). A drop of polyvinyl alcohol-DABCO (PVA-DABCO) (Freer 1984) was placed in the center of the filter. A cover slip (Corning, 25mm square) was placed squarely over the center of the filter, the cover was not pressed down but rather allowed to settle by gravity. The slide was then placed horizonal in a sample box to dry. This procedure was repeated for the two other samples. After the remaining two samples were processed, the tweezers, funnels, and clamps were all rinsed using DI water. The manifold was rinsed with DI water with suction on. The remaining samples were all processed in the same way.

Blank slides were made for each experiment. The blanks were made the same way as other samples except DI water was used. A blank was made after the fifth effluent sample was processed, after the last effluent sample was processed, and after the fifth influent sample was processed. These blank sample's purpose was to determine how many spheres were present on the sample slide due to the sample processing procedure.

The sample slides were analyzed under an epi-fluorescent microscope (Zeiss, Axioskop) at 100X total magnification. The fluorescent filter set has a 450-490 nm excitation wavelength range, a 510 nm dichroic filter, and a 520 nm emission filter. As each sample slide was analyzed, the number of spheres was recorded using a counter.

3.6 Calculation and Statistics

3.6.1 Calculation

The recorded number of microspheres was divided by the volume of sample that passed through the filter; this value was the concentration of microsphere in each sample. The influent and effluent concentration of the three samples at each sample time were averaged. The percentage removal at each time was calculated using the average influent and effluent sample concentration using the equation below.

$$R = \frac{I-E}{I} \times 100\% \tag{3.4}$$

Where: R= Percent removal
I=Influent sphere concentration
E= Effluent sphere concentration.

The standard deviation for each experiment was calculated using Microsoft Excels sample standard deviation function. An overall experiment average and standard deviation was calculated based on the three removals at each time.

3.6.2 Statistics

All statistics were calculated using Minitab on the three calculated removal values for each experiment. In the case that experiments were duplicated, the percent removals from those experiments were combined to make a group of 6 values. Each group of values was tested using a Ryan-Joiner normality test to determine if that group was normally distributed. After the data groups were determined to be normally distributed, two-sample, two-tailed, heteroscedastic t-test were performed to determine if experiments resulted in a statistically significant difference. The t-test was set up to determine differences in experiments with 95% confidence.

3.6.3 Figures

Figures were made using Origin 2022b (OriginLab, Northampton, MA). The removal efficiency of the RMF filter in each condition was graphed with a probability y-axis scale, linear x-axis scale, and error bars displaying the standard deviation of removals of the experiment. The y-axis was the overall calculated removal for the experiment and the x-axis was the date of the experiment. Most figures were made to show the differences between the modified condition and a standard condition experiment. Gage and Bidwell's "Law of Dilution" that found that only 63% of the water returned to the filter for treatment in a single turnover due to mixing (Gage et al. 1926). If the filter is 100% efficient at removing contaminants (as was assumed by Gage & Bidwell), then only 63% of the contaminants (e.g., *Cryptosporidium*) could be removed in a single turnover. As the filter efficiency is reduced to reflect real-world filter performance, the overall impact on removal is relatively small when the filter is above the red line at 90% removal (1-log) and green line at 99% (2-log), which have been added to the figures (Alansari 2018). For example, taking 100%, 99%, and 90% out of the 63% of the water filtered results in overall removals of 63%, 62.37%, and 56.7% per turnover, respectively.

CHAPTER 4: RESULTS AND DISCUSSION

The regenerative media filter percent removal of 4.5-micron diameter microspheres was evaluated under standard conditions over 24-hours of operation as shown in Figure 4.1. The following conditions were modified to study their effects on removal: flow distributor length, the amount of media used, media grade, filter loading rate, time after most recent media regeneration, clogging the filter with test dust, as well a comparison to a full-scale pool. A summary of experimental conditions and results can be seen in Appendix A.

4.1 Standard Conditions

The standard conditions experiments (Figure 4.1) show a baseline for comparing other experiments. Experiments evaluated at 1-hour were performed on 9/26/20 and 1/29/20. The average percent removals of these experiments were 99.7% with a standard deviation of .05% and 99.5% with a standard deviation of .05%. Conditions of the baseline experiment can be seen in Table 4.1 below.

Table 4.1 Standard experimental condition

Media grade	900
Loading rate ($\frac{gpm}{ft^2}$)	1.6
Regeneration procedure	4 minutes at 85, 160, and 200 GPM
Media weight ($\frac{lbs.}{100\ ft^2}$)	7.5
Flow distributor	New

The 24-hour baseline experiment was also performed in duplicate. The first was performed on 9/30/20, and the average percent removal was found to be 97.0% with a standard deviation of .75%. The duplicate experiment was performed 9/22/2022, the percent removal was found to be

97.1% with a standard deviation of .19%. The 8-hour baseline experiment was performed in duplicate. The first was performed on 2/4/2021, and the average percent removal was found to be 98.0% with a standard deviation of .08%. The duplicate experiment was performed 3/14/2021, and the average percent removal was found to be 98.6% with a standard deviation of .10%.

A t-test was used to determine that the results at each 8 and 24-hours had a statistically significant difference with 95% confidence (p-value less than 0.01) when compared to the experiment at 1-hour. A t-test was also used to show significant difference with 95% confidence (p-value of 0.01) between the experiment performed at 8 and 24-hours.

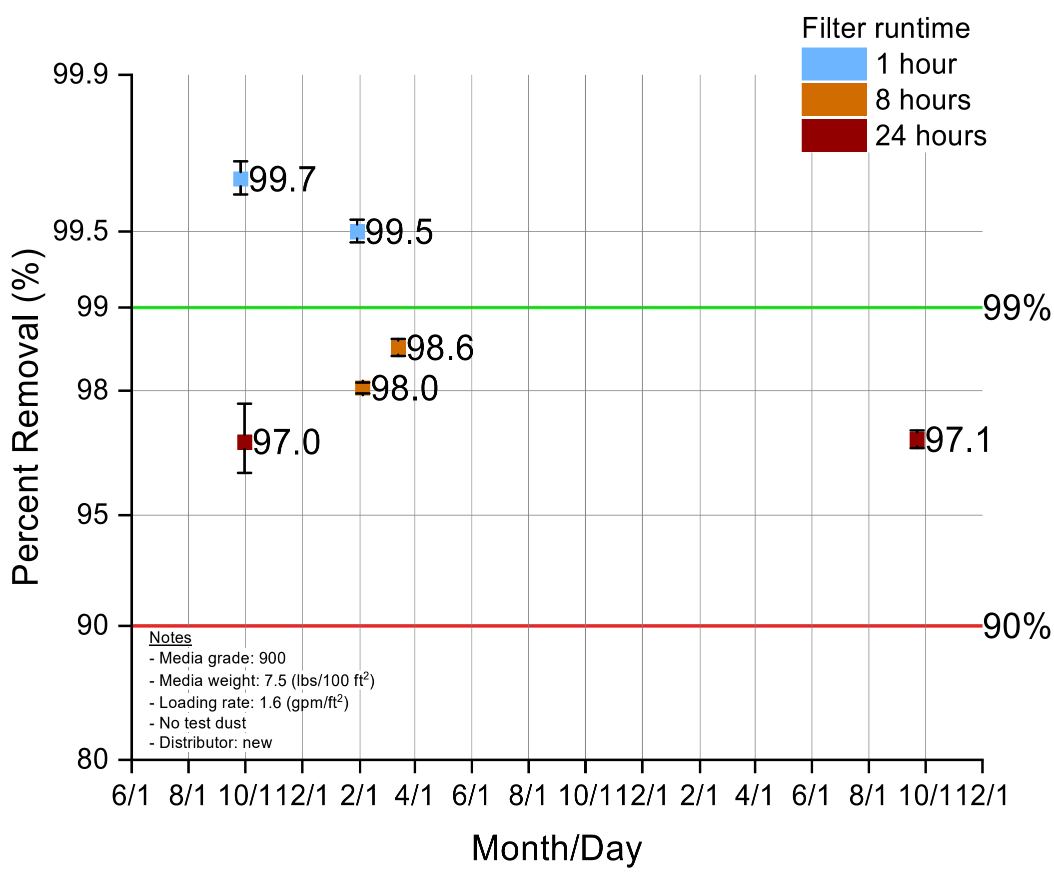

Figure 4.1: Lab-scale filter removal over time in standard conditions

4.2 Flow Distributor

The RMF uses a flow distributor as the water enters the filter to distribute the water throughout the filter body. The flow distributor minimizes turbulence acting on the filter elements. Increased turbulence will remove media from the lower ends of the flex tube filter elements allowing water to pass unfiltered thereby lowering removal efficiency. Two different flow distributors were tested. The initial flow distributor was approximately 15 inches (version 1) while the new distributor was overall similar in design but 3 inches longer (version 2). Several experiments were conducted using the initial version of the flow distributor including a seeding at 1-hour, 24-hours, 2.0 ($\frac{gpm}{ft^2}$) loading rate, and at 1-hour using 700-grade media. These experiments were repeated using the new distributor and are compared in the following section.

The difference in the lab-scale RMF removal efficiency comparing the version 1 and 2 distributors 1-hour after regeneration can be seen below (Figure 4.2). The version 1 distributor achieved a lower removal compared to both experiments using version 2 of the distributor. It should be noted that the old distributor experiment used a different media regeneration procedure than used in the version 2 distributor experiments. The old distributor experiment regeneration procedure was 2-stages, the first 80 GPM for 6 minutes and the second 180 GPM for 10 minutes. A t-test showed a statistically significant difference with 95% confidence (p-value of 0.029) between the experiments using the two versions of distributor at one hour.

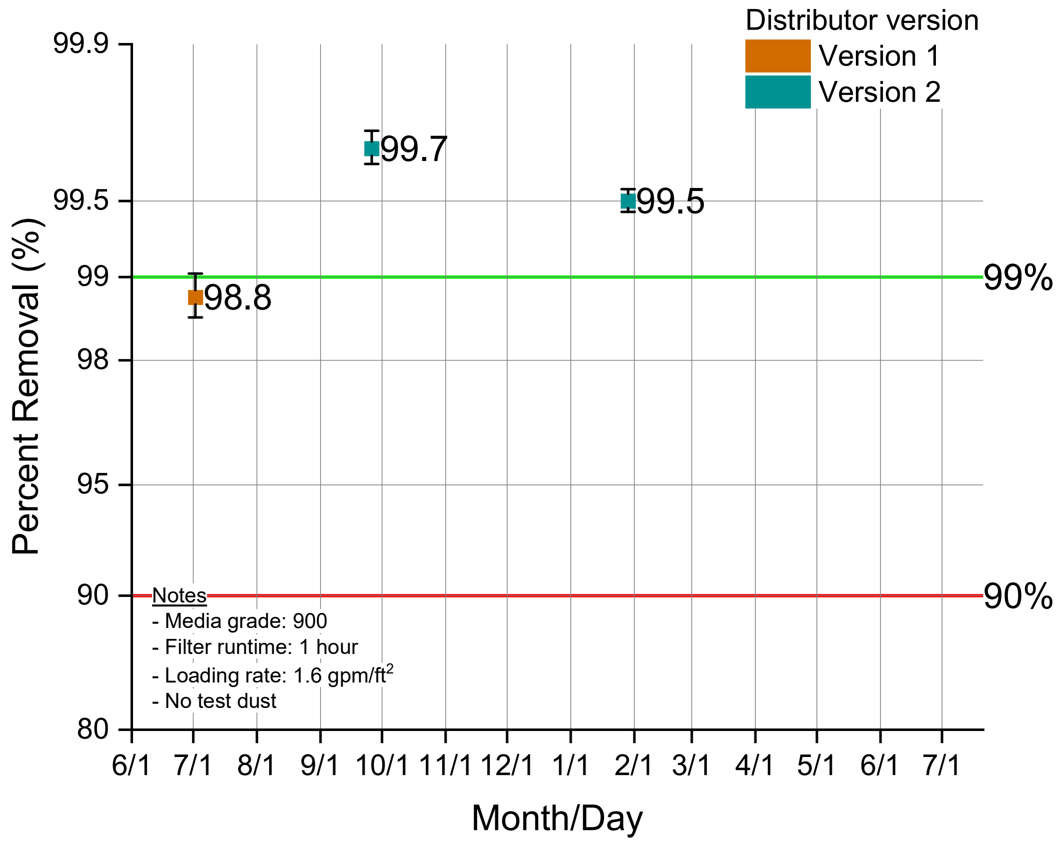

Figure 4.2: Comparison of distributor version 1 and 2 at 1-hour of filtration

The difference measured in removal efficiency of distributor version 1 and 2 at 24-hours after media regeneration are shown below (Figure 4.3). While the same difference in regeneration procedure discussed previously still applies, the version 1 distributor had a higher average removal efficiency than version 2 at 24-hours. The t-test did not show a statistically significant difference with 95% confidence (p-value of .059) between the experiments using versions 1 and 2 of the distributor at 24-hours.

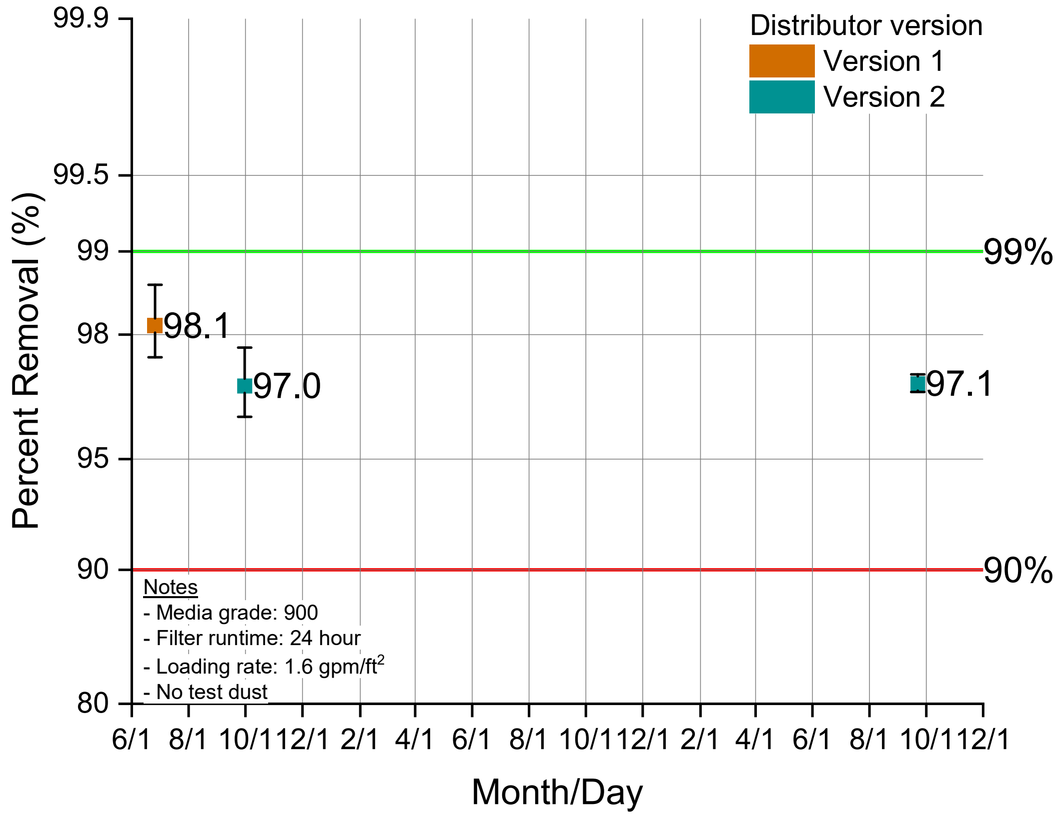

Figure 4.3: Comparison of distributor version 1 and 2 at 24-hours of filtration

The difference in percent removal comparing distributor version 1 and 2 using a loading rate of 2.0 ($\frac{gpm}{ft^2}$) is shown below (Figure 4.4). The regeneration procedure used for both experiments were 3-stages: 4 min at 80 GPM, 4 minutes at 160 GPM, 10 minutes at 200 GPM. A t-test showed a statistically significant difference with 95% confidence (p-value of .005) between the experiments performed one hour after regeneration using the two versions of distributor at 2.0 ($\frac{gpm}{ft^2}$).

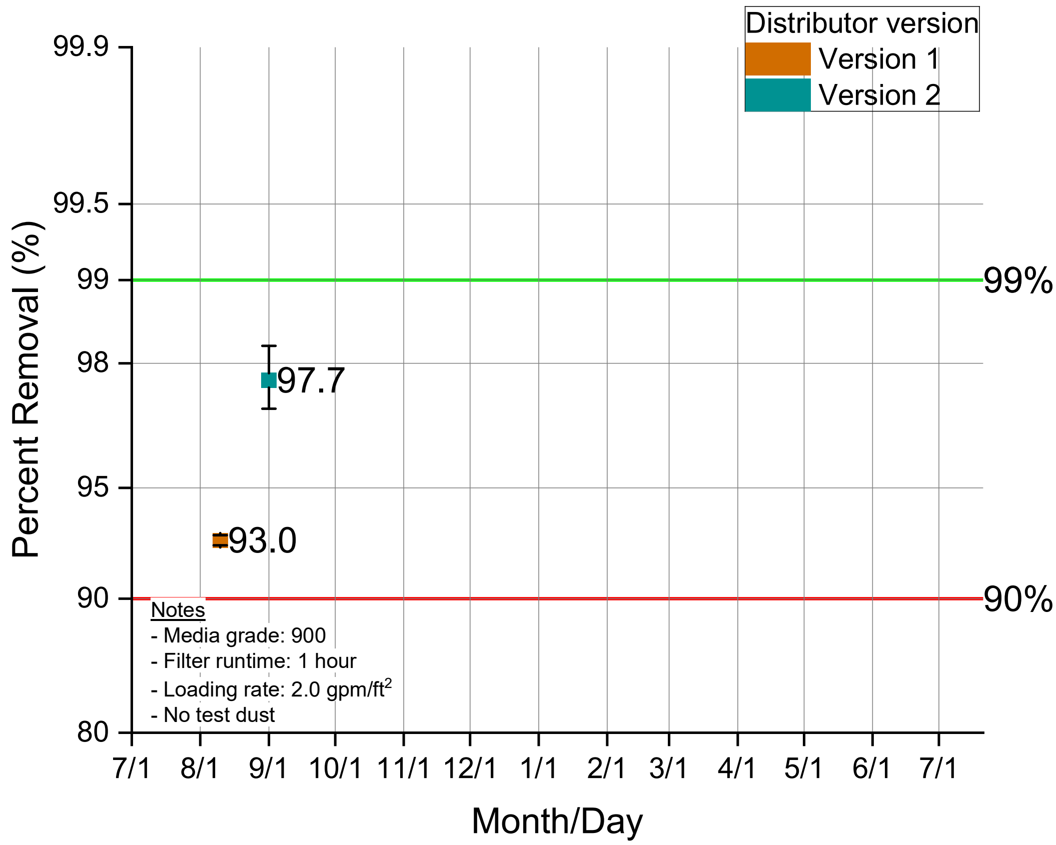

Figure 4.4: Comparison of distributor version 1 and 2 at with a loading rate of 2.0 $\frac{gpm}{ft^2}$

The comparison of percent removal of the filter using distributor version 1 and 2 with 700-grade media is seen below (Figure 4.5). The version 1 experiment regeneration procedure was 2-stages, the first 80 GPM for 6 minutes and the second 180 GPM for 10 minutes. While the version 2 experiment regeneration procedure was 3-stages, 4 minutes each at 80 GPM, 160 GPM, and 200 GPM. The experiment using version 2 and 700-grade media was slightly higher than version 1. The t-test did not show a statistically significant difference with 95% confidence (p-value of .061) between the experiments using the two versions of distributor and 700-grade media at 1-hour.

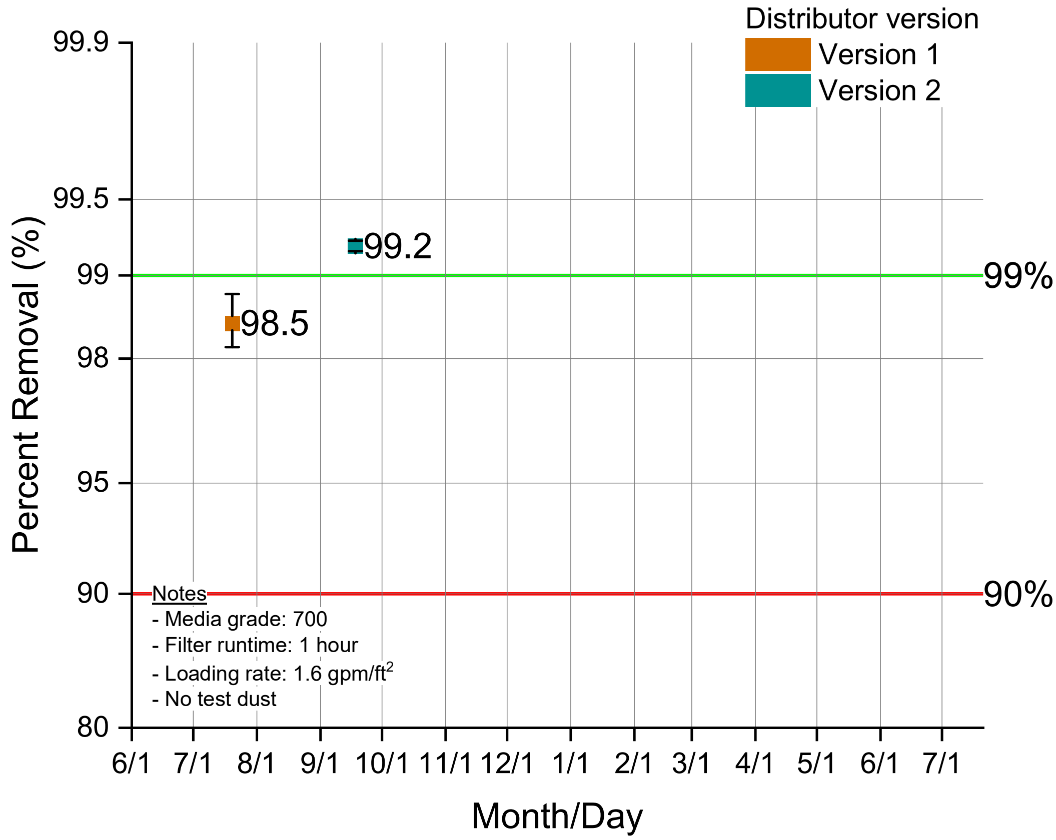

Figure 4.5: Comparison of distributor version 1 and 2 with 700-grade media

4.3 Media Weight

Media weight refers to the weight of the media added to the RMF. The 18-inch RMF filter surface area is approximately 100 square feet with media added. The amount of media used during each experiment are reported in US industry-standard units of pounds per 100 square foot $(\frac{lbs.}{100ft^2})$.

Experiments evaluating media weight used a loading rate of 1.6 gallons per min per square feet $(\frac{gpm}{ft^2})$. Media regeneration was evaluated using $7.5\frac{lbs.}{100ft^2}$ and $11.25\ \frac{lbs.}{100ft^2}$ at 1 and 24-hours after regeneration. Table 4.2 below summarizes the conditions of experiments testing media weight that were the same.

Table 4.2: Media weight experiment conditions

Media grade	900
Loading rate ($\frac{gpm}{ft^2}$)	1.6
Regeneration procedure	4 minutes at 85, 160, & 200 GPM
Flow distributor	New

The difference in percent removal of microspheres by the RMF with 7.5 $\frac{lbs.}{100\ ft^2}$ compared to 11.25 $\frac{lbs.}{100\ ft^2}$ are shown below (Figure 4.6). The two experiments using different media weights were performed in duplicate. When comparing the four experiments, the experiments using 11.25 $\frac{lbs.}{100\ ft^2}$ of media are only slightly better or equal to the percent removal of the experiments using 7.5$\frac{lbs.}{100\ ft^2}$. While the differences in removal were small, the 11.25 $\frac{lbs.}{100\ ft^2}$ required 50% more media than the 7.5$\frac{lbs.}{100\ ft^2}$. The data from duplicate experiments were combined for statistical analysis. A t-test showed a statistically significant difference with 95% confidence (p-value of .021) between the experiments using 7.5 and 11.25 $\frac{lbs.}{100\ ft^2}$ at 1-hour of filtration.

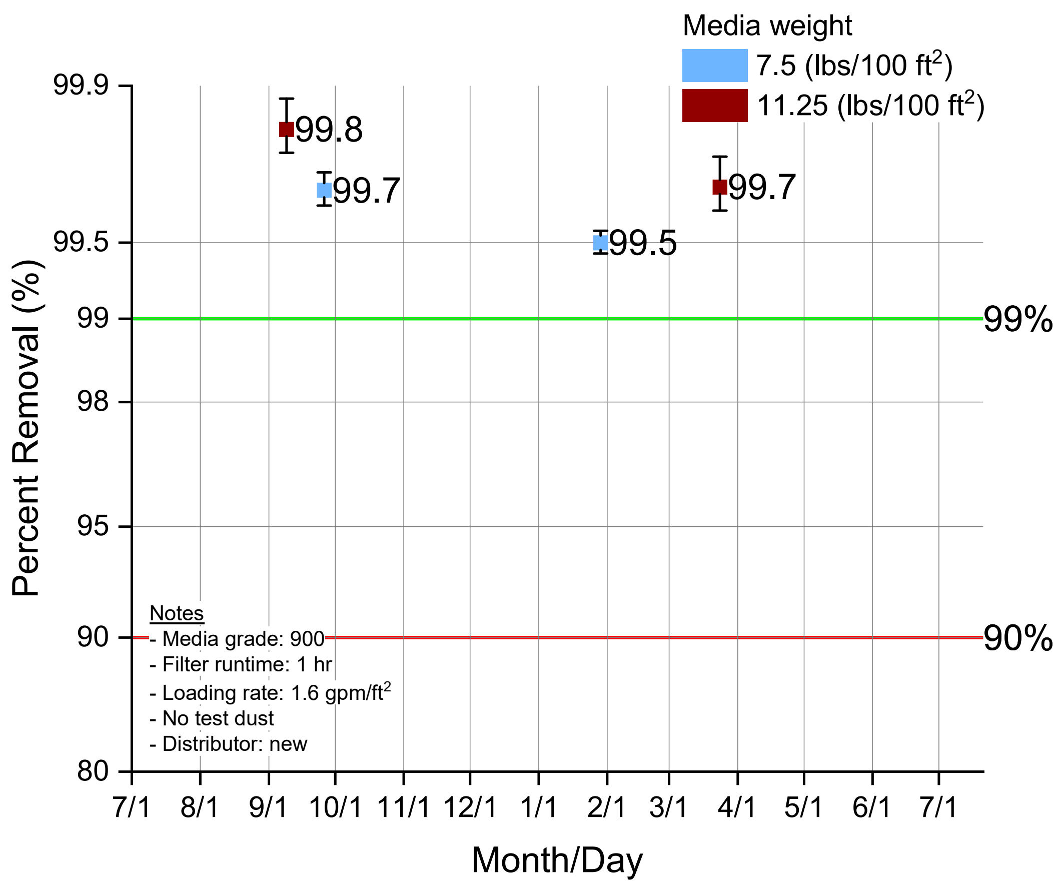

Figure 4.6: Filter removal with 7.5 vs. 11.25 $\frac{lbs.}{100\ ft^2}$ of media at 1-hour after regeneration

The difference in percent removal by the RMF comparing 7.5 $\frac{lbs.}{100\ ft^2}$ to 11.25 $\frac{lbs.}{100\ ft^2}$ 24-hours after regeneration of the filter media are shown below (Figure 4.7). The Removal efficiency of the 11.25 $\frac{lbs.}{100\ ft^2}$ experiments was consistently higher than the 7.5 $\frac{lbs.}{100\ ft^2}$ experiments 24-hours after media regeneration. A t-test showed a statistically significant difference with 95% confidence (p-value: .001) between the experiments using 7.5 and 11.25 $\frac{lbs.}{100\ ft^2}$ at 24-hours of filtration.

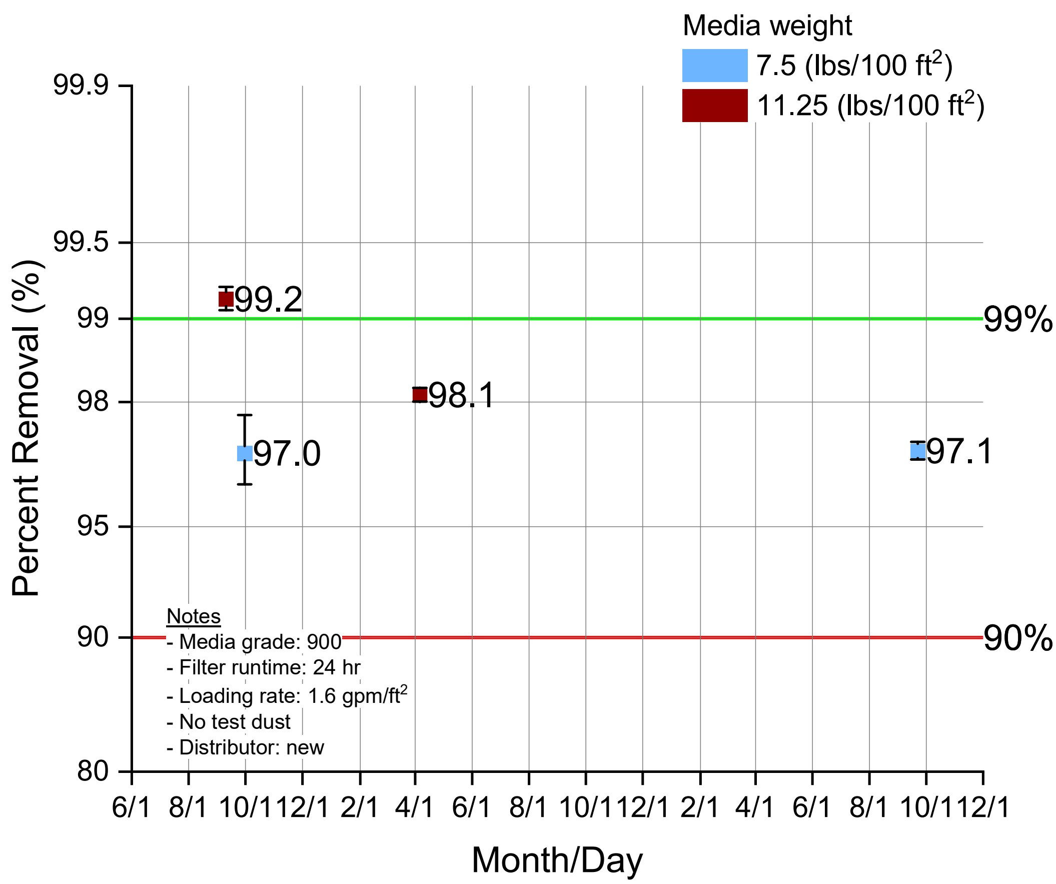

Figure 4.7: Filter removal with 7.5 vs. 11.25 $\frac{lbs.}{100\ ft^2}$ of media after 24-hours after regeneration

4.4 Media Grade

The Media used in all experiments was Harborlite perlite, three different grades of perlite were tested to find any effect on the filter's removal efficiency. Media grades of 635, 700, and 900 were all tested. The Media grades ranged from finer to coarser with 635-grade being mostly made up of smaller particles and the 900-grade being mostly made up of larger particles. A Particle size distribution curve was generated for each of the media grades and can be seen in Appendix B. Table 4.3 below shows the media grades and their median particle size.

Table 4.3: Media particle size analysis

Media Grade	Median (micron)
635	44.0
700	46.9
900	58.4

Experiments testing the three media grades were performed the same with the media grade being the only variable changed between experiments. Table 4.4 below describes the experimental conditions for testing media grades that were the same.

Table 4.4: Media grade experiment conditions

Filter time after regeneration (hour)	1
Loading rate ($\frac{gpm}{ft^2}$)	1.6
Regeneration procedure	4 minutes at 85, 160, & 200 GPM
Media weight ($\frac{lbs.}{100\ ft^2}$)	7.5
Flow distributor	New

Changes in the RMF removal efficiency of 4.5- micron microspheres using Harborlite 635-grade perlite and 900-grade perlite were compared (Figure 4.8). The finer 635-grade of media was found to be less effective at removal than the courser 900-grade media. The 635-grade experiment was not performed in duplicate. A t-test showed a statistically significant difference with 95% confidence (p-value of .001) between the experiments using 635 and 900-grade media at 1-hour of filtration.

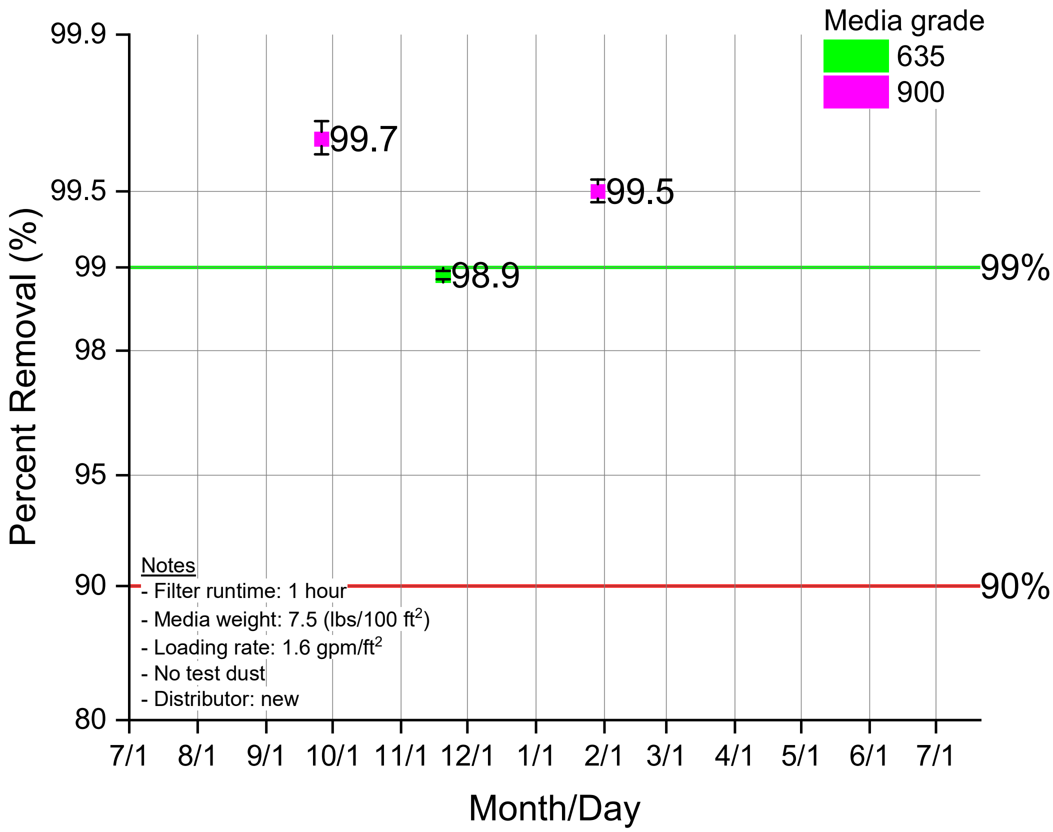

Figure 4.8: Percent removal comparison of 635- and 900-grade media

The changes in the percent removal when using 700- compared to 900-grade media are shown below (Figure 4.9). The experiment using 700-grade media was not performed in duplicate. The percent removal was found to be 99.2%, which was slightly lower than experiments using 900-grade media. The results from the 700-grade media experiment were consistent with what was found with the 635-grade media experiment: as the particles become finer the percent removal decreases. A t-test showed a statistically significant difference with 95% confidence (p-value of .001) between the experiments using 700- and 900-grade media at 1-hour of filtration.

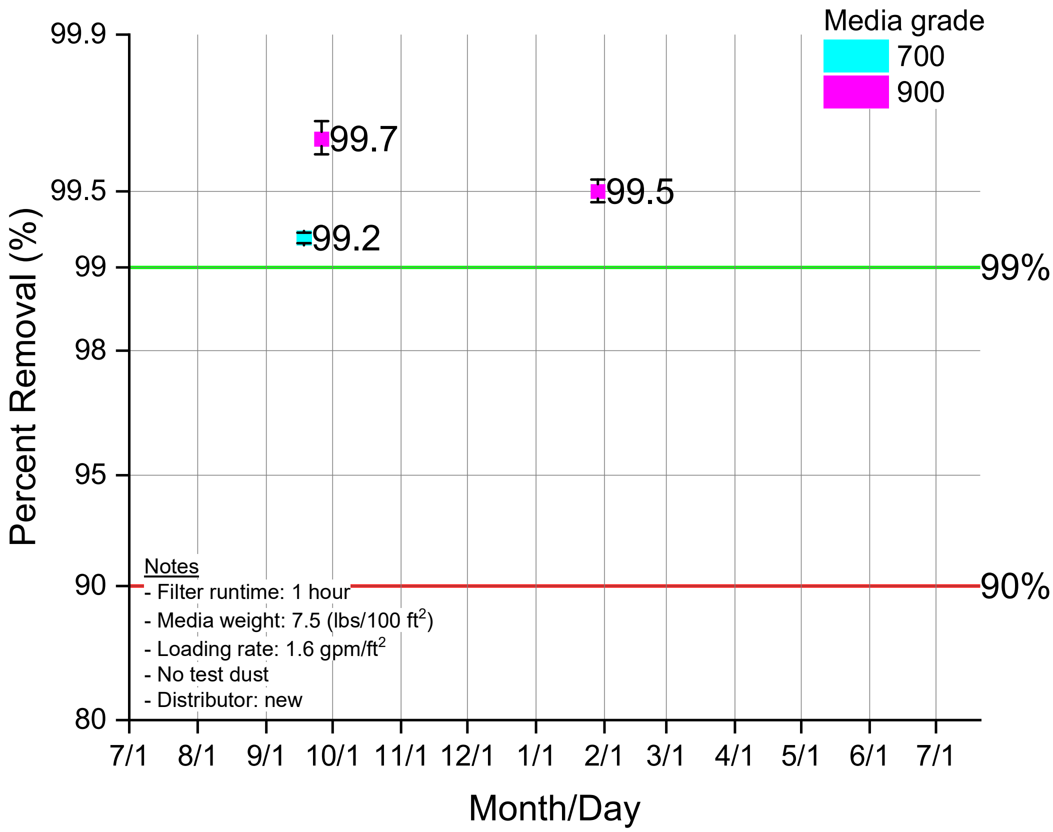

Figure 4.9: Comparison of 700- and 900-grade media

4.5 Flow Rate

The regenerative media filter was tested at three filtration rates. The filtration rates tested were 1.4 $\frac{gpm}{ft^2}$, 1.6 $\frac{gpm}{ft^2}$, and 2.0 $\frac{gpm}{ft^2}$. Experiments using the filtration rate of 1.4 $\frac{gpm}{ft^2}$ had a regeneration procedure that was slightly different from the other experiments. The differences in the regeneration procedure as well as the experimental conditions that were the same are shown in Table 4.5 below.

Table 4.5: Flow rate experiment conditions.

Media grade	900
Regeneration procedure	4 minutes at 85, 160, & 200 GPM (1.6 and 2.0 $\frac{gpm}{ft^2}$) 4 minutes at 85 GPM, 8 minutes at 160 GPM (1.4 $\frac{gpm}{ft^2}$)
Media weight ($\frac{lbs.}{100\ ft^2}$)	7.5
Flow distributor	New

The higher rate of filtration could impact the coverage of the flex tubes by the media. At higher flows, the filter elements are more likely to collide with one another within the filter due to the increased turbulence, and the increased collisions could remove the media from the elements leaving uncovered portions. The bottom of the filter elements that are freely hanging within the filter is where most of the bare places in the media were observed during experiments. Figures 4.10 and 4.11 below show the bottom of the filter elements during a 1.6 $\frac{gpm}{ft^2}$ experiment and a 2.0 $\frac{gpm}{ft^2}$ experiment after 1-hour of filtration.

Figure 4.10: Filter elements after 1-hour of filtration at 1.6 $\frac{gpm}{ft^2}$

Figure 4.11: Filter elements after 1-hour of filtration at 2.0 $\frac{gpm}{ft^2}$

Comparison of the RMF removal when filtering at 2.0 $\frac{gpm}{ft^2}$ and 1.6 $\frac{gpm}{ft^2}$ 1-hour after media regeneration is shown below (Figure 4.12). All conditions of the experiments were identical except for the filtration rate. While the 1.6 $\frac{gpm}{ft^2}$ experiment was performed in duplicate, the 2.0 $\frac{gpm}{ft^2}$ was only performed once. The 2.0 $\frac{gpm}{ft^2}$ resulted in lower removal efficiency compared to the 1.6 $\frac{gpm}{ft^2}$. A t-test showed a statistically significant difference with 95% confidence (p-value of .028) between the experiments using 1.6 $\frac{gpm}{ft^2}$ and 2.0 $\frac{gpm}{ft^2}$ at 1-hour of filtration.

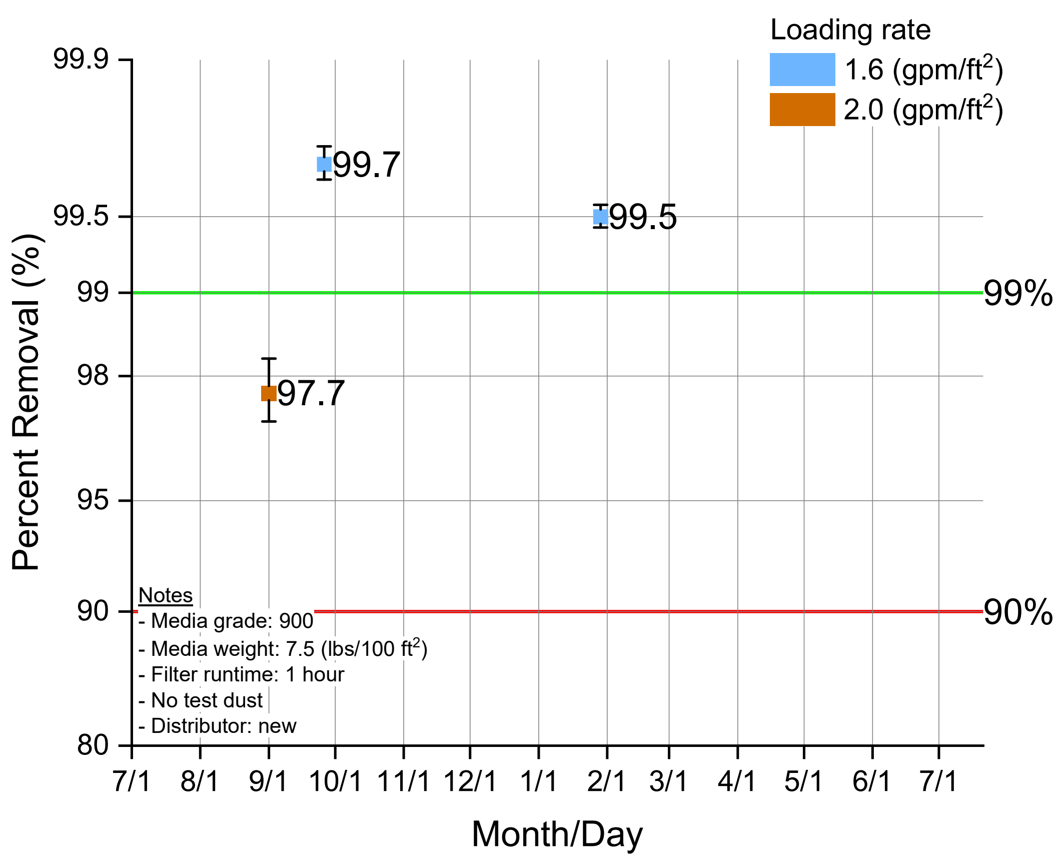

Figure 4.12: Comparison of 1.6 $\frac{gpm}{ft^2}$ and 2.0 $\frac{gpm}{ft^2}$ loading rates at 1-hour of filtration

Comparison of percent removals were made with filtration rates of 1.6 $\frac{gpm}{ft^2}$ and 2.0 $\frac{gpm}{ft^2}$ at 24-hours after the most recent media regeneration (Figure 4.13). There was no other difference in the two experiments apart from the filtration rate. The trend that was seen after 1-hour of filtration continued at 24-hours, and the RMF removal of *Cryptosporidium*-sized microspheres decreased when filtered at 2.0 $\frac{gpm}{ft^2}$ compared to 1.6 $\frac{gpm}{ft^2}$. A t-test showed a statistically significant difference with 95% confidence (p-value of .025) between the experiments using 1.6 $\frac{gpm}{ft^2}$ and 2.0 $\frac{gpm}{ft^2}$ at 24-hours of filtration.

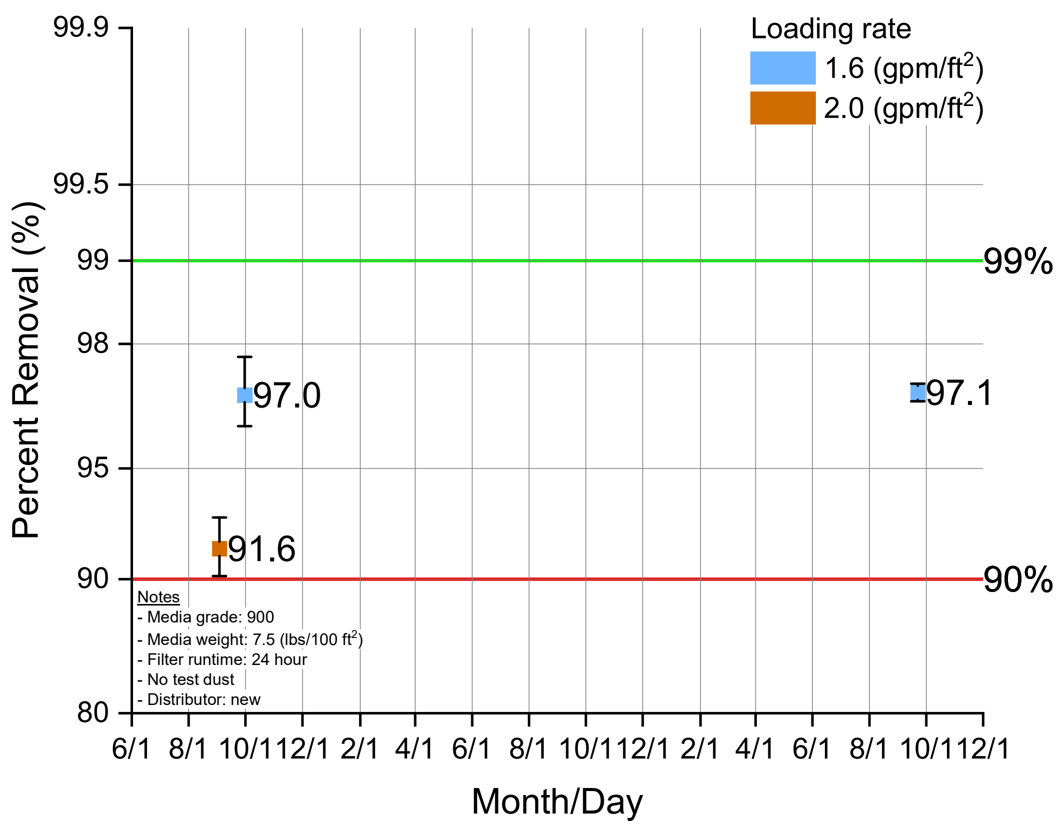

Figure 4.13: Comparison of 1.6 $\frac{gpm}{ft^2}$ and 2.0 $\frac{gpm}{ft^2}$ loading rates at 24-hours of filtration

The RMF removal with a loading rate of 1.4 $\frac{gpm}{ft^2}$ and 2-stage regeneration to 1.6 $\frac{gpm}{ft^2}$ and 3-stage regeneration after one hour of filtration were compared (Figure 4.14). Regeneration procedures used are described in Table 4.5. A t-test showed a statistically significant difference with 95% confidence (p-value of .026) between the experiments using 1.6 $\frac{gpm}{ft^2}$ and 1.4 $\frac{gpm}{ft^2}$ at 1-hour of filtration. Because two parameters are different between experiments, statistical difference should not be attributed to either individual change without further evidence.

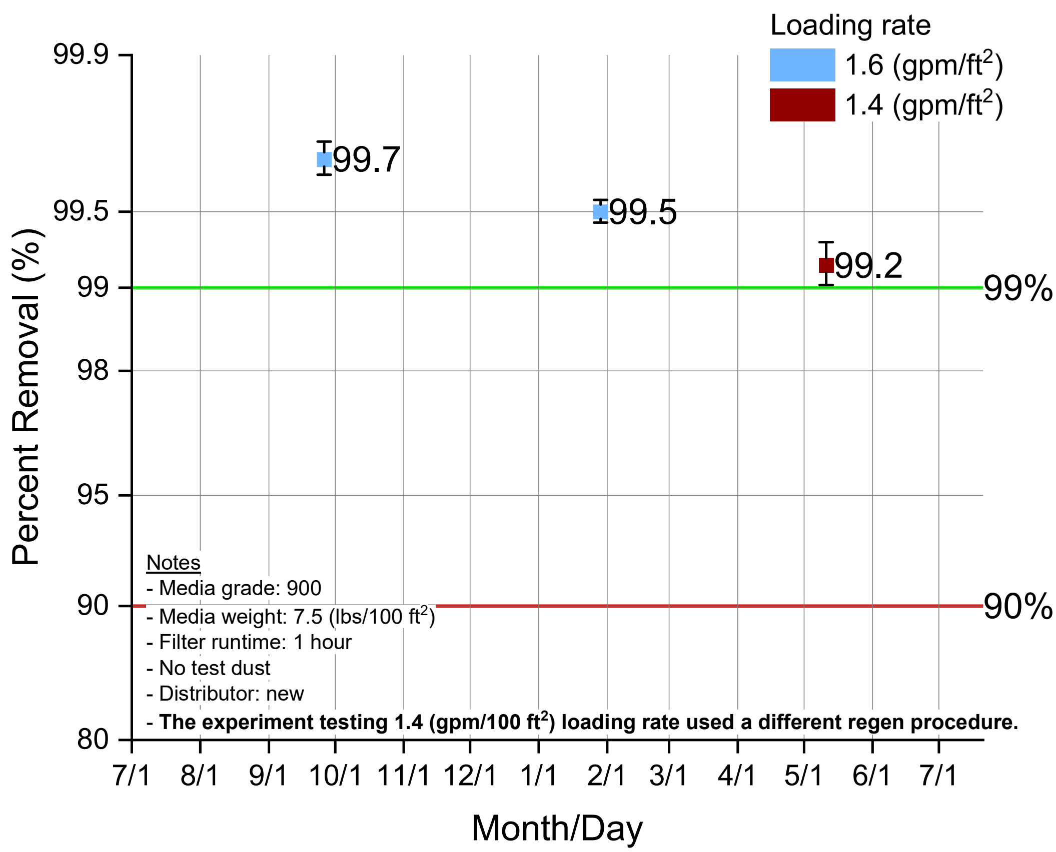

Figure 4.14: Comparison of 1.4 $\frac{gpm}{ft^2}$, 2-stage regeneration to 1.6 $\frac{gpm}{ft^2}$, 3-stage regeneration at 1-hour of filtration

Below, 1.4 $\frac{gpm}{ft^2}$, 2-stage regeneration is compared to 1.6 $\frac{gpm}{ft^2}$, 3-stage regeneration after 24-hours of filtration (Figure 4.15). After 24-hours of filtration the 1.4 $\frac{gpm}{ft^2}$, 2-stage regeneration experiment achieved better filtration than the 1.6 $\frac{gpm}{ft^2}$, 3-stage. This is different from the evaluation at 1-hour of filtration where using 1.6 $\frac{gpm}{ft^2}$ flow rate had a better removal when compared to 1.4 $\frac{gpm}{ft^2}$. A t-test showed a statistically significant difference with 95% confidence (p-value of .001) between the experiments using 1.6 $\frac{gpm}{ft^2}$ and 1.4 $\frac{gpm}{ft^2}$ at 24-hours of filtration. Because two parameters are different between experiments, statistical difference should not be attributed to either individual change without further evidence.

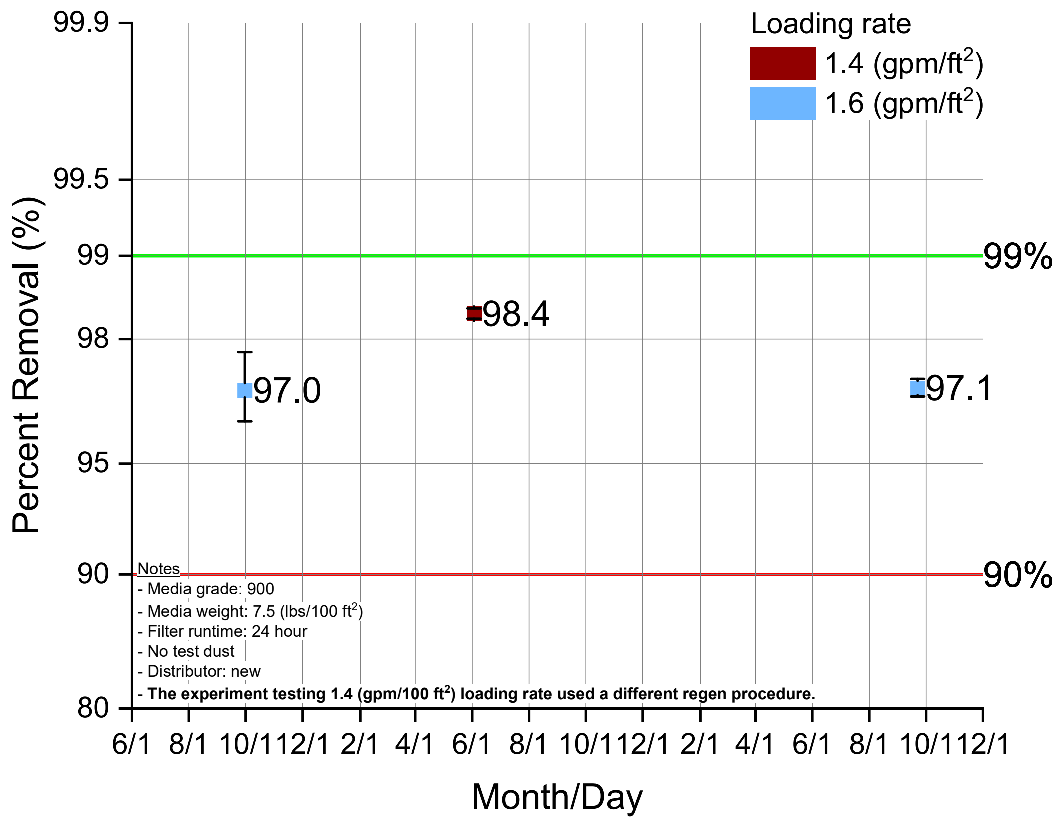

Figure 4.15: Comparison of 1.4 $\frac{gpm}{ft^2}$, 2-stage regeneration to 1.6 $\frac{gpm}{ft^2}$, 3-stage regeneration with 24-hours of filtration

4.6 Clogging Experiments

Test dust was fed in to the RMF to determine how the removal of *Cryptosporidium*-sized microspheres would change as the filter clogged. Different amounts of test dust were added to the filter at different rates. Experiments were also conducted to determine whether the effects on the percent removal after the clogged media were retained after the filter was regenerated. An additional experiment was performed to compare how percent removal changed when the pressure on the filter was applied by closing a valve installed on the effluent rather than pressure applied through clogging the media. Table 4.6 below describes all the conditions of these experiments that were kept the same.

Table 4.6: Clogging experimental conditions.

Media grade	900
Loading rate ($\frac{gpm}{ft^2}$)	1.6
Regeneration procedure	4 minutes at 85, 160, & 200 GPM
Media weight ($\frac{lbs.}{100\ ft^2}$)	7.5
Flow distributor	New

The percent removals when 1100 grams of test dust were added to the filter over a time period of 1-hour are shown below (Figure 4.16). The added dust increased the differential filter pressure by 3.4 PSI. For the initial seeding of spheres after adding the test dust, a removal of 92.1% was calculated. This experiment was performed with no regeneration of the media. After the filters media was regenerated, the removal was found to be 99.7%. After the clogged media was regenerated, the removal was found to be approximately equal to the experiments with no test dust added. A t-test showed a statistically significant difference with 95% confidence between the experiments using 1100 grams of dust and no dust at 1-hour of filtration before the media regeneration (p-value less than .004). Another t-test showed no statistically significant difference with 95% confidence between the experiments using 1100 grams of dust and no dust at 1-hour of filtration after media regeneration (p-value of .161).

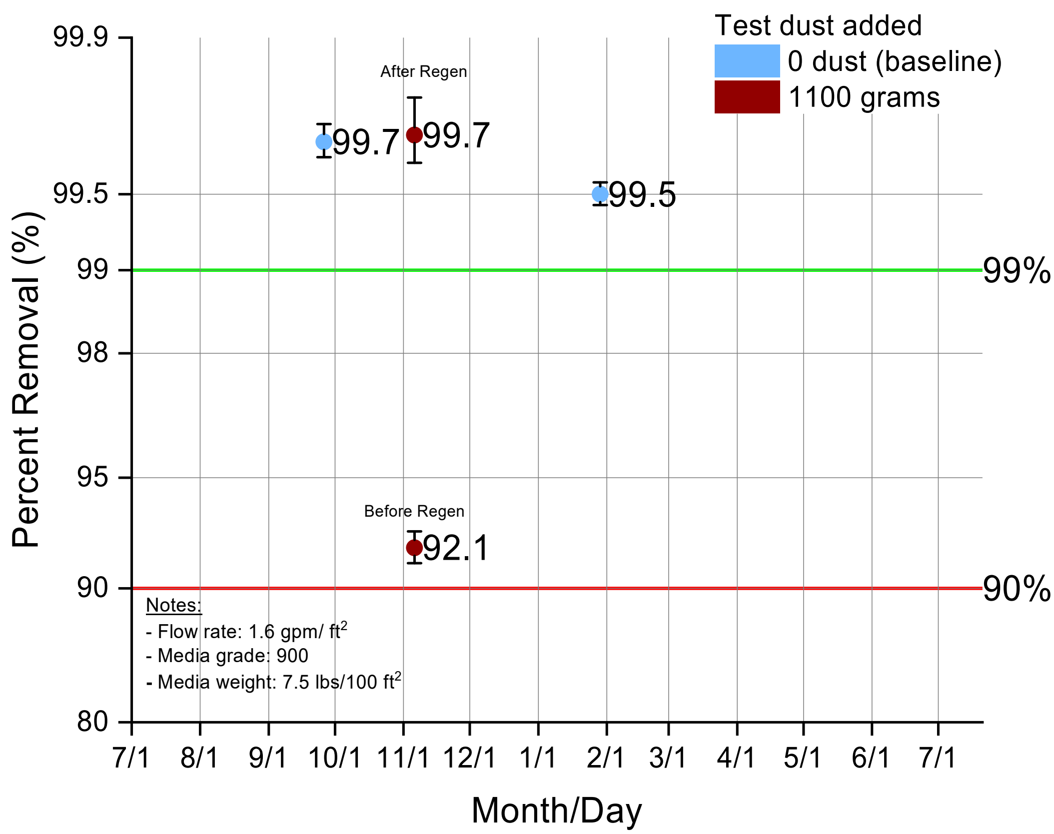

Figure 4.16: Filter clogged in 8-minutes with 1100 grams of test dust before and after media regeneration

A comparison of the results from the addition of the second half of 2200 grams of test dust over 8 minutes and then seeded 1-hour after regeneration is shown below (Figure 4.17). The first seeding of microspheres before regeneration of the media was found to be 97.5% removal. The media was regenerated with the 2200 grams of test, and a second seeding was performed. The percent removal was found to be 99.8%. After the media was regenerated with the 2200 grams of test dust inside the filter, the removal was slightly higher than the baseline experiment. A t-test showed a statistically significant difference with 95% confidence between the experiments using

2200 grams of dust and no dust at 1-hour of filtration before the media regeneration (p-value of .005), but there was no significant difference after regeneration (p-value of .015).

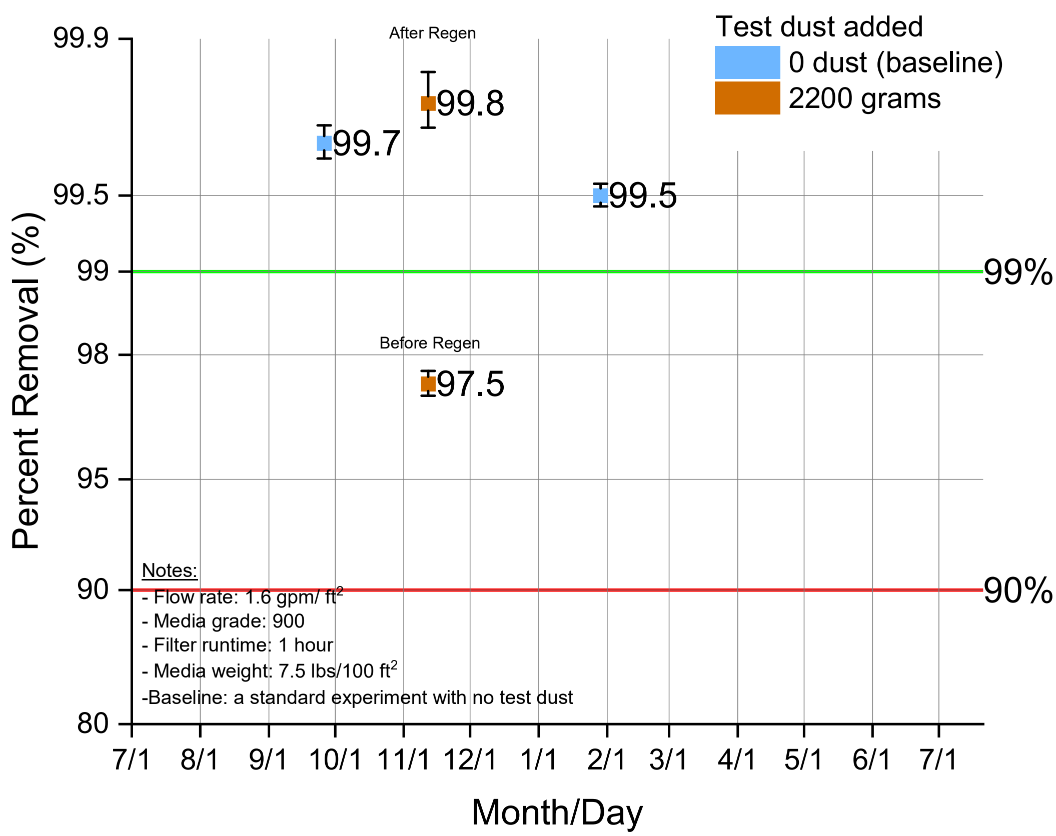

Figure 4.17: Filter clogged in 8-minutes with 2200 grams of test dust before and after media regeneration

A comparison of the percent removals after 1100 grams of test dust were added slowly over a time of 45 minutes seeded, and then evaluated again 1-hour after regeneration is shown below (Figure 4.18). It is important to note the two differences between this experiment and the previous clogging experiment using 1100 grams of test dust. The first deviation is that in this experiment the dust was fed into the filter continuously over 45 minutes. In the previous experiment the dust was fed into the filter quickly and intermittently. The second deviation from the previous experiment is that in the first experiment after the test dust was added to the filter, 1-hour passed and then the microsphere seeding was started and sampled. In this experiment, the seeding was started and sampled immediately after the dust was added to the filter. A t-test showed a statistically significant difference with 95% confidence between the experiments using 1100 grams of dust and no dust at 1-hour of filtration before the media regeneration (p-value less than .012). Another t-test showed a no statistically significant difference with 95% confidence between the experiments using 1100 grams of dust and no dust at 1-hour of filtration after media regeneration (p-value of .673).

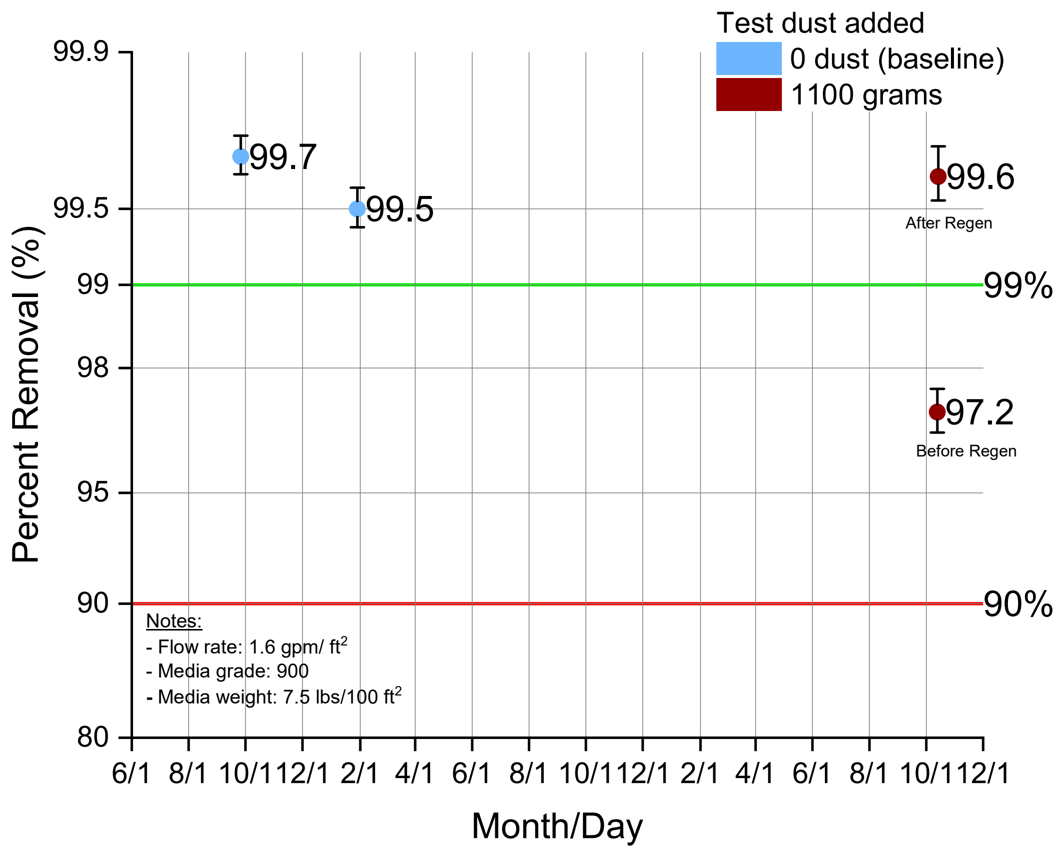

Figure 4.18: Filter clogged in 45-minutes with 1100 grams of test dust before and after media regeneration

The results of an experiment used to model more realistic conditions of recreational water use is made below (Figure 4.19). The test dust was added over a period of eight hours as well as a smaller amount of dust was used to simulate a typical daily load in a pool. The baseline experiments where the seeding and samples took place after 8-hours of filtration rather than 1 were used for this comparison. The percent removal was found to be 97.2% after adding the test dust. The removal was found to be lower than the baseline experiment performed at 8-hours of filtration with no test dust. A t-test showed a statistically significant difference with 95% confidence (p-value of .004) between the experiments using 72 grams of dust and no dust after 8-hours of filtration.

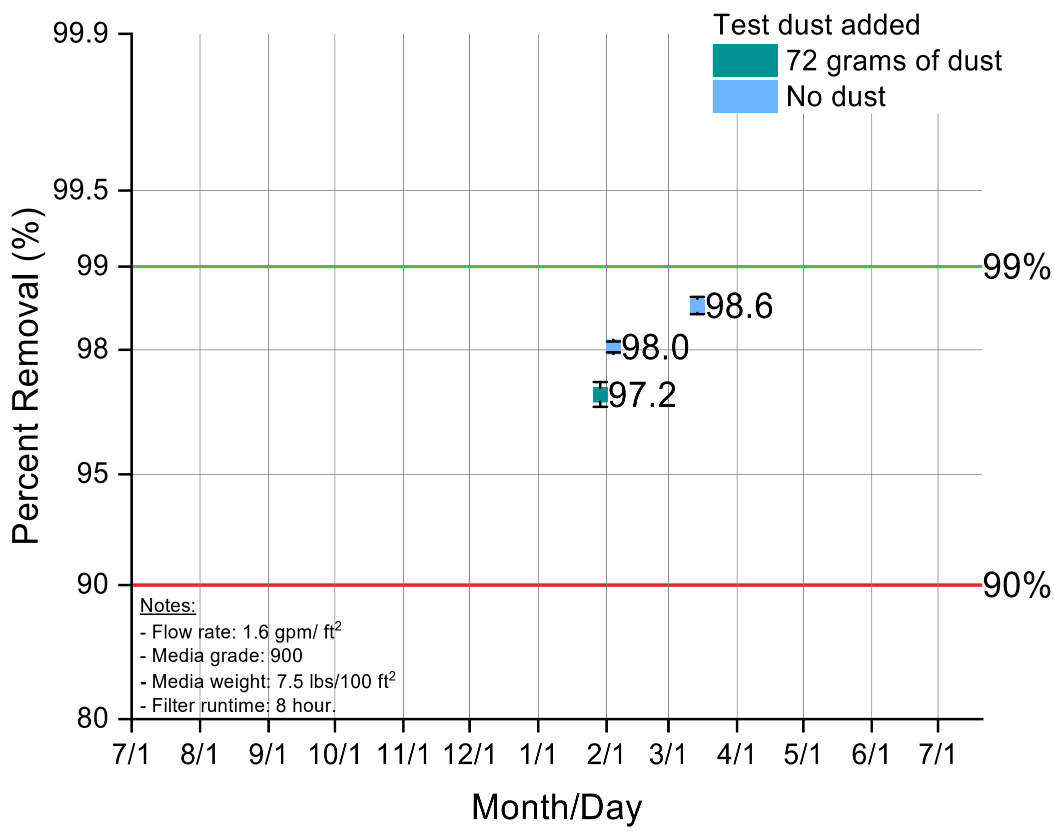

Figure 4.19: Filter clogged with 72 grams of dust added over 8-hours

A comparison of the removal of the RMF after 72 grams of test dust were added at 2 and 8-hours is seen below (Figure 4.20). The test dust added over a 2-hour time had a better removal than when the dust was added over 8-hours. While the 2-hour experiment that included 72 grams of dust is lower than a standard baseline experiment performed at one hour, no experiments were performed with no dust at exactly 2 hours of filtration. A t-test showed a statistically significant difference with 95% confidence (p-value of .004) between the experiments at 2 and 8-hours of filtration using 72 grams of test dust.

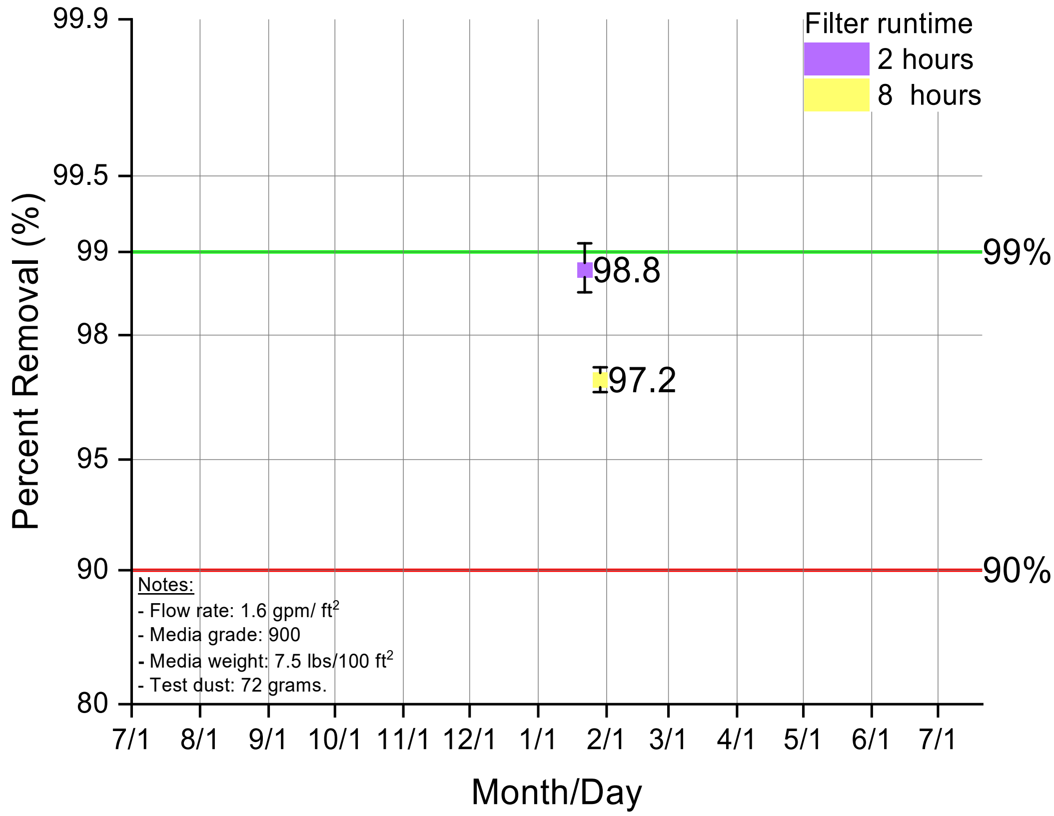

Figure 4.20: Filter clogged with 72 grams of test dust at 2- and 8-hours

Below is shown the differences in removal when a manual valve was used to increase the pressure inside the filter compared to a baseline experiment (Figure 4.21). The valve was closed to apply 4 PSI of pressure on the filter, the same pressure change seen after the 1100 grams of test dust was added to the filter. The percent removal that was found was slightly lower but very similar to the standard baseline experiment with no closed valve. A t-test showed a statistically significant difference with 95% confidence (p-value of .012) between the experiments using the manual valve the standard condition experiments at one hour.

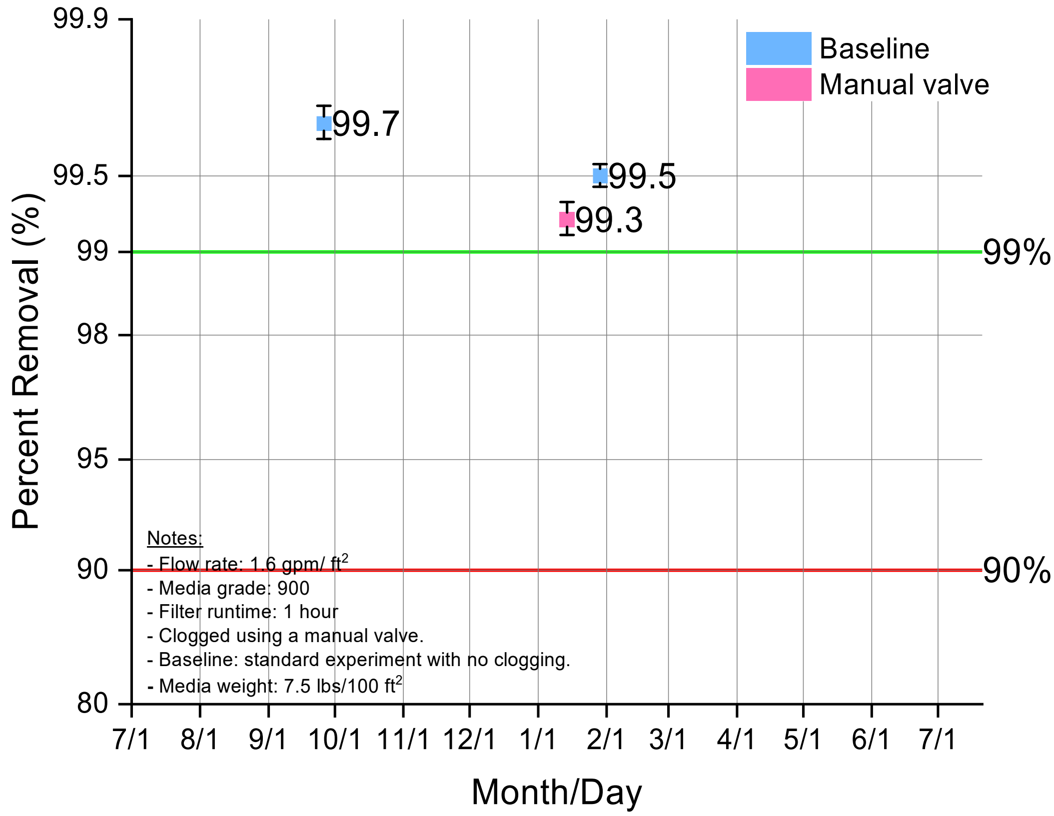

Figure 4.21: Filter clogging with a manual valve

4.7 Media Regeneration

Shown below is an experiment performed in duplicate to find the optimum duration of the precoat phase of media regeneration (Figure 4.22). The filter was set to precoat the media for 30 minutes at a single flowrate of 140 GPM. Samples were taken throughout the thirty minutes to find the concentration of microspheres recirculated in the filter media. The concentration of spheres is approximately .1 per mL at 11 minutes and decreases little afterwards. The initial concentration of spheres in the system was calculated to be approximately 390 spheres per mL. After the measured samples reached steady-state at 11 minutes, the percent reduction in sphere concentration was 99.97%.

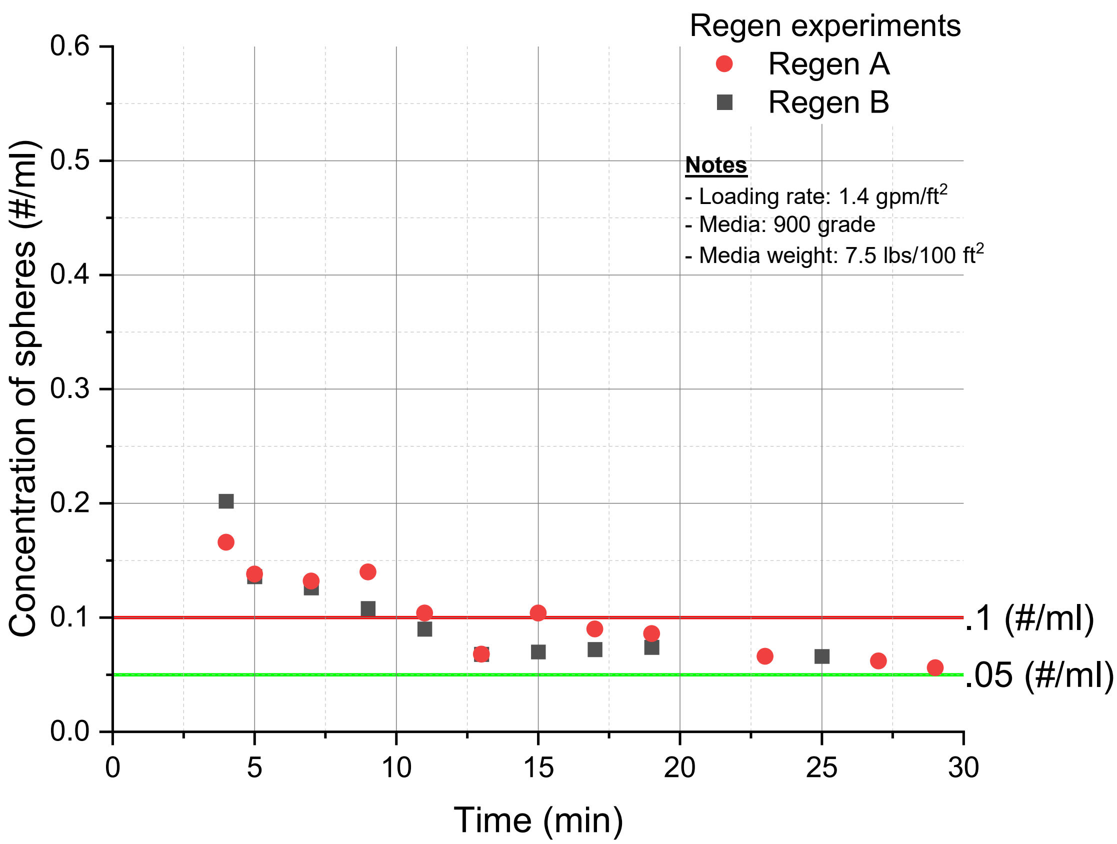

Figure 4.22: Microsphere concentration during the precoat phase of media regeneration

4.8 Full-Scale

A full-scale regenerative media filter was tested to compare its removal ability to that of the 18-inch RMF used in the other experiments. While the full-scale filter used a pneumatic bump system in its media regeneration cycle, the 18-inch RMF used a hydraulic power bumping system. Two media regeneration procedures were tested using the 18-inch RMF and compared to the full-scale filter. The first regeneration procedure was a 3-stage regeneration, four minutes each at 80, 160, and 200 GPM. The second regeneration procedure was 10 minutes and 1-stage of 140 GPM. The full-scale filter regeneration cycle included 10 pneumatic bumps and a 10-minute single speed precoat period. The single speed media regeneration procedure mimics the full-scale RMF media regeneration, however the method the media is removed from elements was different. Experiments were conducted using both regeneration procedures with the lab-scale RMF and compared to the full-scale RMF's removal efficiency.

Comparison of the difference in percent removal 1-hour after media regeneration for 1- and 3-stage media regeneration on the lab-scale RMF to the removal of a full-scale RMF are seen below (Figure 4.23). The 3-stage regeneration achieved a slightly higher removal than both the full-scale and the 1-stage regeneration cycle. A t-test showed a statistically significant difference with 95% confidence (p-value of .033) between the experiments with 1-stage regeneration and 3-stage regeneration at 1-hour of filtration. Another t-test showed a statistically significant difference with 95% confidence (p-value of .007) between the experiments 1-stage regeneration and full-scale at 1-hour of filtration. A t-test showed a statistically significant difference with 95% confidence (p-value of .004) between the experiments using lab-scale 3-stage media regeneration and full-scale at 1-hour of filtration. Two parameters are different between these experiments, statistical difference should not be attributed to either individual change without further evidence.

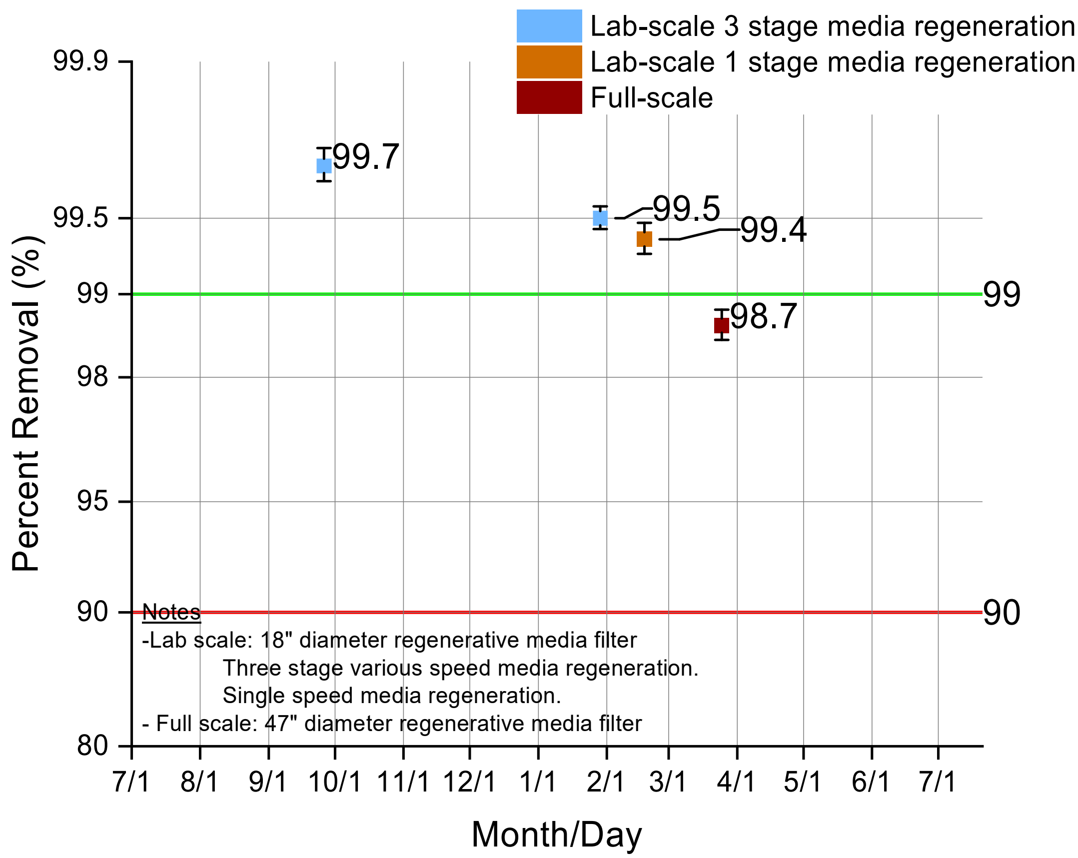

Figure 4.23: Comparison of regeneration cycles and full-scale filter at 1-hour

The differences in removal 24-hours after regeneration of media of the regeneration procedure and the full-scale RMF are seen below (Figure 4.24). After 24-hours, the full-scale RMF percent removal was the highest compared to both regeneration cycles tested on the lab-scale RMF. The 1-stage removal decreased the most over 24-hours of the regeneration cycles. A t-test showed a statistically significant difference with 95% confidence (p-value of .001) between the experiments with 1-stage regeneration and 3-stage regeneration at 24-hours of filtration. Another t-test showed a statistically significant difference with 95% confidence (p-value of .001) between the experiments 1-stage regeneration and full-scale at 24-hours of filtration. A t-test was not performed on 3-stage regeneration and full-scale due to multiple variables changing. A t-test showed a statistically significant difference with 95% confidence (p-value of .004) between the experiments using lab-scale 3-stage media regeneration and full-scale at 24-hours of filtration. Two parameters are different between these experiments, statistical difference should not be attributed to either individual change without further evidence.

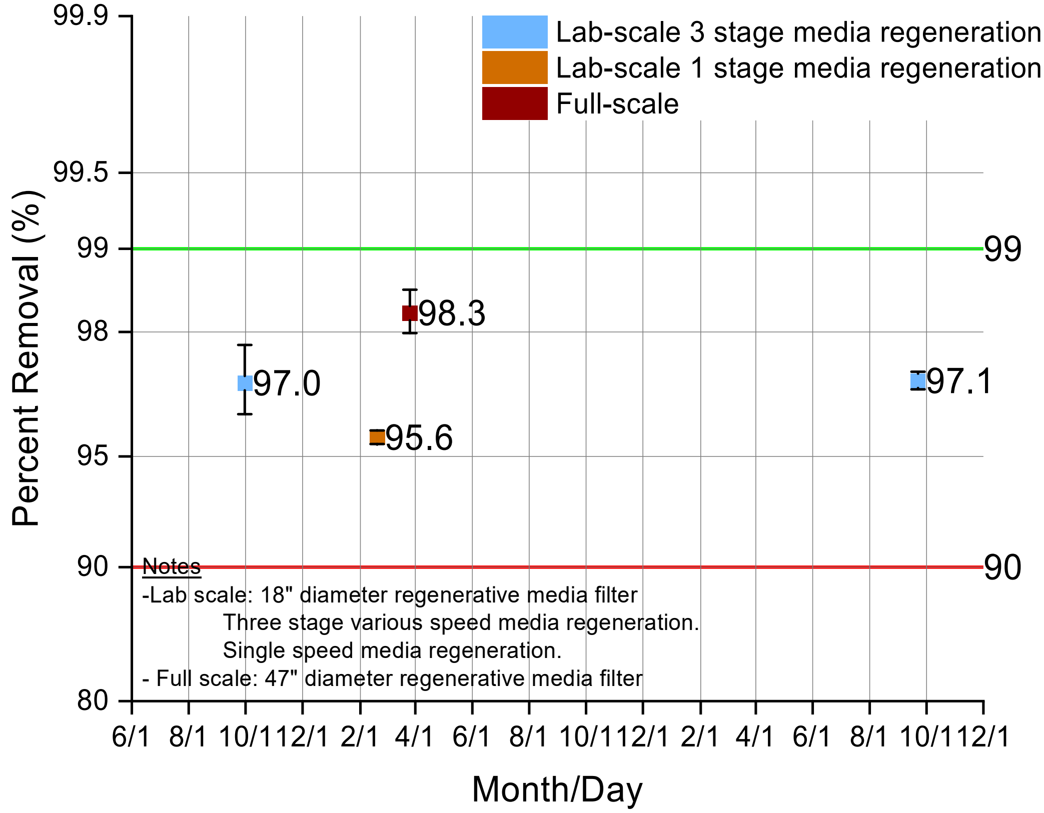

Figure 4.24: Comparison of regeneration cycles and full-scale filter at 24-hours

Compared below is the percent removal of the full-scale RMF at 1-hour and 24-hours after media regeneration (Figure 4.25). The full-scale 1-hour removal of 98.7% is lower than the removal of the lab-scale RMF with 1-stage regeneration at 1-hour; however, the 24-hour removal of 98.3% is higher than the lab-scale at 24-hours. This differs from what was seen with both versions of regeneration on the lab-scale RMF where the percent removal had a large drop when comparing 1 and 24-hours. A t-test showed no statistically significant difference with 95% confidence (p-value less than .130) between the experiments at 1-hour and 24-hours of the full-scale RMF.

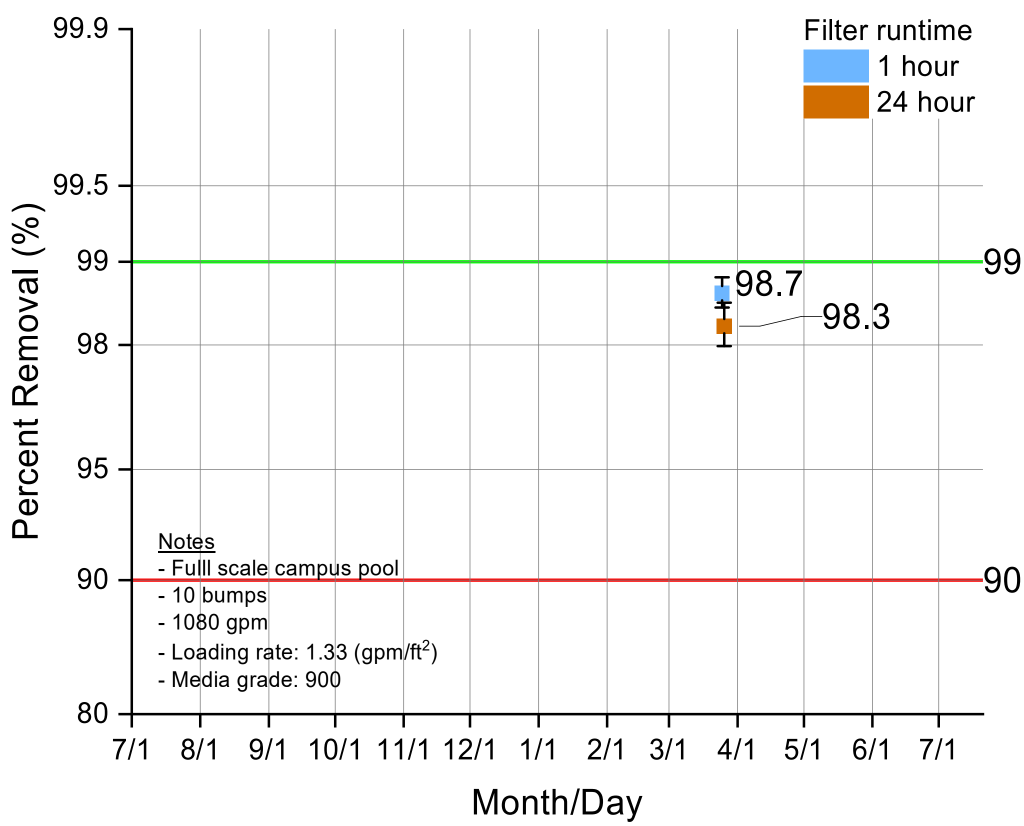

Figure 4.25: Full-scale RMF after 1 and 24-hours of filtration

Shown below is the difference in percent removal of the 1-stage regeneration procedure comparing 1 and 24-hours on the lab-scale filter (Figure 4.26). A t-test showed a statistically significant difference with 95% confidence (p-value less than .001) between the experiments at 1-hour and 24-hours using 1-stage regeneration.

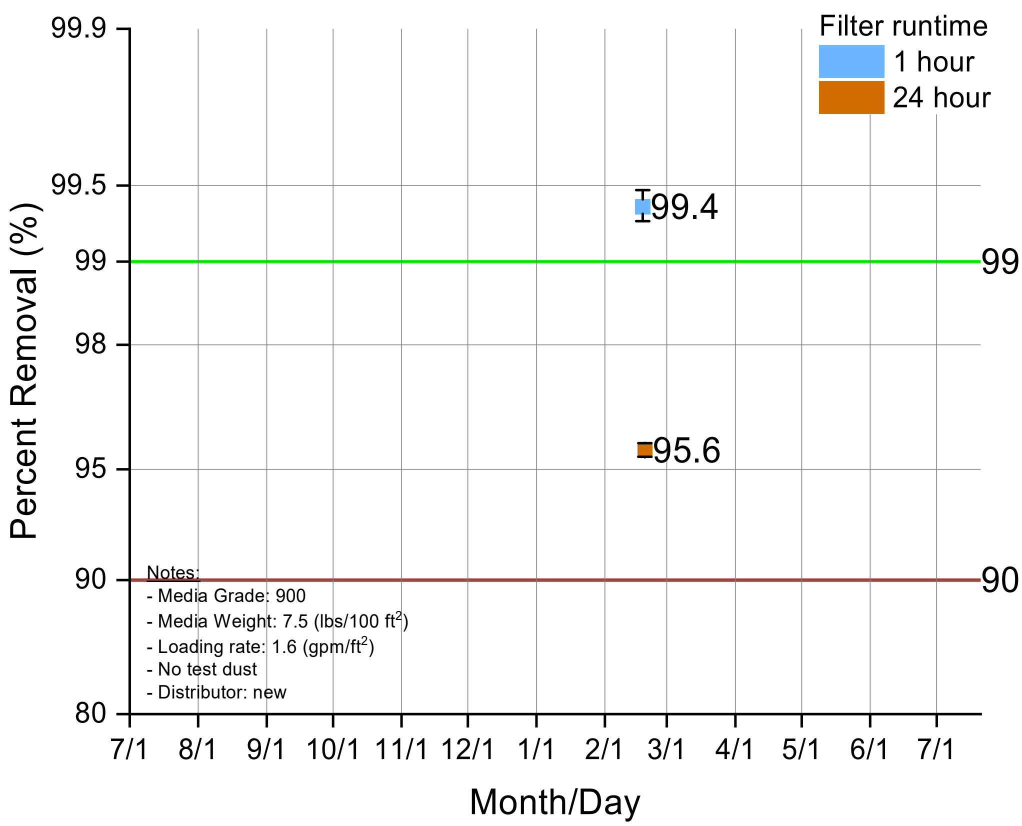

Figure 4.26: Single-stage regeneration after 1 and 24-hours of filtration

CHAPTER 5: SUMMARY

The overall objective of this research was to determine how effective regenerative media filters are at the removal of *Cryptosporidium*-sized microspheres. The research further evaluated how the adjustment of filter operation and design parameters affected removal of the microspheres in an 18-inch diameter RMF in a controlled laboratory setting. The filter parameters evaluated include flow distributor version, filtration time, media grade, flowrate, degree of clogging, and the amount of media used. The experiments also included the evaluation of a full-scale RMF on the UNC Charlotte campus pool.

The regenerative media filter was shown be to effective at the removal of *Cryptosporidium*-sized microspheres under both standard and non-standard operating conditions between 1 and 24-hours after media regeneration. Removals decreased in certain conditions, but they never dropped below 90% (1 log) under any tested condition. Two flow distributors were evaluated (version 1 and version 2). The difference in design was version 2 of the distributor was longer than version 1. Version 2 of the distributor was compared to version 1 after 1 and 24-hours of filtration at 200 GPM with 700-grade media. Version 2 performed significantly better than version 1 in every evaluation except when evaluated at 24 hours where the difference was not statistically significant (p-value of .059).

The RMF was evaluated using 7.5 $\frac{lbs.}{100\,ft^2}$ and 11.25 $\frac{lbs.}{100\,ft^2}$ of media with all other conditions the same. The removal was compared at both 1 and 24-hours after media regeneration. At both times, the filter achieved better removal with the 50% increase in filter media. A t-test showed a statistically significant difference with 95% confidence at both times with a p-value of .021 at 1-hour and .001 at 24-hours.

Three media grades were evaluated with three different mean particle sizes. The media grades used were 635, 700, and 900-grade, the mean particle sizes are 44.0, 46.9 and 58.4 microns respectively. The filter removals decreased as the media size decreased. The media found to achieve the worst removal was Harborlite 635-grade. The highest removals were found using 900-grade media, which had the largest particle size. The filter was evaluated at 160 GPM and 200 GPM at 1 and 24-hours after media regeneration. The removals at both times using 200 GPM were shown to be lower than the removals using 160 GPM.

Test dust was added to test filter performance as the filter removed particles and began to clog. The filter removals decreased compared to when no test dust was added. After the filter was regenerated (with the dust still in the filter), the removal efficiency was found to be as good as or better than when no dust was added. Since filters are regenerated daily, the amount of test dust was decreased from 1100 grams to 72 grams to simulate a typical daily particle loading. The removals always decreased when dust was added.

Microspheres were added to the filter so the concentration would be 35 spheres per mL in the filter system. The filter was manually set to regenerate the media for 30 minutes instead of the standard 3 minutes. The concentration of microspheres recirculating through the filter was found to reach steady state at approximately 11 minutes with a reduction in microspheres of 99.7% indicating that increasing the regeneration time would be unlikely to make significant reductions in pathogen passage.

Three-stage media regeneration cycles were compared to 1-stage media regeneration cycles by measuring filter performance at 1 and 24-hours after media regeneration was completed. The removals were not significantly different after 1-hour of filtration. After 24-hours of filtration, the three-stage media regeneration achieved a slightly higher removal than the one-stage media regeneration. A full-scale regenerative media filter was compared to the 1-stage media regeneration of the lab-scale RMF. The full-scale RMF was only compared to the 1-stage media regeneration procedure because the full-scale filter was only programmed to use a 1-stage regeneration procedure. The lab-scale filter achieved a higher removal at 1-hour compared to the full-scale filter. The full-scale filter removal efficiency did not change over 24-hours, but the lab-scale filter removals decreased significantly over 24-hours.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following conclusions were made based on the analysis of the data collected from experiments described in this document.

1. After evaluating regenerative media filters in every scenario discussed in this document the removal of cryptosporidium-sized microsphere was never found to be less than 90% (1-log). Under normal operating conditions, RMF removals were even higher (ranging from 99.6% to 97.1% over 24 hours). Regenerative media filter's ability to remove Cryptosporidium-sized microsphere was found to be much higher than sand filters (31%) and cartridge filters (36%) based on peer-reviewed data from a prior study from the same research lab.

2. Distributor version 2 improved 4.5-micron microsphere removal efficiency compared to version 1 from 98.8% to 99.6% at 1.6 $\frac{gpm}{ft^2}$ and from 93.0% to 97.7% at 2.0 $\frac{gpm}{ft^2}$. These experiments were performed using 7.5 $\frac{lbs.}{100\ ft^2}$ of 900-grade after 1-hour of filtration. Due to the increased performance, all subsequent experiments were performed with distributor version two.

3. A three-stage media regeneration procedure increased 4.5-micron microsphere removal efficiency compared to a single stage regeneration. Removals increased from 99.4% (1-hour) and 95.6% (24 hour) to 99.6% (1-hour) and 97.1% (24 hour) for the three-stage

regeneration procedure. These experiments were performed using 7.5 $\frac{lbs.}{100\, ft^2}$ of 900-grade media at a loading rate of 1.6 $\frac{gpm}{ft^2}$.

4. Increasing loading rate by 25% from 1.6 $\frac{gpm}{ft^2}$ to 2.0 $\frac{gpm}{ft^2}$ decreased 4.5-micron microsphere removal efficiency at 1-hour from 99.6% to 97.7% and at 24-hours from 97.1% to 91.6%. These experiments were performed using 7.5 $\frac{lbs.}{100\, ft^2}$ of 900-grade media and 3-stage regeneration.

5. With 7.5 $\frac{lbs.}{100\, ft^2}$ of media, 4.5-micron microsphere removal efficiency decreased over 24-hours from 99.6% to 97.1% compared to a decrease from 99.8% to 98.7% using 50% more media at 11.25 $\frac{lbs.}{100\, ft^2}$ of perlite. These experiments were performed at 1.6 $\frac{gpm}{ft^2}$ with 900-grade media and 3-stage regeneration.

6. With 72 grams of test dust added to clog the filter by an approximated daily bather load over 8-hours, 4.5-micron microspheres removal efficiency decreased from the removal efficiency baseline measured at 8-hours with no test dust of 98.3% to 97.2% using 7.5 $\frac{lbs.}{100\, ft^2}$ of 900-grade media at a loading rate of 1.6 $\frac{gpm}{ft^2}$.

7. Microsphere concentrations during the media regeneration cycle (when water and perlite were being recirculated through the filter without return flow to the pool) showed a decrease in 4.5-micron microsphere concentration from 390 per mL to 0.1 per mL. The measured

concentration of spheres reached steady-state in 11 minutes and had a 99.97% total reduction in sphere concentration. This experiment was performed in duplicate, both experiments were performed using 7.5 $\frac{lbs.}{100\ ft^2}$ of 900-grade media at a single loading rate of 1.4 $\frac{gpm}{ft^2}$ with distributor version 2.

8. Adding 1100 grams of test dust caused a pressure increase of 4 psi in the RMF over an 8-minute period and decreased the 4.5-micron microspheres removal efficiency removal from 99.6% to 92.1%. After the filter was regenerated with the test dust remaining inside the filter, the removal efficiency increased to 99.7%. When test dust was added to the filter over a .75-hour period, the filter removal efficiency only decreased from 99.6% to 97.2%. These experiments were performed using 7.5 $\frac{lbs.}{100\ ft^2}$ of 900-grade media, a loading rate of 1.6 $\frac{gpm}{ft^2}$ and distributor version 2.

6.2 Recommendations for Further Research

It is recommended that further research be done to determine the effect of using less than 7.5 $\frac{lbs.}{100\ ft^2}$ of media in an RMF. It was shown from experiments that removal was 1.6% higher with 50% additional media at 24-hours. Evaluating the filter with less media could potentially have a greater impact on removal. The 30-minutes regeneration experiment could be re-evaluated with a change in procedure. The samples collected and evaluated prior to 4-minutes were 100 mL. These samples contained enough media that all spheres could not be counted. The concentrations before 4-minutes are also expected to be the highest, so a smaller volume (such as 1 mL samples) would be more appropriate. The smaller sample volume would have less media covering the microspheres allowing them to be seen.

The research using test dust suggests that adding large amounts of test dust quickly to the filter lowers the removal of the filter, but the conditions are not realistic because such a large amount of particles could take 30 days to accumulate in a real-world pool, which would also include 30 regeneration cycles that were shown to increase removals after adding test dust. It is recommended that filter performance tests use an amount of test dust over a period of time that the filter would normally experience that amount of clogging under typical operating conditions.

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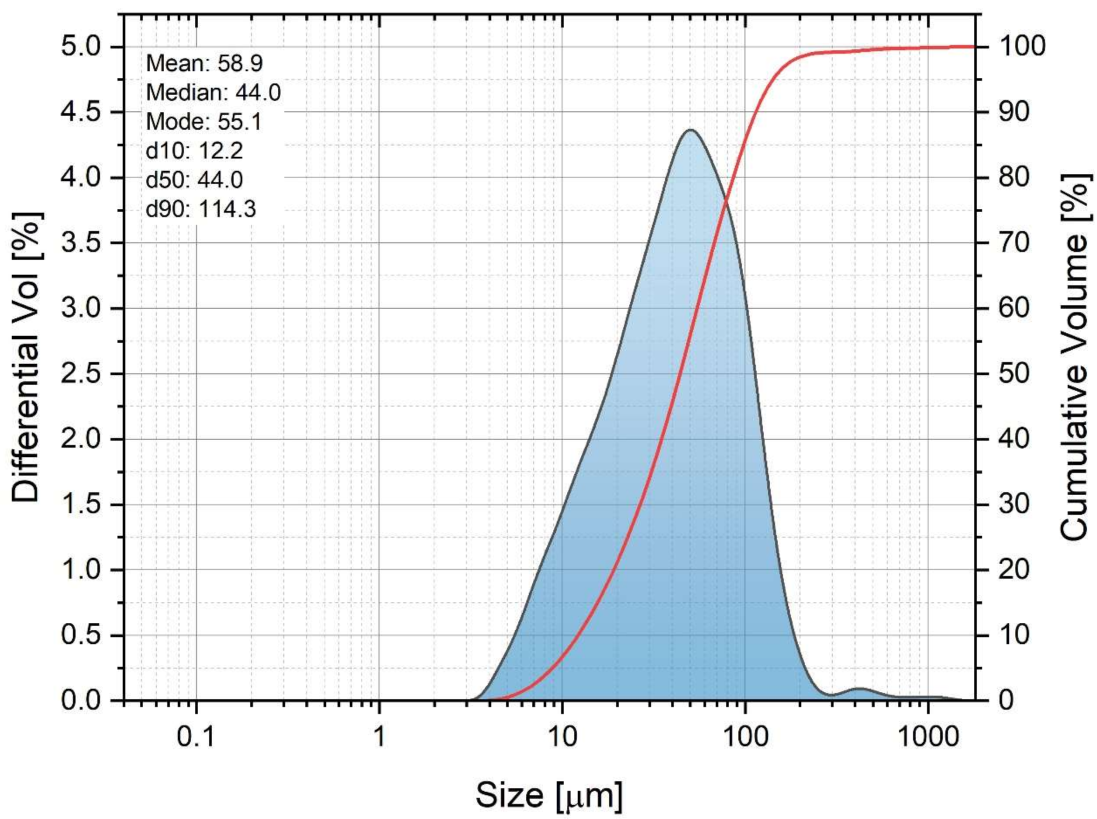
APPENDIX A: EXPERIMENT SUMARRY

Date	Removal %	STD. DEV.	Name	Distributor	Regeneration Procedure	Media Wt. (lbs./100sf)	Loading Rate (GPM/sf)	Time after bump (hrs.)	Media grade	Test Dust Wt. (grams)
6/26/2020	98.14	0.53	worst-case scenario	old	2-stage (6 & 10 min)	7.5	1.4	24	900	n/a
7/2/2020	98.81	0.22	900 Grade	old	2-stage (6 & 10 min)	7.5	1.4	1	900	n/a
7/20/2020	98.50	0.33	700 Grade	old	2-stage (6 & 10 min)	7.5	1.4	1	700	n/a
8/10/2020	92.96	0.22	Max NSF	old	2-stage (6 & 10 min)	7.5	2	1	900	n/a
9/1/2020	97.71	0.55	Max NSF Regeneration 3	new	3-stage (4/4/10 min ea.)	7.5	2	1	900	n/a
9/3/2020	91.64	1.47	worst-case scenario	new	3-stage (4/4/10 min ea.)	7.5	2	24	900	n/a
9/9/2020	99.84	0.04	11.25lbs/100sqft	new	3-stage (4 min ea.)	11.25	1.6	1	900	n/a
9/10/2020	99.16	0.09	11.25lb, 24hr	new	3-stage (4 min ea.)	11.25	1.6	24	900	n/a
9/18/2020	99.23	0.04	700 Grade new	new	3-stage (4 min ea.)	7.5	1.6	1	700	n/a
9/25/2020	97.13	0.17	700-grade	new	3-stage (4 min ea.)	7.5	1.6	24	700	n/a

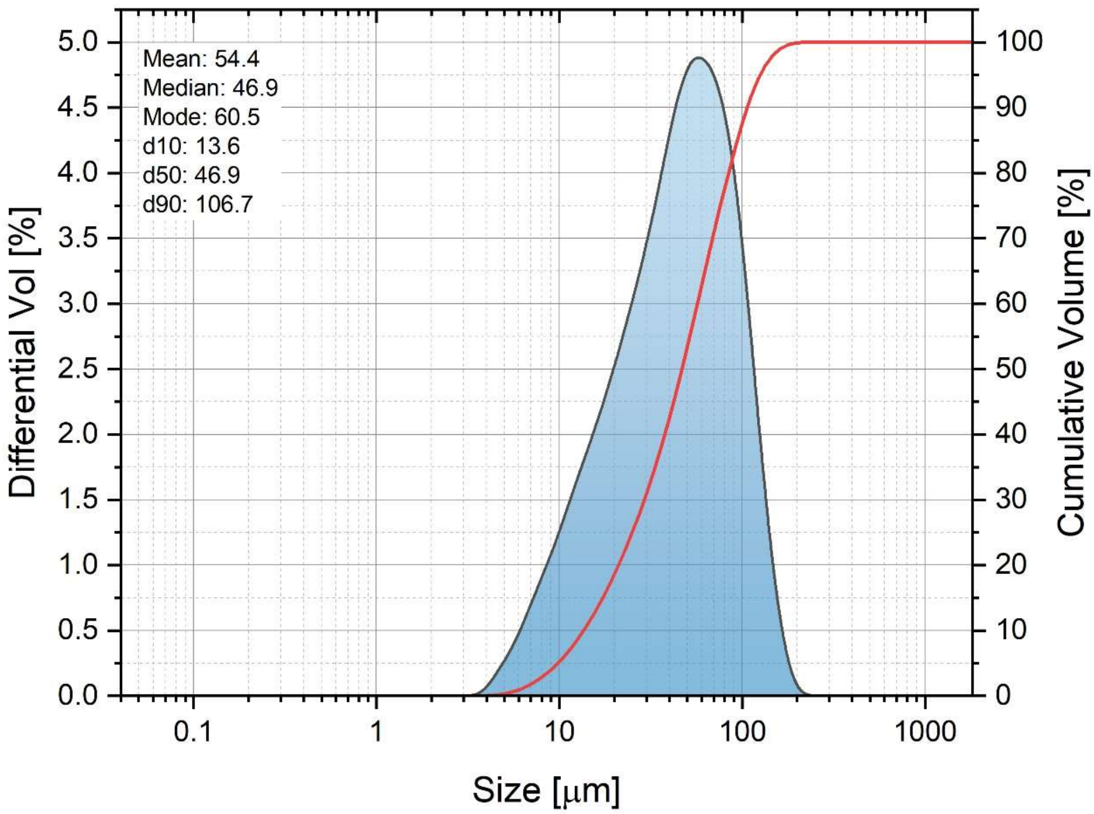
9/26/2020	99.70	0.05	Baseline	new	3-stage (4 min ea.)	7.5	1.6	1	900	n/a
9/30/2020	97.03	0.75	900-grade, new, 24hr, "baseline"	new	3-stage (4 min ea.)	7.5	1.6	24	900	n/a
11/6/2020	92.14	0.76	+4psi before bumping	new	3-stage (4 min ea.)	7.5	1.6	1	900	1100
11/6/2020	99.72	0.09	+4psi After Bumping	new	3-stage (4 min ea.)	7.5	1.6	1	900	1100
11/12/2020	97.49	0.24	+8psi before bumping	new	3-stage (4 min ea.)	7.5	1.6	1	900	2200
11/12/2020	99.80	0.06	+8psi After Bumping	new	3-stage (4 min ea.)	7.5	1.6	1	900	2200
11/20/2020	98.93	0.04	635-grade	new	3-stage (4 min ea.)	7.5	1.6	1	635	n/a
1/14/2021	99.25	0.11	Manual valve	new	3-stage (2 min ea.)	7.5	1.6	1	900	n/a
1/22/2021	98.83	0.24	realistic conditions	new	3-stage (4 min ea.)	7.5	1.6	1	900	72
1/29/2021	99.50	0.05	Baseline	new	3-stage (4 min ea.)	7.5	1.6	1	900	n/a
1/29/2021	97.16	0.26	realistic conditions	new	3-stage (4 min ea.)	7.5	1.6	1	900	72
2/4/2021	98.04	0.08	realistic conditions, baseline	new	3-stage (4 min ea.)	7.5	1.6	8	900	n/a
2/18/2021	99.39	0.09	baseline for full scale	new	1-stage (10 min)	7.5	1.6	1	900	n/a
2/19/2021	95.61	0.21	baseline for full scale	new	1-stage (10 min)	7.5	1.6	24	900	n/a

3/14/2021	98.60	0.10	realistic conditions, baseline	new	3-stage (4 min ea.)	7.5	1.6	8	900	n/a
3/24/2021	99.71	0.08	11.25lbs/100sqft	new	3-stage (4 min ea.)	11.25	1.6	1	900	n/a
3/25/2021	98.69	0.17	Full scale	n/a	10 bumps	64	1.33	1	900	n/a
3/26/2021	98.28	0.30	Full scale	n/a	10 bumps	64	1.33	24	900	n/a
4/6/2021	98.11	0.10	11.25lb, 24 hr.	new	3-stage (4 min ea.)	11.25	1.6	24	900	n/a
5/11/2021	99.18	0.16	Exactly 140 GPM	new	2 -stage (4 & 8 min	7.5	1.4	1	900	n/a
6/3/2021	98.37	0.07	Exactly 140 GPM, 24 hr.	new	2 -stage (4 & 8 min	7.5	1.4	24	900	n/a
9/22/2022	97.08	0.19	Baseline 24 hr.	new	3-stage (4 min ea.)	7.5	1.6	24	900	n/a
10/13/2022	97.19	0.46	+4 PSI Before Regeneration	new	3-stage (4 min ea.)	7.5	1.6	1	900	n/a
10/13/2022	99.63	0.09	+4 PSI After Regeneration	new	3-stage (4 min ea.)	7.5	1.6	24	900	n/a

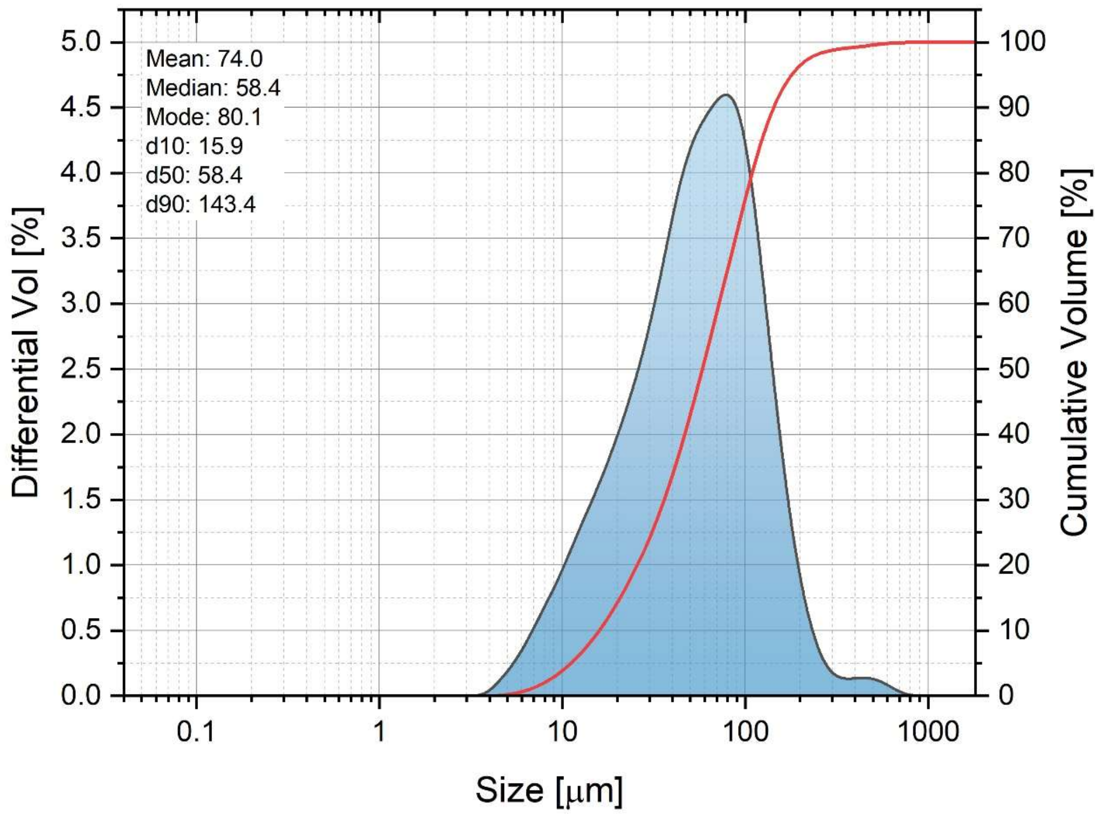
APPENDIX B: PARTICLE SIZE ANALYSIS RESULTS



Particle size analysis results of 635-grade media

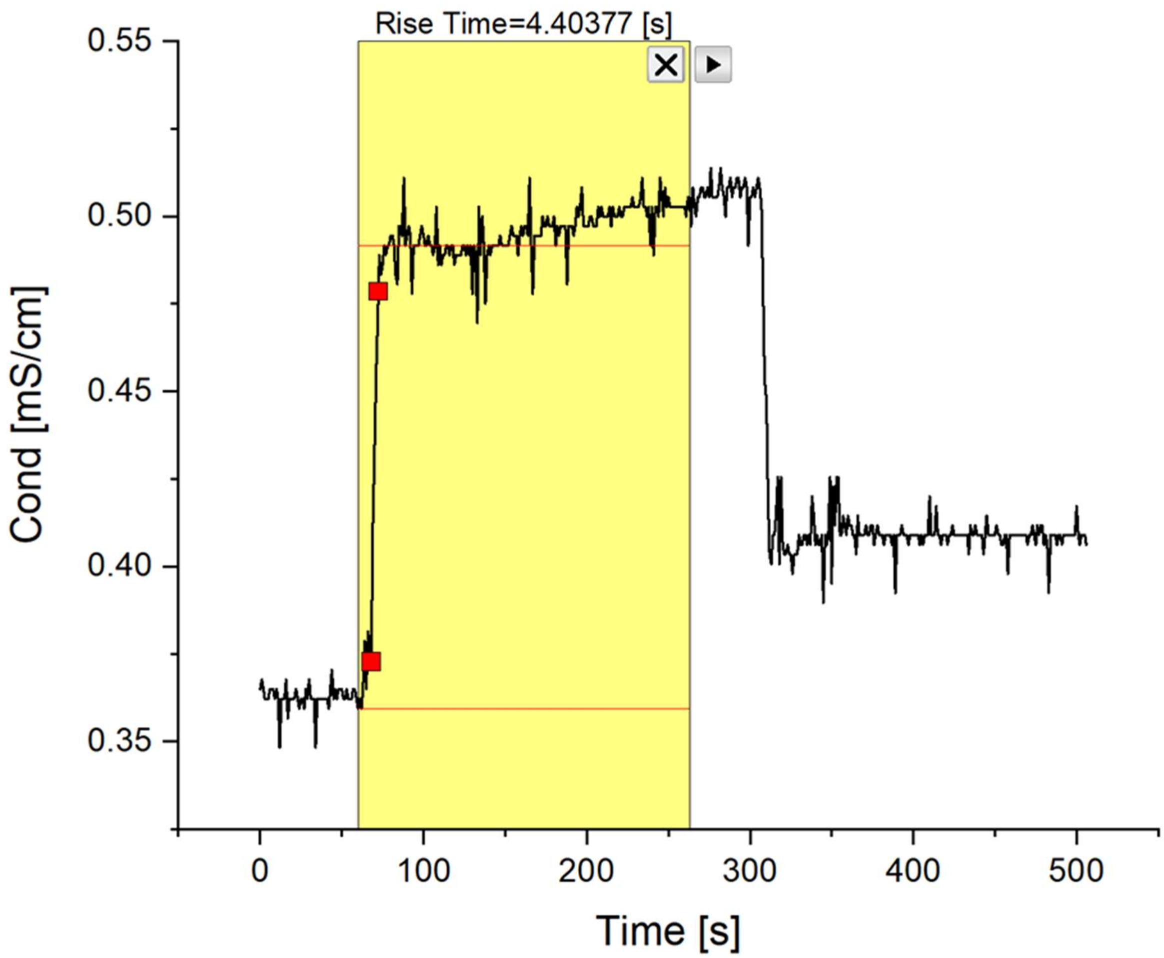


Particle size analysis results of 700-grade media

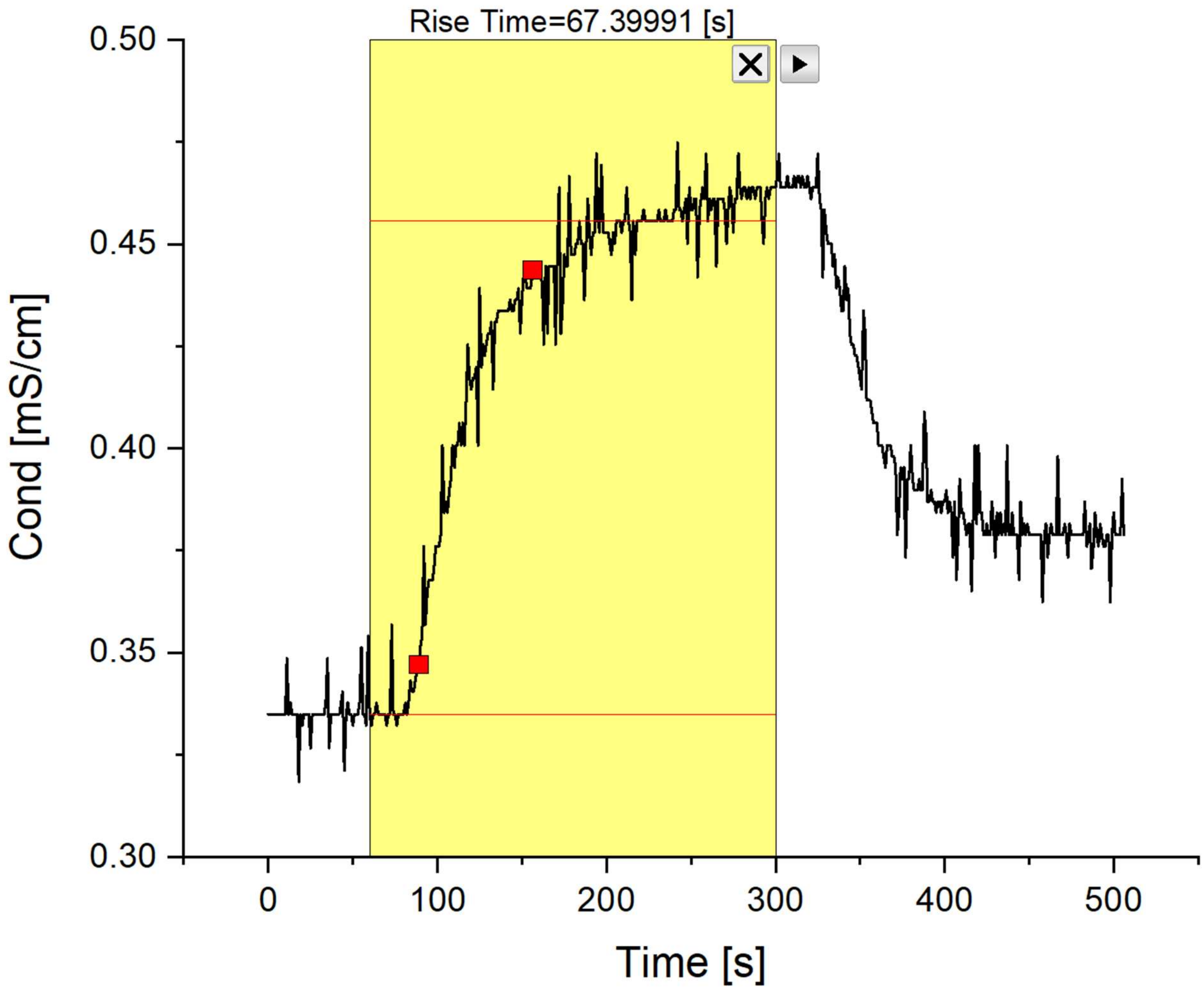


Particle size analysis results of 900-grade media

APPENDIX C: TRACER STUDY RESULTS



Conductivity tracer study influent results at 140 GPM



Conductivity tracer study effluent results at 140 GPM