ENHANCED REMOVAL OF *CRYPTOSPORIDIUM PARVUM* OOCYSTS AND *CRYPTOSPORIDIUM*-SIZED MICROSPHERES FROM RECREATIONAL WATER THROUGH FILTRATION

by

Ping Lu

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Approved by:

____
Dr. James E. Amburgey

____
Dr. Helene A. Hilger

____
Dr. John L. Daniels

____
Dr. Jordan C. Poler

____
Dr. Jing Zhou

ABSTRACT

PING LU. Enhanced removal of *Cryptosporidium parvum* oocysts and *Cryptosporidium*-sized microspheres from recreational water through filtration.
(Under the direction of DR. JAMES E. AMBURGEY)

Cryptosporidium species are the cause of cryptosporidiosis, which has symptoms such as watery diarrhea, dehydration, fever, nausea, body fatigue, and abdominal cramps. Infants, the elderly, and people with severely compromised immune systems are more susceptible and could die from cryptosporidiosis. Numerous waterborne outbreaks of cryptosporidiosis have been linked to swimming pools in United Kingdom, United States, Australia, and Canada. The concerns of public health and increasing demands for recreational opportunities have pushed the need for enhanced removals of *Cryptosporidium* from swimming pools to emergent. Unfortunately, relatively little information is available on *Cryptosporidium* removal from pilot-scale or full-scale swimming pools or spas.

Water quality was evaluated for thirty five national swimming pools at first to evaluate the chemical constituents of the swimming pools. Based on these data, three representative swimming pool waters were developed using cluster analysis, which were applied in subsequent experiments. Based on this survey, an average pool would have a pH of 7.5 with 1.5 mg/L of free chlorine, and the alkalinity and hardness would be 94 mg/L and 238 mg/L as $CaCO_3$, respectively. The average turbidity would be 0.33 NTU, and the DOC concentration would be 5 mg/L.

Zeta potentials of *Cryptosporidium* oocyst-sized microspheres in three pool waters were titrated with six coagulants to determine dose-response relationships.

Overdosing of organic polymer coagulants (i.e., coagulants A, B, and F) was shown to be possible. No significant differences were observed for any of the coagulants' performance in the three water formulations test.

High-rate sand filtration (which refers to a filtration rate up to 37 m/h with coagulant addition before sand filtration) was evaluated in this study. A series of experiments were conducted to develop a novel operational procedure for high-rate sand filtration and provide field-relevant results. Results indicated that the highest removals occurred when coagulant was fed continuously by a coagulant pump. Extended/excessive dosing coagulant A (the only coagulant used in this part of the study) led to coagulant A build up in the system and reduced microsphere removal efficiency.

Three alternative treatment techniques were evaluated for ability to enhance *Cryptosporidium*-sized microsphere removals from a 5,500 L pilot-scale pool, including feeding coagulants prior to sand filter, adding a layer of perlite on top of the sand filter's media without coagulation, and diatomaceous earth (DE) filtration. High-rate sand filtration without coagulation (control experiment) removed 20% - 63% of microspheres. Up to 99% *Cryptosporidium*-sized microsphere removal was achieved through high-rate sand filtration with coagulants A, B, D, and F at 37 m/h. Coagulant C was a chitosan-based product that removed less than 80% of microspheres under the studied conditions. Coagulant E (polyaluminum chloride) removed more than 90% of microspheres at 30 m/h. Adding perlite on the top of a sand filter increased the *Cryptosporidium* oocysts-sized microsphere removals to 79%, 99%, 99.7%, and 99.8% with 0.24 kg·perlite/m^2, 0.37 kg·perlite/m^2, 0.49 kg·perlite/m^2 and 0.61 kg·perlite/m^2, respectively. At least 0.7 kg·DE/m^2 was required to achieve approximately 99% of *Cryptosporidium*-sized microspheres by DE filtration.

Cryptosporidium parvum and *Cryptosporidium*-sized microsphere removals from full-scale swimming pools were evaluated. Coagulants B, D, E, and F were individually fed into swimming pools both with remediation dose and maintenance dose. Approximately 90% of *Cryptosporidium parvum* and microspheres were removed by filtration with coagulant B (1.56 mg/L), coagulant D (305g/m^2), and coagulant F (1.56 mg/L) under remediation conditions. Eighty two percent of *Cryptosporidium* and 97% of microspheres were removed with coagulant E (0.1 mg·Al/L) under remediation conditions. Under maintenance dosing conditions: up to 93% of *Cryptosporidium* and 77% of microsphere were removed by coagulant B; as high as 99% of *Cryptosporidium* and 98% of microsphere were removed with coagulant D; 98% of *Cryptosporidium* and 93% of microsphere were removed with coagulant E; up to 85% of *Cryptosporidium* and 82% of microsphere were removed with coagulant F. Organic polymer coagulants accumulated in the swimming pool water (as measured for coagulant A concentration under the study conditions) and led to poor filter performance over time. Additionally, *Cryptosporidium parvum* removals by perlite/sand filter was 88%, and microspheres removal was 99.8% (0.5 kg·perlite/m^2). DE filtration provided above 99.8% removals both for *Cryptosporidium parvum* and microspheres. Cartridge filters only achieved 22% removal of microspheres from a full-scale spa.

To summarize, *Cryptosporidium* and microspheres could be effectively removed on a continuing basis by DE filtration, perlite/sand filtration, and high-rate sand filtration with continuously feeding of coagulant D or E. Performance of coagulant D and E tended to decrease with increased filter pressure, which could warrant additional research. Coagulant A, B, and F achieved up to 99% removal at the recommended dosage, but *Cryptosporidium* and microsphere removals decreased to less than 90% (typically within 48 hours) as the polymer coagulants accumulated in the pool.

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DEDICATION

I would like to dedicate this dissertation to my family and especially my father Lu, my mother Li, and my husband Xiaojian. You have all been there for me throughout this process. Your support has made this possible. Thank you!

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LIST OF SYMBOLS

A	Hamaker Constant, between 10^{-19} to 10^{-20} J (N·m) or 10^{-10} to 10^{-11} nJ (N·nm)
A_s	Porosity-dependent Parameter of Happel's Model
C_C	Correlation Coefficient
°C	Centidegree Degree Celsius
dc	Sand Grains
k	Function of the Ionic Composition
L	Liter
L_d	Filter Media Depth
$M_{\text{Microsphere}}$	Mass of One Microsphere
N	Number of Pairs of Samples
N_{Pe}	Peclet Number
N_R	Aspect Ratio
N_{vdw}	Van der Waals Number
$V_{\text{Microsphere}}$	Volume of One Microsphere
R	Radius of the Particle/Microsphere
r	Distance between the Two Particles
r_e	Removal Efficiency
α	Coagulation Efficiency (dimensionless)
ε	Permittivity constant, equals to $6.95 \cdot 10^{-7}$ nN/(mV^2)
ε_p	Porosity
σ	Collision Diameter (nm)

Ψ	Zeta Potential of the Particle (mV)
ρ	Density

LIST OF ABBREVIATIONS

Al	Aluminum
ANOVA	Analysis of Variance
ASTM	International Standard Worldwide
BFA	Body Fluid Analog
CA	Cluster Analysis (Statistical Analysis Method)
Ca	Calcium
CCA	Coagulant Charge Analyzer
CCC	Critical Coagulant Concentration
CDC	Centers for Disease Control and Prevention
Conc.	Concentration
CYA	Cyanuric Acid
Ct	Concentration (mg/L) multiplied by Time (minutes) (mg/L·min)
C. parvum	*Cryptosporidium parvum*
d_{10}	Size for which 10% of the Grains are Smaller by Weight
d_{60}	Size for which 60% of the Grains are Smaller by Weight
d_{90}	Size for which 90% of the Grains are Smaller by Weight
dc	Diameter of the Collector
DE	Diatomaceous Earth
DLVO	Derjaguin, Landau, Verwey, and Overbeek
DOC	Dissolved Organic Carbon
E_B	Born repulsion force
E_E	Electrical Double Layer Repulsive Force

E_V	Van der Waals Attractive Force
EFF	Filter Effluent
EPA	United States Environmental Protection Agency
Expt.	Experiment
Fe	Iron
gpm	Gallons per Minute
gpm/ft^2	Gallons per minute per Square Feet
HLR	Hydraulic Loading Rates
HOCl	Hypochlorous Acid, HOCl
HPA	Health Protection Agency
hr	Hour
INF	Filter Influent
ISO	International Organization for Standardization
kPa	Kilo Pascal
lbs/ft^2	Pounds per Square Feet
log	Log Reductions, calculated as the difference between the $\log_{10}$ of the influent concentration and the $\log_{10}$ of the filtrate concentrate.
LSI	Langelier Saturation Index
L/h	Liters per Hour
L/m^2	Liters per Square Meter
Mg	Magnesium
mg/L	Milligram per Liter
mg·Al/L	Milligram per Liter as Aluminum
mJ/cm^2	Millijoule per Square Centimeter

Min.	Minimum Value
min	Minute
mV	Millivolt
NSPF	National Swimming Pool Foundation (US)
NSF	National Science Foundation (US)
NTU	Nephelometric Turbidity Unit
OCL^-	Hypochlorite Ion, OCl^-
ORP	Oxidation Reduction Potential
oz/ft^2	Ounce per Square Feet
PACl	Polyaluminum Chloride
PAM	Polyacrylamide
PHLS	Public Health Laboratory Service
polyDADMAC	Polydiallyl dimethyl Ammonium Chloride
ppm	Parts per Million
psi	Pounds per Square Inch
PVC	Polyvinyl Chloride
PWTAG	Pool Water Treatment Advisory Group (UK)
PZC	Point of Zero Charge
R^2	Coefficient of Determination
REML	Residual Maximum Likelihood Approach (Statistical Analysis Method)
SCU	Streaming Current Unit
SLR	Surface Loading Rate
SOP	Standard Operating Procedure

Std. Dev.	Standard Deviation
SUVA	Specific Ultraviolet Absorbance
TDS	Total Dissolved Solid
TO	Turn Over Time of the Swimming Pools
TOC	Total Organic Carbon
UK	United Kingdom
US	United States
UV	Ultraviolet Light
UV_{254}	Ultraviolet Absorbance at 254 nm
WEP	Watertec Engineering Pty Ltd
WHO	World Health Organization
Vol.	Volume
#/L	Number of Microspheres per Liter
#/mL	Number of Microspheres per Milliliter
$\Delta q_{\text{Microsphere}}$	Charge of the Microsphere

CHAPTER 1: NATIONAL SWIMMING POOL WATER EVALUATION

1.1 Introduction

(Appendix A shows abstract for each chapter.)

1.1.1 Swimming Pool Water Contaminants and Indicators

Water recreational activities such as swimming can add significant quantities of microorganisms to a water body. Swimming pool water poses a risk to the patrons inadvertently ingesting contaminated water. Possible pool water contaminants include disinfection by-products, urine, sweat, dirt, cosmetics, bacteria, algae, *Cryptosporidium, Giardia*, and viruses. Microorganisms such as *Cryptosporidium* and *Giardia* are of special concern because the traditional disinfection method of free chlorine is not effective for treating these organisms, and associated waterborne disease outbreaks are well-documented every year (CDC, 1990; CDC, 1993; CDC, 2000; CDC, 2003; CDC, 2004; CDC, 2005; CDC, 2006; CDC, 2007). A 1 mg/L free chlorine residual in public swimming pools enables them to inactivate 99.9% of *Cryptosporidium* approximate 11 days (Ct = 15,300 mg/L·min) (Shields, et al., 2008).

1.1.1.1 Organic Matter Indicators

Natural organic matter (NOM) is a heterogeneous mixture of organic compounds with large molecules and containing many functional groups that affect their chemical behavior (Edzwald and Tobiason, 1999). NOM is typically quantified in water treatment plants by dissolved organic carbon (DOC) measurements and ultraviolet light absorbance at 254 nm (UV_{254}). Coagulation is controlled by NOM concentration in water treatment plants (Amburgey, 2002; Amburgey, et al., 2004; Brown and Emelko, 2009; Edzwald and Tobiason, 1999; Pernitsky and Edzwald, 2006).

DOC is an indicator of organic loadings in water body (Edwards, 1997). DOC consists of truly dissolved substances and macromolecules with colloid-like properties. DOC plays an important role in carbon cycle, providing a key energy source for bacterial assimilation and also influencing the bioavailability of carbon (Kirchman, et al., 1991). Analytical methods for DOC can be found in Standard Methods for the Examination of Water and Wastewater with vacuum-filtered or pressure filtered through a 0.45 μm pore size filter (AWWA, 2012; Eaton, 2005).

UV_{254} is a useful surrogate measure of selected organic constituents, and it is analyzed after filtration through 0.45 μm membrane filters (Karanfil, et al., 2003). A strong correlation may exist between UV absorption and organic carbon content, color, and precursors of trihalomethanes (THMs) and other disinfection byproducts (Edzwald and Tobiason, 1999). Double bonds and aromatic rings in organic molecules absorb UV_{254}, and it thus can provide a quick estimate of the organic carbon content of raw water samples (Edzwald and Tobiason, 1999).

UV_{254} samples must be filtered through a 0.45 μm pore-sized membrane filter and measured in waters prior to the addition of an oxidant or disinfectant (Eaton, 2005). This is necessary because oxidants react with organic compounds and cleave the double bonds that absorb UV. The disinfection by-products (DBPs) produced by the reaction between the aromatic organics and chlorine are carcinogenic for humans. In European swimming pool systems, ozone is commonly applied to reduce the organic load in water (Finney, 2012). The disinfection byproducts are then removed by various filtration processes prior to the water being returned to the pool with a slight dose of chlorine (Finney, 2012).

SUVA indicates the nature of NOM and the likely effectiveness of coagulation in removing NOM (Pernitsky and Edzwald, 2006). SUVA correlates well with the aromaticity and the hydrophobicity of the organic carbon. High hydrophobicity is associated with good treatability by coagulation. NOM controls coagulation if SUVA is greater than 4 m^{-1}/mg/L, strongly influences coagulation if SUVA is between 2 m^{-1}/mg/L and 4 m^{-1}/mg/L, and has little influence if SUVA is less than 2 m^{-1}/mg/L (Edzwald and Tobiason, 1999; Pernitsky and Edzwald, 2006). The DOC and UV_{254} determinations are used in the calculation of the Specific UV Absorbance (SUVA). Its value offers a simple characterization of the nature of the NOM based on the UV absorbance and DOC (as shown in Equation (1.1)) (Edzwald and Tobiason, 1999).

$$SUVA = \frac{UV_{254}(cm^{-1}) \times 100(cm/m)}{DOC(mg/L)} \tag{1.1}$$

1.1.1.2 Particle Measurement

Increased coagulant demand will also be caused by increased particle concentration (Pernitsky and Edzwald, 2006). Both turbidity and particle size distribution have been recognized as parameters detecting the particle concentration in water (Bellamy, et al., 1993).

Turbidity reflects ‘cloudiness’ of water sample, which needs to be controlled for safety and effective disinfection (ISO, 1999). For easy visual identification of bodies at the bottom of a pool, a universal turbidity value is not considered to be appropriate as much depends on characteristics of the pool, such as surface reflection and pool construction (Perkins, 2000). It is recommended that a small child should be seen at the bottom of the pool from the lifeguard position while the water surface is in movement (WHO, 2000). In terms of effective disinfection, a useful but not absolute, upper-limit guideline for turbidity is 0.5 NTU (ISO, 1999). Turbidimeters measure the amount of 90^{o} light scatter from particles in water, which is sensitive to a wide range of particle sizes (0.01 μm and larger). Turbidity readings are mostly influenced by the number of submicron particles (<1 μm) present in the sample (Gregory, 1994; Hunt, 1993).

Particle counters can be more sensitive to changes in water quality (Gregory, 1994; Hunt, 1995; Lewis, et al., 1992). The light obscuration of each particle is proportional to its size, and particle counters measure a change in light intensity as particles pass through a laser beam to report the particle size distribution in water, usually 1 μm and larger (Hunt, 1995; Lewis, et al., 1992). In many instances, turbidity and particle count trends correlate strongly with each other (Gregory, 1994; Hunt, 1993; Hunt, 1995; ISO, 1999; Lewis, et al., 1992).

1.1.2 Swimming Pool Water Chemistry

1.1.2.1 Water pH

The bulk properties of pool water, specifically pH, must be controlled to ensure efficient disinfection and coagulation (Hendricks, 2006; Lewis, et al., 1992; NSPF, 2009; Perkins, 2000; WHO, 2000). The desired pH for disinfection and bather comfort should be maintained between 7.2 and 7.8 for chlorine disinfectants and between 7.2 and 8.0 for bromine-based and other non-chlorine disinfectants (NSPF, 2009; Perkins, 2000; WHO, 2000).

1.1.2.2 Free Chlorine

Chlorine is one of the most commonly used disinfectants for water disinfection. Ct values (Ct = concentration of disinfectant (mg/L) × exposure time (minutes)) for a 3 log reduction in *Cryptosporidium* oocyst viability were from 10,400 to 15,300 at pH 7.5 (Shields, et al., 2008). Chlorine is commercially available as gaseous chlorine (Cl_2) and as sodium hypochlorite liquid ($NaOCl$) or calcium hypochlorite ($Ca(OCl)_2$). Hypochlorous acid ($HOCl$) and hypochlorite ion (OCl^-) are the products of NaOCl dissociation in water and are the two forms of free chlorine. The dissociation formula of HOCl in water is shown in chemical reaction below (Equation (1.2)) (NSPF, 2009; Perkins, 2000; WHO, 2000):

$$HOCl \leftrightarrow H^+ + OCl^- \tag{1.2}$$

The efficacy of disinfection is determined by the pH. Disinfection will take place optimally when the pH is between 5 and 7 as then a maximum proportion of HOCl is present (Hendricks, 2006). HOCl is 80-100 times more effective than OCl^- (Hendricks, 2006). HOCl does not evaporate and does not cause severe corrosion like Cl_2. Cl_2 exposed in air can be very dangerous. For this reason, the ideal pH is > 6 as no Cl_2 is present. The highest level of HOCl is at pH value of 5.5. With a pH value of 6.5 the level of HOCl is more than 90%, whereas the concentration of OCl^- is less than 10%. Free available chlorine compounds with regard to pH are shown in Figure 1.1.

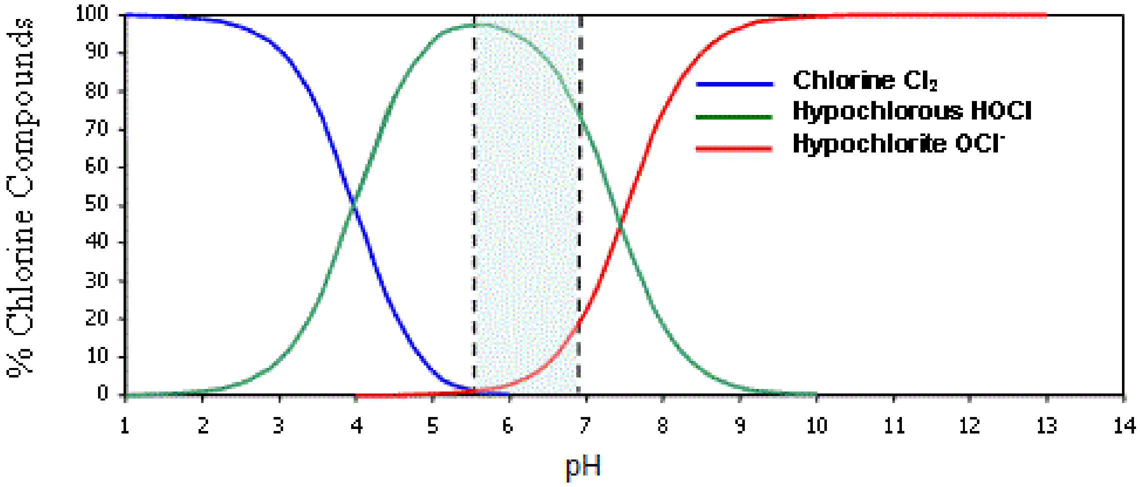
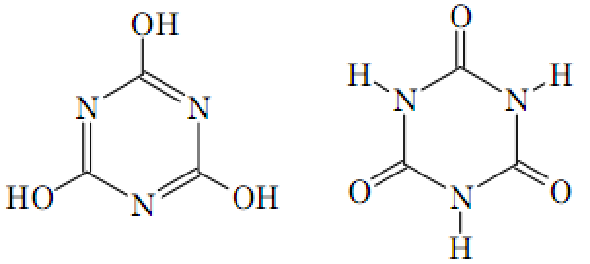


Figure 1.1 Chlorine Compounds Content versus Water pH (Dickerson, 2012; Gordon, et al., 1999)

1.1.2.3 Cyanuric Acid (CYA)

The chlorinated salts of cyanuric acid (CYA, $(CNOH)_3$) have found an important role in recreational swimming pool waters (Cantú, et al., 2001; Wojtowicz, 2001). Figure 1.2 shows two structures CYA can exist. CYA is from the dissociated chlorinated isocyanurate and is used in outdoor pools with the inorganic chlorines such as calcium hypochlorite, sodium hypochlorite, lithium hypochlorite, and chlorine gas. CYA can release disinfectant chlorine and keep HOCl from being decomposed by ultraviolet light (Cantú, et al., 2001; Cantú, et al., 2001). When CYA is used in an outdoor pool, chlorine consumption is reduced because the chlorine degradation caused by ultraviolet light is reduced. In solution, CYA has the ability to tie up residual chlorine through complex equilibria to form up to six-chlorine isocyanurates at various pHs (Cantú, et al., 2001). The recommends levels of the CYA stabilizer in the 10-100 mg/L recommended by the National Swimming Pool Foundation (NSPF, 2009; Perkins, 2000; WHO, 2000). The level of CYA is reduced by dilution due to filter backwashing, bather dragout, or dumping. CYA is a suspected gastrointestinal or liver toxicant in humans, thus pools above 100 mg/L need to be partially drained, and have fresh water added (Perkins, 2000; Yilmaz and Yazar, 2010). High levels of CYA also cause a situation known as ‘chlorine lock’, which inhibits chlorine disinfection (WHO, 2000).



enol
Cyanuric Acid

keto
Isocyanuric Acid

Figure 1.2 Cyanuric Acid Structure (Wojtowicz, 2001)

CYA significantly decreases the rate of inactivation for *Cryptosporidium parvum* oocysts. Disinfection and remediation of swimming pools containing CYA-based chlorine disinfectants require increased exposure time, and/or higher concentrations of free chlorine, to achieve the same level of oocysts inactivation that can be expected for hyperchlorination when CYA is not present (Shields, et al., 2009). When 50 mg/L CYA was present there was a 0.7 log reduction in *Cryptosporidium* oocysts viability after 10 hours as compared to a 3.7 log reduction without CYA (Shields, et al., 2009).

1.1.2.4 Oxidation Reduction Potential (ORP)

Oxidation reduction potential (ORP) control of sanitizers in pools and spas is used all over the world. ORP is used in pool water treatment as an indication of sanitation in relation to free chlorine parameter (Steininger, 1985). As shown in Figure 1.3, the most important factor affecting sanitizer activity is pH, because it changes the concentration of the more active form of free chlorine (HOCl). As a result, chlorine becomes less effective at higher pH. The recommended ORP level for pools and spas is typically between 650 and 750 mV (Steininger, 1985; Steininger, 1998), but it can be even higher in very clean water.

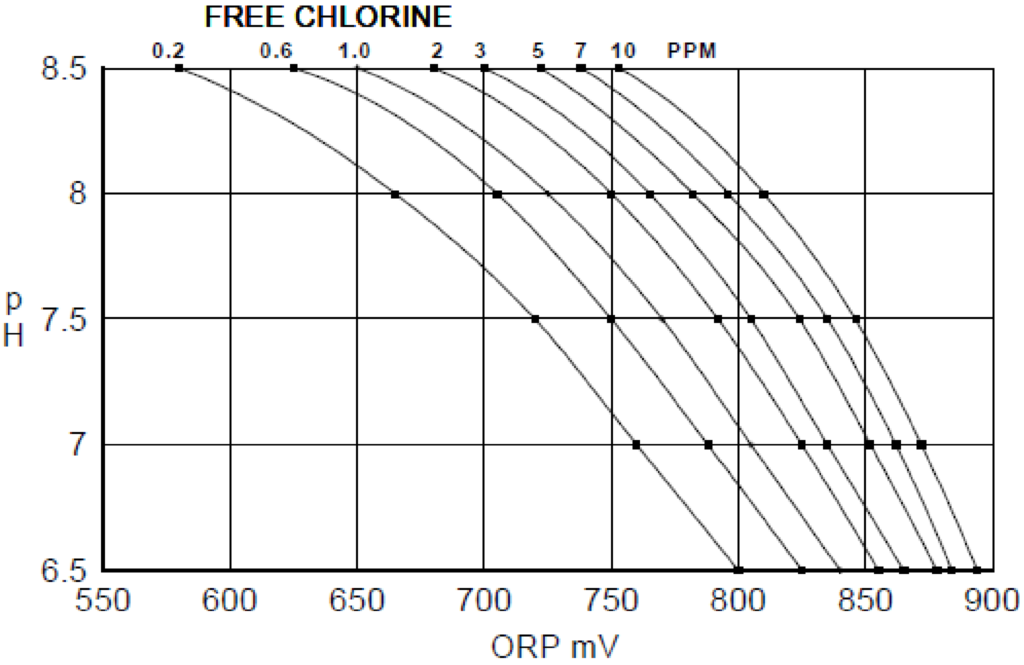


Figure 1.3 PPM Readings versus ORP and pH
(temperature = 25 °C, alkalinity = 100 mg/L, total dissolved solid = 500 mg/L)
(Steininger, 1998)

1.1.2.5 Alkalinity and Hardness

Alkalinity (with units of mg/L as $CaCO_3$) is an operational measure showing the acid neutralization capacity of the pool water (Hendricks, 2006). The higher the alkalinity, the more resistant the water is to large changes in pH in response to the addition of acidic chemicals. Calcium hardness (also with units of mg/L as $CaCO_3$) is a

measure of the quantity of divalent cation such as calcium, magnesium and/or iron in water (Hendricks, 2006). The pool operator must control both the amount of carbonate alkalinity and the pH to provide enough calcium carbonate to saturate the water.
In general, total alkalinity must be kept between 80 mg/L and 125 mg/L (NSPF, 2009). A low total alkalinity makes it difficult to maintain a desired pH and can lead to corrosive water, which causes damage to equipment. High total alkalinity can also cause scale to form and the water to become cloudy (Perkins, 2000). Scale is the whitish crystallized deposit formed by mineral salts such as carbonates of magnesium and calcium (Perkins, 2000; WHO, 2000).

Calcium hardness (Ca) and magnesium hardness (Mg) are the primary ions contributing to water hardness with calcium typically accounting for 97% of the hardness (NSPF, 2009; Perkins, 2000). Other hardness contributors are iron (Fe) and aluminum (Al) but are generally ignored because they are easily removed in the water treatment process, or by the addition of sequestering agents. Generally, calcium hardness levels are kept at 200 to 400 mg/L (NSPF, 2009; Perkins, 2000). Low calcium hardness presents a larger problem to pools than high calcium hardness does. If pH, total alkalinity, and calcium hardness are low, the corrosiveness and aggressiveness of the pool water will be greatly increased. This causes problems in deterioration of the pool walls and corrosion of metal parts. The higher the hardness, the more scaling the water is.

1.1.2.6 Total Dissolved Solid (TDS) and Conductivity

The amount of salts in solution is referred to as total dissolved solids (TDS). The National Swimming Pool Foundation suggests keeping the levels of TDS under 1,500 ppm (NSPF, 2009). High TDS may lead to erratic and unreliable pool testing results and the water will look pale and cloudy (Perkins, 2000). The TDS and the electrical conductivity are closely related. The more salts dissolved in the water, the higher the value of the electric conductivity. Conductivity is the ability to conduct or transmit electricity. The electrical current is transported by the ions in solution, thus the conductivity increases as the concentration of ions increases (Mihelcic, 1999).

1.1.2.7 Temperature

Temperature impacts the corrosiveness or scale forming properties of water. As water temperature increases, the water tends to become more basic and scale-forming. Conversely, as the temperature decreases, water becomes more corrosive (Perkins, 2000). In addition, bather comfort is the primary consideration for temperature setting.

1.1.2.8 Water Balance

A commonly used tool in determining the degree of calcium carbonate saturation in pool water is the Langelier Saturation Index (LSI). The degree of saturation calculation is shown as Equation (1.3) and Table 1.1 (NSPF, 2009; Perkins, 2000). LSI is determined by the pH, temperature, total alkalinity and calcium hardness found in the pool water. Pool water would be balanced at LSI in the range of -0.5 to 0.5. It may also be defined as pool water that is either corrosive (< -0.5) or scaling (> 0.5) (NSPF, 2009; Perkins, 2000).

$$\text{Langelier Saturation Index (SI)} = pH + TF + CF + AF - TDS \qquad (1.3)$$

where, pH is the pH value of the water
TF is temperature factor converted from the real temperature of water
CF is calcium hardness factor converted from the real hardness of water
AF is total alkalinity factor converted from the real alkalinity of water
TDS is a factor for total dissolved solids, equals to 12.1
when TDS < 1000 mg/L (ppm) and 12.2 when TDS > 1000 mg/L (ppm).

Table 1.1 Numerical Values for Saturation Index Formula (Perkins, 2000)

Water Temperature (°C)	Temperature Factor	Hardness (mg/L)	Calcium Factor	Alkalinity (mg/L)	Alkalinity Factor
0	0.0	5	0.3	5	0.7
3	0.1	25	1.0	25	1.4
8	0.2	50	1.3	50	1.7
12	0.3	75	1.5	75	1.9
16	0.4	100	1.6	100	2.0
19	0.5	150	1.8	150	2.2
24	0.6	200	1.9	200	2.3
29	0.7	300	2.1	300	2.5
34	0.8	400	2.2	400	2.6
40	0.9	800	2.5	800	2.9
53	1.0	1000	2.6	1000	3.0

1.2 Materials and Methods

1.2.1 Objectives

The intent of this chapter is to investigate the national swimming pool water chemical properties, such as pH, cyanuric acid (CYA), total alkalinity as $CaCO_3$, calcium hardness as $CaCO_3$, as well as other water quality parameters, such as turbidity, particle size distribution, UV_{254} absorbance, dissolved organic carbon (DOC) concentration, SUVA, and conductivity. Samples were collected and analyzed for chemical constituents and water quality from thirty-five swimming pools geographically distributed around the US pools including of indoor, outdoor, public, private, hotels, apartment complexes, community pools, water parks, swim clubs, etc, over the course of the spring and summer of 2010. Spatial and temporal swimming pool water quality variation will be analyzed using t-test; three representative swimming pool waters will be provided based on the investigated pools using a cluster analysis method. This study will reveal typical swimming pool water quality in order to lay a foundation for the remediation of contaminated swimming pool water. It will be the first nationwide water quality evaluation of US swimming pool water.

1.2.2 Sample Collection

Swimming pool water samples from thirty five swimming pools were collected in the United States, among which 18 pools' samples were collected both in spring and summer, and 17 pools' samples were only collected in summer or in spring. Most of swimming pool samples were collected in North Carolina. Other pools were collated in Hawaii, Florida, Massachusetts, Wisconsin and Texas, etc. Samples were collected in 500 mL high-density polyethylene (HDPE) plastic bottles, shipped to Charlotte, NC, and stored at 4 °C. Duplicate samples were taken.

1.2.3 Chemical Analyses

Chemical constituents of each sample were analyzed using a Pooltest 25 Professional Plus (Palintest, Erlanger, Kentucky, USA). The constituents measured were pH, free chlorine, calcium hardness, total alkalinity, sulfate, and CYA. The Pooltest 25 is a colorimeter that uses 10 mL round glass cuvettes. A background reading of the pool water, without additional chemical reagents, was taken of each pool sample prior to testing to eliminate background colors from affecting the results of the tests. The particle counter used in this analysis was a Liquid Sampler LS-200 (LiQuilaz® Particle Measuring Systems, Boulder, Colorado, USA). The instrument was flushed, prior to each test, with ultra-pure water. The turbidimeter used in this study was a Hach 2100 AN Turbidimeter (Hach Company, Loveland, Colorado, USA). Sample cells were cleaned prior to each test and instrument calibrations were performed regularly. Samples for UV_{254} absorbance and DOC measurements were filtered using a 25 mm, 0.4 μm polycarbonate filter (Product # K04CP02500, GE Osmonics, Minnetonka, Minnesota, USA). The filter was applied to the filter housing and flushed with 30 mL of ultra-pure water. UV_{254} absorbance was done using a UV-visible spectrophotometer (Agilent Technologies, Varian Cary 100 BIO UV Spectrophotometer, Santa Clara, California, USA). The DOC of each pool sample was measured for each filtered pool water sample (GE Water and Process Technologies, Sievers 900 on-line, Boulder, CO, USA). Samples were stored in 40 mL glass vials. 6 M (molar/L) phosphoric acid (H_3PO_4) and 15% ammonium persulfate ($(NH_4)_2S_2O_8$) were used as measurement reagents. All sample data were taken in triplicate to ensure accuracy.

1.2.4 Statistical Analysis

A correlation is a single number that describes the degree of relationship between two variables. The correlation coefficient (C_C) is calculated as Equation (1.4) (Bendat and Piersol, 1993; Miles and Shevlin, 2000).

$$C_C = \frac{N\sum xy - (\sum x)(\sum y)}{\sqrt{[N\sum x^2 - (\sum x)^2][N\sum y^2 - (\sum y)^2]}} \qquad (1.4)$$

where N is the number of pairs of samples, x and y are investigated variables.

In most studies, there are considerably more than two variables. A correlation matrix lists all the correlation between paired variables (Miles and Shevlin, 2000). This paper discussed the correlation between pH, alkalinity, hardness, and free chlorine concentration in the pool water using the correlation matrix with the residual maximum likelihood (REML) approach. REML estimation is a form of maximum likelihood estimation, which does not base estimates on a maximum likelihood fit of all the information (Harville, 1977; See, et al., 1993).

Cluster analysis (CA) is a group of multivariate techniques to assemble objects based on the characteristics they possess. CA divides a large number of objects into a smaller number of homogenous groups on the basis of their correlation structure. The resulting clusters of objects should then exhibit high internal (within-cluster) homogeneity and high external (between clusters) heterogeneity. Hierarchical agglomerative clustering is a common approach, which provides intuitive similarity relationships between any one sample and the entire data set, and what is typically illustrated by a dendrogram (tree diagram) (Everitt, et al., 2011). The dendrogram provides a visual summary of the clustering processes, presenting a picture of the groups and their proximity, with a dramatic reduction in dimensionality of the original data. The Euclidean distance usually gives the similarity between two samples, and a distance can be represented by the difference between analytical values from the samples (Everitt, et al., 2011).

In this study, hierarchical agglomerative CA was performed on the normalized data set by means of the Ward's method, using squared Euclidean distances as a measure of similarity. Ward's method is most-used hierarchical clustering technique, and this procedure links the pair of groups that produce the smallest variance in the merged group. The Ward's method uses an analysis of variance approach to evaluate the distances between clusters in an attempt to minimize the sum of squares of any two clusters that can be formed at each step (Everitt, et al., 2011). The statistics software JMP (SAS Institute Inc.) was applied for all the statistical calculation.

Type 1 t-test was performed by Microsoft Excel. Two tailed t-test was applied with $\alpha = 0.05$. A P-value below 0.05 was considered statistically significant, while one of 0.05 or greater indicated no difference between the groups.

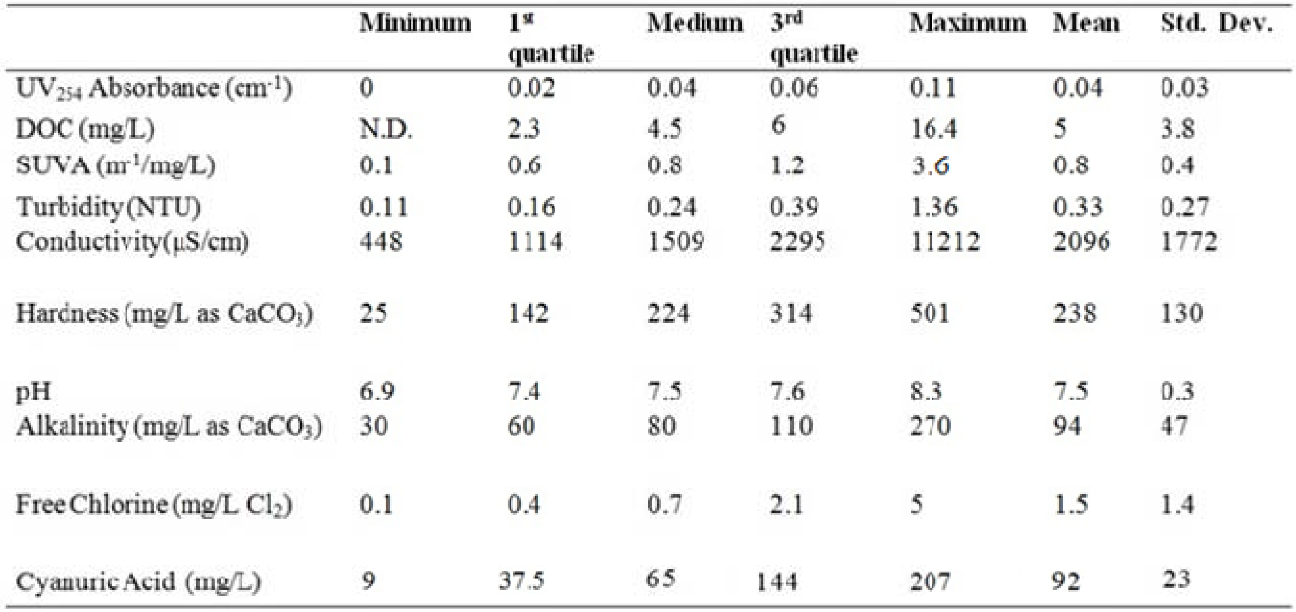
1.3 Results and Discussions

Thirty-five swimming pools were investigated with the mean pool volume of 500 m^3 (0.22 - 1892 m^3). Flow rates for pools were from 302 to 9,462 L/min. The mean number of swimmers per day were in the range of 10 to 1,500 with a mean of 120, and the maximum number of swimmers for one day was from 12 to 2,200 (mean was 240) according to the survey questionnaire. The full list of questions and information supplied by each pool can be viewed in Appendix B.

The measured parameters were divided into two categories, water quality parameters (i.e., turbidity, particle size distribution, UV_{254} absorbance, conductivity, and DOC concentration) and water chemistry properties or operational parameters (i.e., pH, free chlorine, temperature, total alkalinity, and calcium hardness). Tables 1.2 and 1.3 briefly summarize statistical values for each parameter. The box plot was also provided to descript swimming pool water quality parameters and chemistry properties.

In statistics, a box plot is a convenient way of graphically depicting groups of numerical data through their five-number summaries: the sample minimum value (lower portion of the line), 25th percentile of samples (lower portion of the box), median of samples (the line in the box), 75th percentile (upper portion of the box), and sample maximum value (upper portion of the line).

Table 1.2 Statistical Descriptive for the National Swimming Pool Water Samples



	Minimum	1st quartile	Medium	3rd quartile	Maximum	Mean	Std. Dev.
UV_{254} Absorbance (cm^{-1})	0	0.02	0.04	0.06	0.11	0.04	0.03
DOC (mg/L)	N.D.	2.3	4.5	6	16.4	5	3.8
SUVA (m^{-1}/mg/L)	0.1	0.6	0.8	1.2	3.6	0.8	0.4
Turbidity(NTU)	0.11	0.16	0.24	0.39	1.36	0.33	0.27
Conductivity(µS/cm)	448	1114	1509	2295	11212	2096	1772
Hardness (mg/L as $CaCO_3$)	25	142	224	314	501	238	130
pH	6.9	7.4	7.5	7.6	8.3	7.5	0.3
Alkalinity (mg/L as $CaCO_3$)	30	60	80	110	270	94	47
Free Chlorine (mg/L Cl_2)	0.1	0.4	0.7	2.1	5	1.5	1.4
Cyanuric Acid (mg/L)	9	37.5	65	144	207	92	23

Table 1.3 Particle Counts for the National Swimming Pool Water Samples

Particle Size	Minimum	1st Quartile	Medium	3rd Quartile	Maximum	Mean	Std. Dev.	Cumulative Percent of Total Count
2 µm	32	156	225	551	1640	387	381	41%
3 µm	16	66	90	192	613	147	131	57%
4 µm	10	37	55	102	346	81	71	65%
5 µm	7	24	33	58	238	50	46	71%
6 µm	5	42	24	17	223	40	45	75%
7 µm	4	16	21	33	292	39	55	79%
8 µm	4	15	19	29	398	42	75	83%
9 µm	5	13	18	25	399	39	76	88%
10 µm	11	65	44	36	652	79	116	96%
15 µm	1	7	10	17	88	14	14	97%
20 µm	1	6	9	17	234	17	34	99%
30 µm	0	1	3	4	81	6	12	100%
50 µm	0	0	0	1	11	1	2	100%
75 µm	0	0	0	0	4	0	1	100%
125 µm	0	0	0	0	0	0	0	100%

Recommended values of parameters for the swimming pool are illustrated in Table 1.4. Figure 1.4 shows the hardness and alkalinity values for 35 swimming pools. Eight pools hardness were below the minimum of 200 mg/L, and six pools were above 400 mg/L. It recommends that calcium hardness be maintained at a minimum of 200 mg/L as $CaCO_3$ to prevent corrosion or pipe scale accumulation (NSPF, 2009). Alkalinities for one third of the invested pools were below 80 mg/L, which may cause pH values to fluctuate widely due to a lack of pH buffer capacity. Alkalinity greater than 200 mg/L was observed in two pools, which could lead to difficulty in adjusting pH (NSPF, 2009).

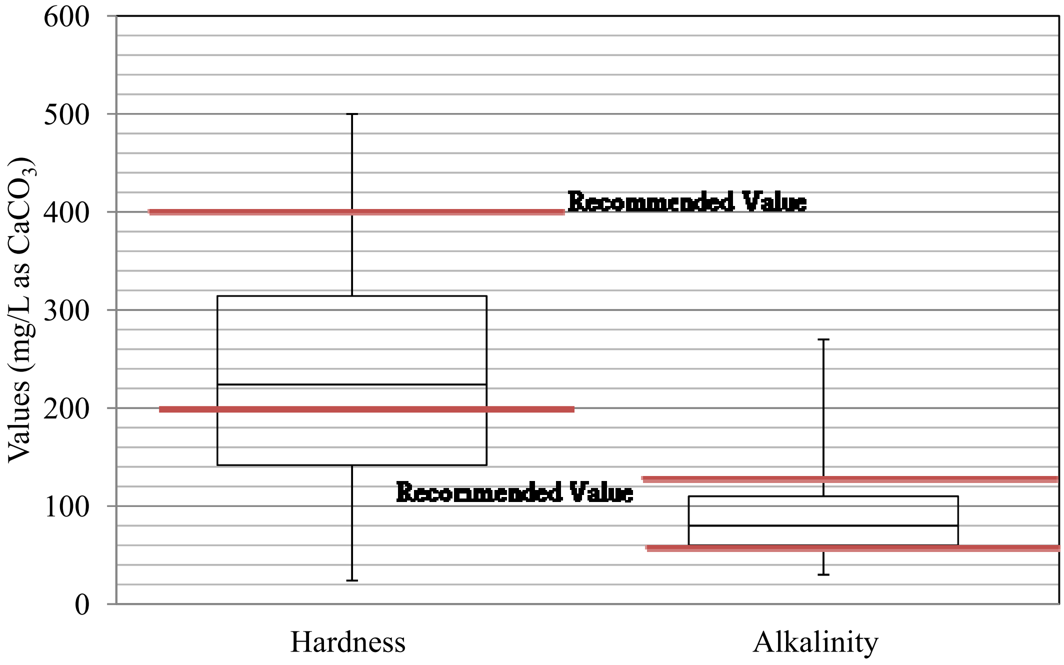


Figure 1.4 Hardness and Alkalinity for 35 Swimming Pools (Red lines show recommended values)

Figure 1.5 shows free chlorine values for 35 swimming pools. Adequate routine disinfection should be achieved with a free chlorine level of 1 mg/L, and these should not exceed 5 mg/L for public pools by reducing the formation of disinfection byproducts (NSPF, 2009). Free chlorine concentrations of the investigated pools were less than 5 mg/L. Five pools had CYA levels higher than 100 mg/L in this investigation, and this concentration would interfere with the release of free chlorine (NSPF, 2009; Perkins, 2000).

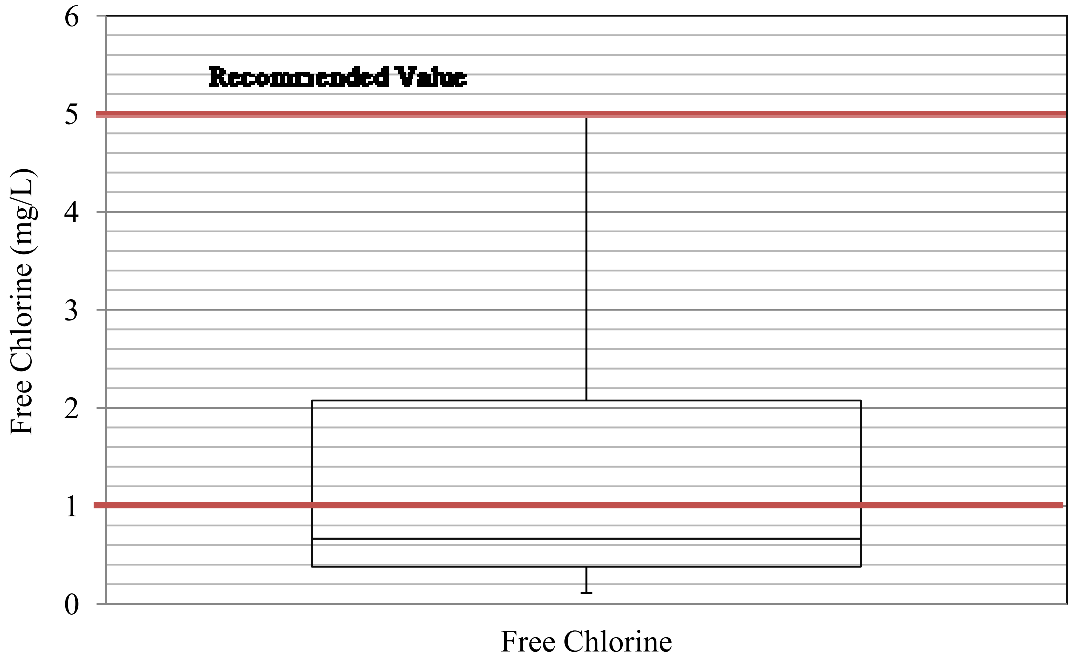


Figure 1.5 Free Chlorine Values for 35 Swimming Pools (Red lines show recommended values)

Figure 1.6 shows pH values for 35 swimming pools. Eight pools' pH were out of the recommended pH range (7.2 -7.8). High pH can lead to less effective disinfection, poor metal-based coagulation, and pipe scale (Perkins, 2000). Swimming pools operate in a narrow pH range, thus they must select a coagulant will function at the operational pH and then determine an effective dosage.

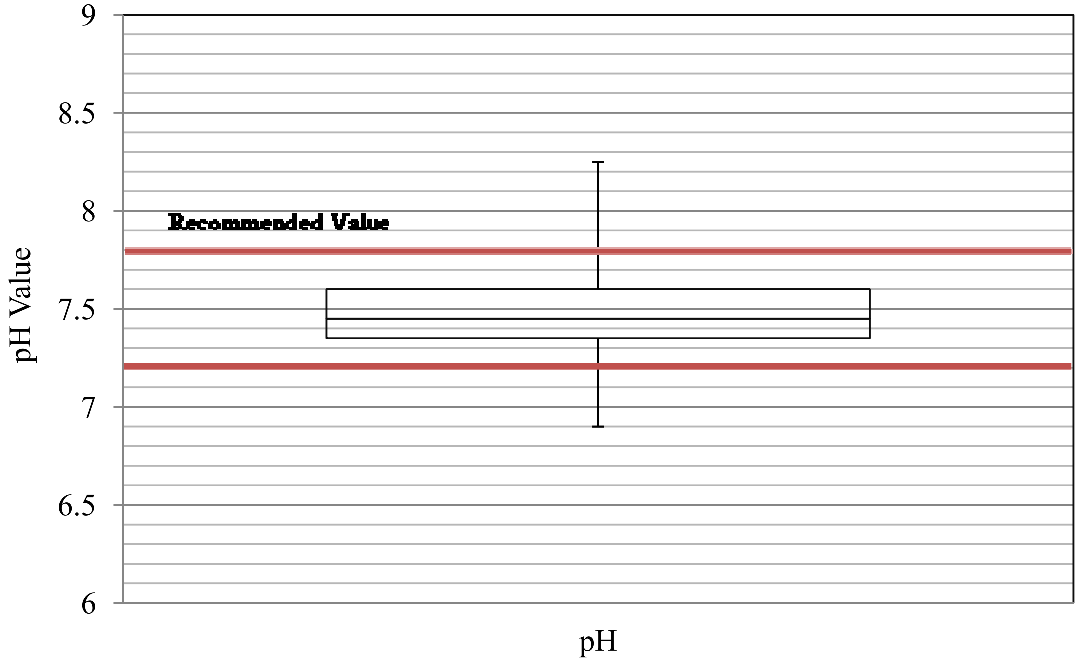


Figure 1.6 pH Values for 35 Swimming Pools (Red lines show recommended values)

Conductivities for 35 swimming pools are shown in Figure 1.7. The conductivity for the national pool water varied widely with the mean of 2,096 µS/cm, and standard deviation of 1,772 µS/cm. The high dispersion of variables (high standard deviations) indicates variability in chemical composition between samples, which was primarily caused by some of the pools with salt chlorine generation systems.

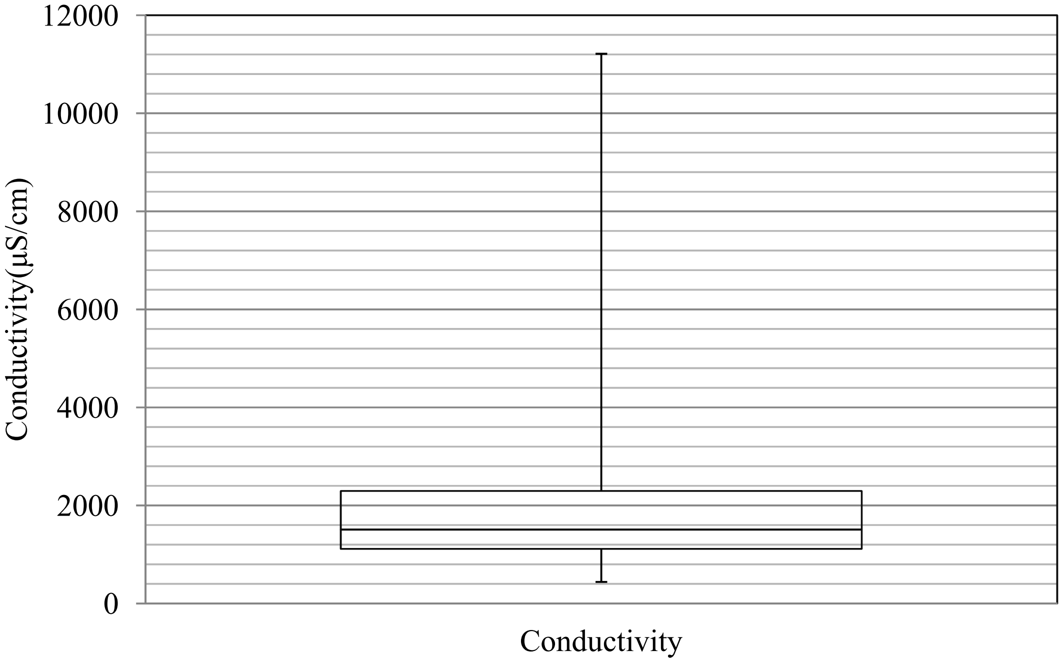


Figure 1.7 Conductivities for 35 Swimming Pools

Table 1.4 Recommended Chemical Values for the Swimming Pool (NSPF, 2009)

pH	7.2 - 7.8
Free Chlorine (mg/L)	1 - 5
CYA (mg/L)	< 100
Alkalinity (mg/L as $CaCO_3$)	80 - 125
Hardness (mg/L as $CaCO_3$)	200 - 400

1.3.1 Swimming Pool Water Quality Spatial and Temporal Variation

Turbidities for the pools are shown in Figure 1.8. Turbidities for the pools were from 0.11 NTU to 1.36 NTU. Most (more than 75%) pools' turbidity was less than 0.5 NTU. Particle counters can be more sensitive at low turbidities (Hunt 1995, Hunt 1993). It can be seen from the particles data that the majority of particles (57%) were 3 µm or less in diameter, and over 90% of particles in pool water were 10 µm or less in diameter, as shown in Table 1.3.

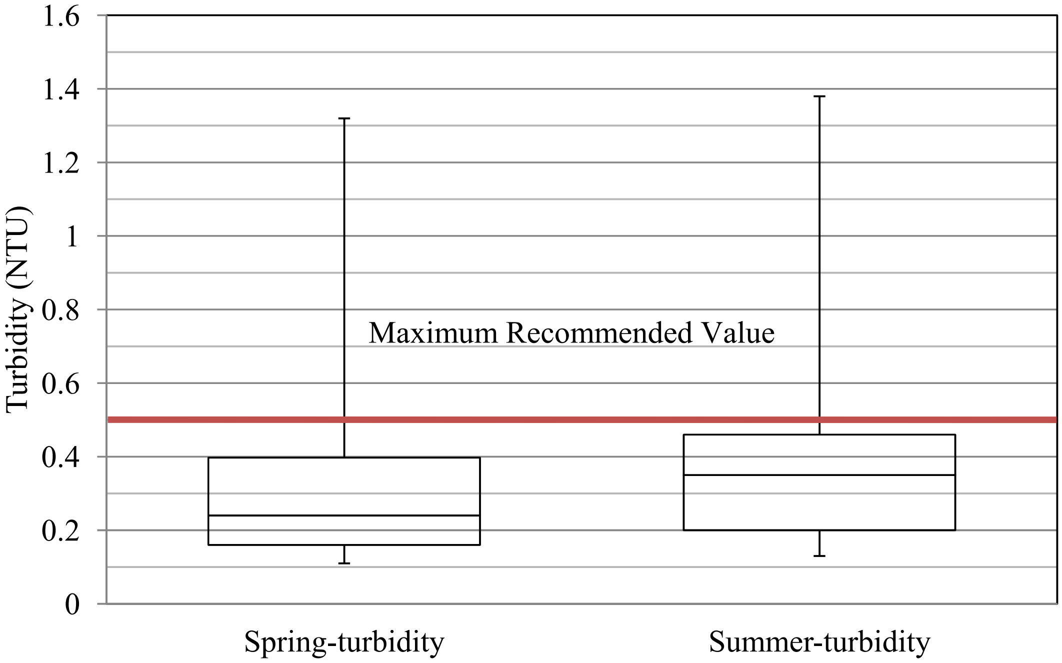


Figure 1.8 Swimming Pool Turbidity Variation versus Time (n=18) (Red lines show recommended values)

DOC values are shown in Figure 1.9. The DOC values for the pools were less than 16 mg/L (with mean of 5 mg/L). UV_{254} are shown in Figure 1.10. UV_{254} of the pool samples were less than 0.11 cm^{-1}. SUVA data showed more than 75% of pools were less than 2 m^{-1}/mg/L, which indicated mostly non-humics organic contained in the pool with low hydrophobicity (Edzwald and Tobiason 1999, Pernitsky and Edzwald 2006).

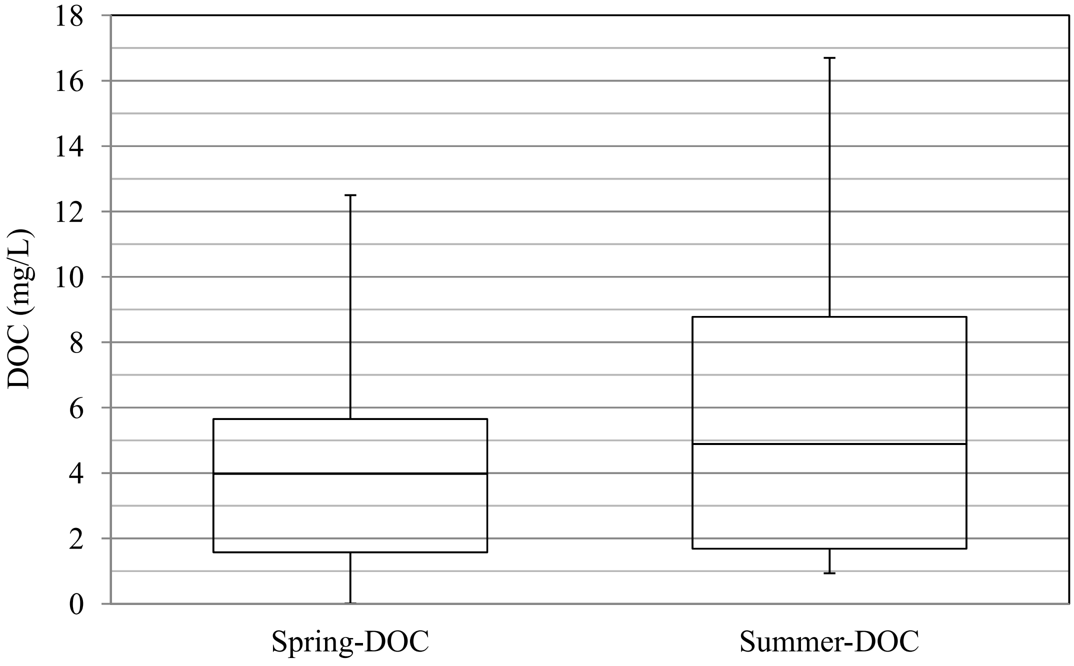


Figure 1.9 Swimming Pool DOC Variation versus Time (n=18)

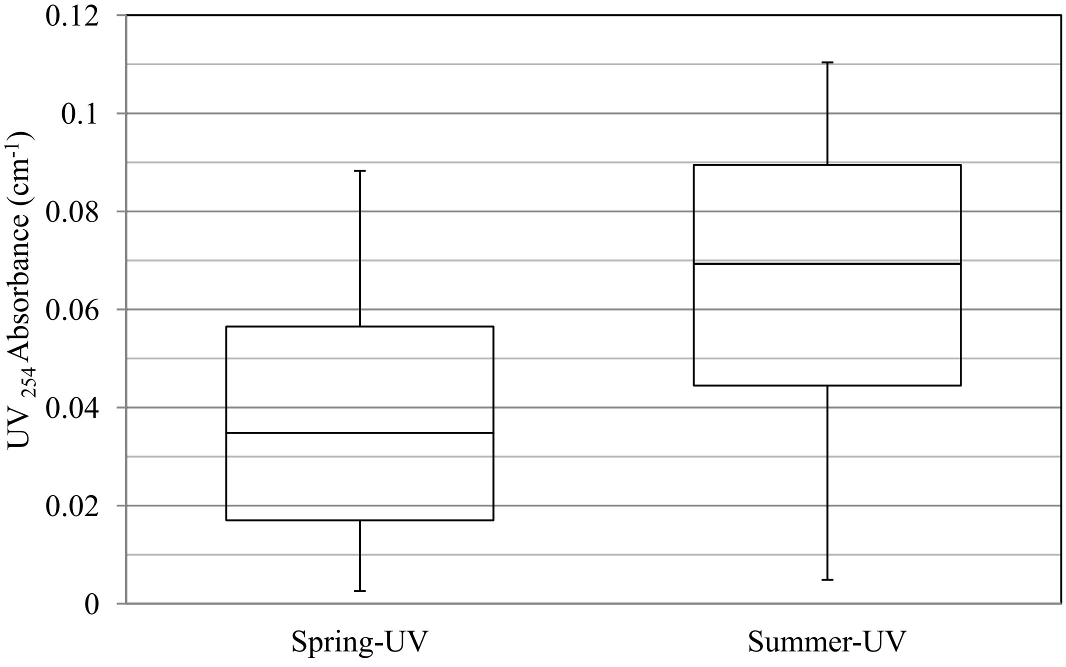


Figure 1.10 Swimming Pool UV_{254} Variation versus Time (n=18)

T-tests were conducted to assess the water quality temporal variation using parameters including turbidity, UV_{254}, DOC, and conductivity. There was significant seasonal variation according to the paired t-tests results for turbidity ($P<0.01$), UV_{254} ($P < 0.0001$) and DOC ($P < 0.01$). Turbidity, UV_{254} and DOC values in summer (July, August, and September) were higher than in spring (April, May and June) (as shown in Figures 1.8, 1.9, and 1.10). Seasonal water quality variation likely corresponds to the number of swimmers. The potential contamination sources derive from the skin and excretion products of swimmers, such as skin cells, sebum, hairs, cosmetics, sweat, urine, mucus, and saliva. These components are not necessarily harmful for human health. However, they can react with disinfectants in the water, such as free chlorine, to form unwanted reaction by-products (e.g., chloramines and disinfection by-products).

Spatial variation of swimming pool water quality is determined by t-test based on the indoor and outdoor swimming pool investigation data (Figures 1.11, 1.12, and 1.13). There were significant differences between DOC ($P = 0.02$) for the indoor and outdoor swimming pools. Indoor pools had the higher DOC than outdoor pools. Turbidity and UV_{254} variation had no statistical significance.

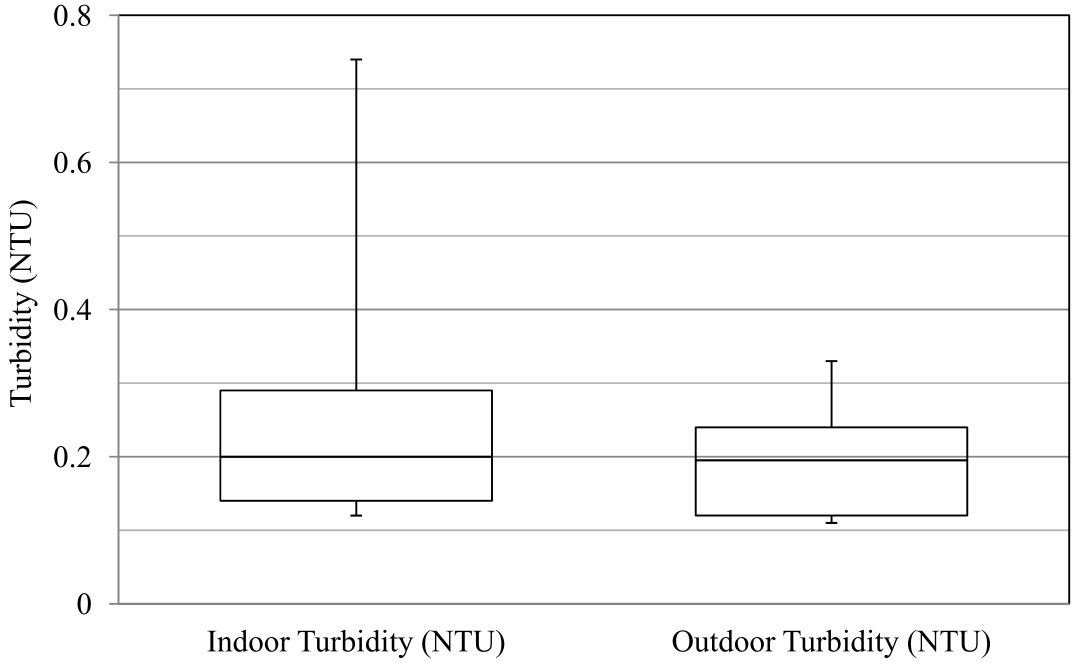


Figure 1.11 Indoor and Outdoor Swimming Pools Turbidity Variation (n=35)

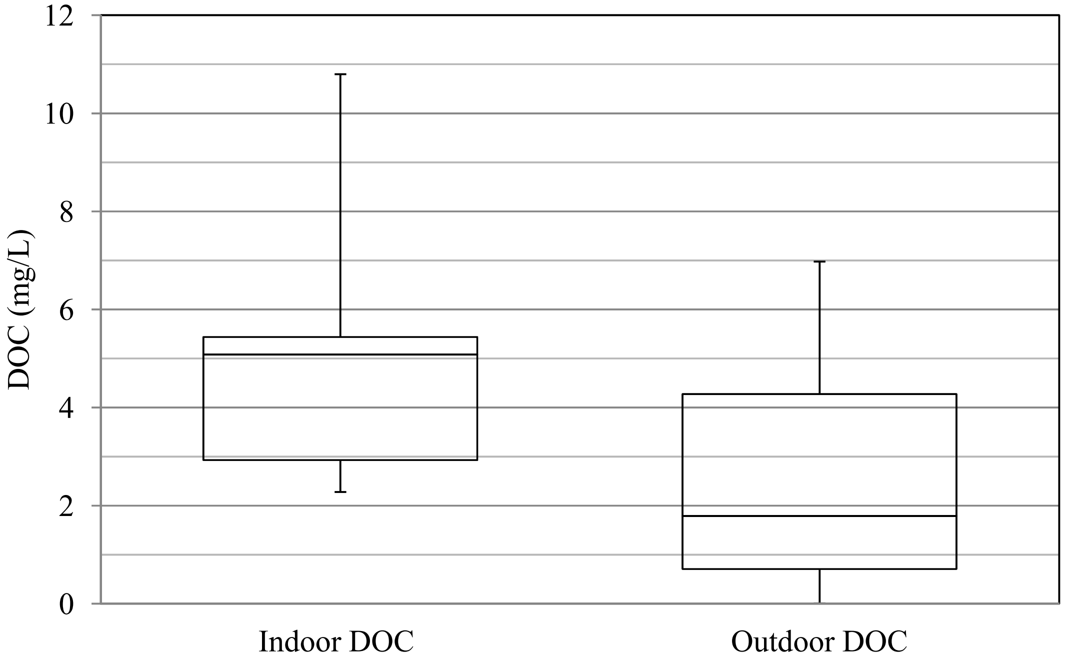


Figure 1.12 Indoor and Outdoor Swimming Pools DOC Variation (n=35)

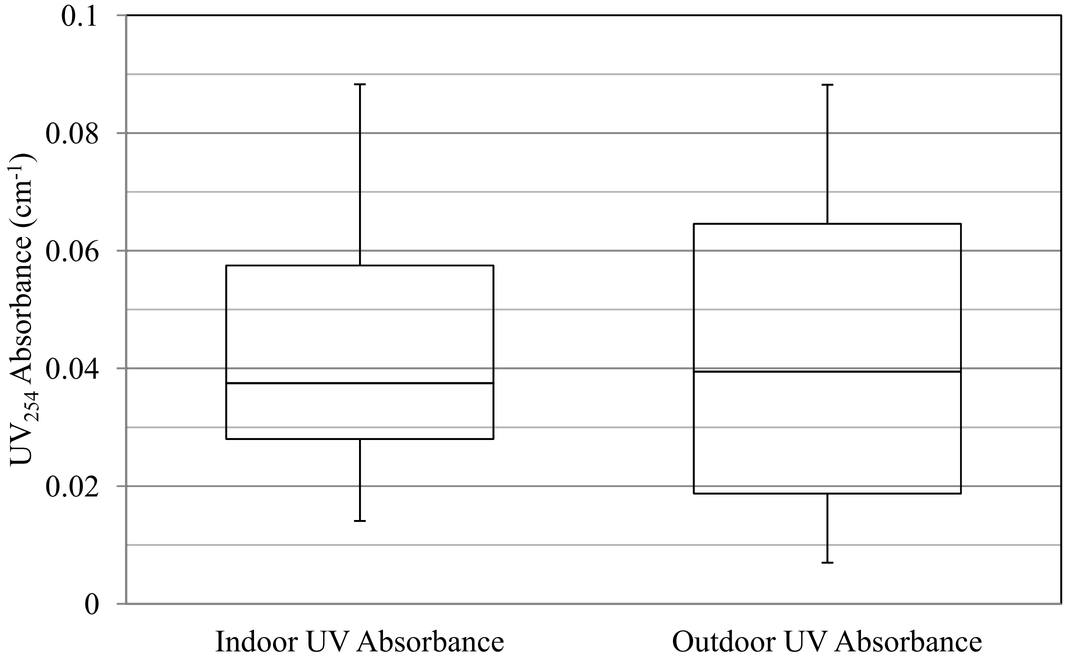


Figure 1.13 Indoor and Outdoor Swimming Pools UV_{254} Variation (n=35)

1.3.2 Swimming Pool Water Chemical Properties and Water Balance

A correlations matrix with all the paired correlations between the four operational parameters, pH, hardness, alkalinity and free chlorine, were examined by REML method. From the correlation matrix, the hardness of samples was negatively correlated with the other parameters, which indicated the high hardness generally existed in low pH, alkalinity and free chlorine water. Swimming pool water sample pH was positively correlated with alkalinity and free chlorine. Other relationships between these variables were also evident as shown in Table 1.5.

Table 1.5 Paired Correlations for Operational Parameters

	Hardness	pH	Alkalinity	Free Chlorine
Hardness	1	-0.54	-0.05	-0.33
pH	-0.54	1	0.33	0.25
Alkalinity	-0.05	0.33	1	-0.27
Free Chlorine	-0.33	0.25	-0.27	1

Cluster analysis (CA) allows the grouping of swimming pool water samples on the basis of their similarities in chemical composition. The purpose is to assemble the samples based on the characteristics they possess. Each sample is similar to the others in the cluster with respect to a predetermined selection criterion. The resulting clusters of objects should exhibit high internal homogeneity and high external heterogeneity. Cluster analysis uses operational parameters including pH, free chlorine, hardness, and alkalinity in the original data set. Hierarchical agglomerative clustering by the Ward's method was selected for sample classification. The dendrogram of samples obtained is shown in Figure 1.14. Data from 53 selected pool samples (pH, alkalinity, hardness, and free chlorine) were applied to analyses, among which 18 pools provided spring and summer data, and 17 pools only provided summer data or spring data. Two well differentiated clusters, each formed by two subgroups, can be seen. Mean values for each group representing the characteristic of each group are shown in Table 1.6.

The four chemical parameters in the first two main groups agreed with the values recommended by NSPF Pool and Spa Handbook (pH 7.2 - 7.8, free chlorine 1 - 5 mg/L, alkalinity 80 - 120 mg/L, and hardness 200 - 400 mg/L) (NSPF, 2009; Perkins, 2000). The third main cluster indicates the high pH, alkalinity and free chlorine, but low hardness, which is consistent with the correlation analysis. On the other hand, the fourth main cluster shows the low pH, alkalinity and free chlorine and high hardness. Thus, all the swimming pool water samples were divided into three representative groups based on the CA analysis and recommended operational parameters. The three representative groups are water type-1 (CA main group 1 and 2), water type-2 (CA main group 4) and water type-3 (CA main group 3). Pool water type-1 has a pH of 7.5, alkalinity of 100 mg/L, hardness of 200 mg/L, and free chlorine of 2 mg/L. Pool water type-2 has a pH of 7.9, alkalinity of 200 mg/L, hardness of 120 mg/L, and free chlorine of 3 mg/L. Pool water type-3 has a pH of 7.2, alkalinity of 60 mg/L, hardness of 350 mg/L, and free chlorine of 1 mg/L (as shown in Appendix E). Balanced pool water has proper levels of pH, total alkalinity and calcium hardness. Properly balanced or saturated water prevents damage to the pool and equipment. Unsaturated water corrodes plaster walls, fixtures, plumbing, etc., and causes staining. Oversaturated water deposits scale or becomes cloudy. Calculated SI values at 20 °C to 35 °C for the three representative pool water can be found in Appendix E.

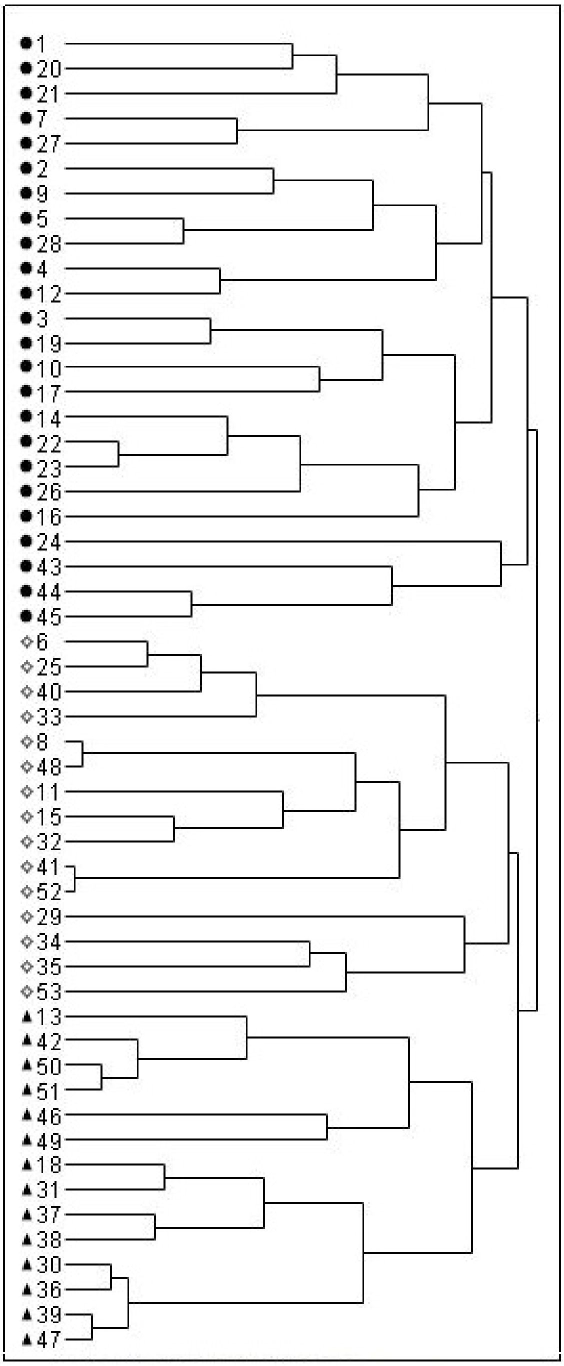


Figure 1.14 Dendrogram Based on Agglomerative Hierarchical Clustering (Ward's method) for 35 Swimming Pools Water (18 pools water samples were collected in two seasons; the other 17 pools samples were collected only in one season; total of 53 paired data were applied to calculation)

Table 1.6 Statistical Descriptive for Each CA Group

Group	pH		Alkalinity (mg/L as $CaCO_3$)		Hardness (mg/L as $CaCO_3$)		Free Chlorine (mg/L)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
1	7.6	0.15	80	26	162	110	2.7	1.2
2	7.4	0.15	119	41	272	111	0.5	0.3
3	7.9	0.23	195	50	124	69	1.7	2.2
4	7.2	0.15	57	8	346	102	0.61	0.41

1.4 Conclusions

Swimming pools water quality was evaluated by UV_{254}, turbidity, and DOC concentration. UV_{254} of the pool samples were less than 0.11 cm^{-1}. The DOC values for the pools were less than 16 mg/L, with mean of 5 mg/L. Seventy five percent of SUVA of the pools was less than 2 m^{-1}/mg/L. Turbidities for the pools were from 0.11 NTU to 1.36 NTU, 75% was less than 0.5 NTU. The majority of particles (57%) were 3 μm or less in diameter, and over 90% of particles in pool water are 10 μm or less in diameter. Spring swimming pool water contained lower contaminant concentration than summer as expected.

Most of the sampled pools (77%) pH agreed with the recommended values, 7.2 - 7.8. Free chlorine concentrations of the investigated pools were all less than 5 mg/L. Alkalinity for 60% of swimming pools was in the recommended range of 80 - 125 mg/L as $CaCO_3$. Hardness for 60% of swimming pools was in the recommended range of 200 - 400 mg/L as $CaCO_3$.

Based on the pools surveyed, an average pool would have a pH of 7.5 (standard deviation: 0.3) with 1.5 mg/L (standard deviation: 1.4) of free chlorine, and the alkalinity and hardness would be 94 mg/L (standard deviation: 47) and 238 mg/L (standard deviation: 130) as $CaCO_3$, respectively. The average turbidity would be 0.33 NTU (standard deviation: 0.27), and the DOC concentration would be 5 mg/L (standard deviation: 3.8).

Relationships between pH, free chlorine, hardness and alkalinity were evident. The hardness of samples was negatively correlated with the other parameters indicating the high hardness generally existed in low pH, alkalinity and free chlorine water. Swimming pool water sample pH was positively correlated with alkalinity and free chlorine. Three representative swimming pool waters are developed using cluster analysis, which will be applied for swimming pool water treatment. Saturation index for developed pool water is satisfied as being neither too corrosive nor likely to cause scaling.

CHAPTER 2: EVALUATION COAGULATION OF *CRYPTOSPORIDIUM* OOCYST-SIZED MICROSPHERE IN SWIMMING POOL WATERS USING ZETA POTENTIAL TITRATION

2.1 Introduction

2.1.1 Stability of Particle Suspensions

Most of the natural particles in water have a negative surface charge (Hendricks, 2006). These negative charges cause mutual repulsion and can result in a suspension characterized as “stable” (Hendricks, 2006). As particles in a suspension approach one another or as a particle in a flowing fluid approaches a stationary surface such as a filter grain, forces of electrostatic repulsion arise that tend to keep the surfaces apart.

2.1.1.1 Double Layer and Zeta Potential

The idea of measuring the charges on particles provides a rationale for determining coagulant dose. The behavior of colloidal particles in water is strongly influenced by their electrostatic charge. There are three approaches to measure particle charges (i.e., zeta potential, colloid titration, and streaming current) (Hankins, et al., 2006).

Figure 2.1 displays the double layer of a particle’s surface. Negative particles in water move toward the cathode in an electric field. When charged particle moves in the electric field, some of the counter ions in the ion cloud around the particle move with it. A surface of hydrodynamic shear or “slipping plane” is developed in the diffuse layer (where the ions are strongly bound) and an outer diffuse layer (region where they are less firmly attached) are two parts of existing liquid layers surrounding the particle. A surface in a liquid may be charged by dissociation of surface groups or by adsorption of charged molecules such as polyelectrolyte from the surrounding solution. This results in the development of a surface potential, which will attract counter-ions and achieve equilibrium in solution (Letterman and Yiacoumi, 2010). The region near the surface of enhanced counter-ion concentration is called the electrical double layer. The double layer can be approximated by a sub-division into two regions. Within the diffuse layer there is a notional boundary inside which the ions and particles form a stable entity.

When a particle moves, ions within the boundary move with it, but any ions beyond the boundary do not travel with the particle. Ions in the region closest to the charged surface are strongly bound to the surface. This immobile layer is called the Stern or Helmholtz layer. The region adjacent to the Stern layer is called the diffuse layer and contains loosely associated ions that are comparatively mobile. The potential that exists at this boundary is known as the zeta-potential (Lyklema, 1995).

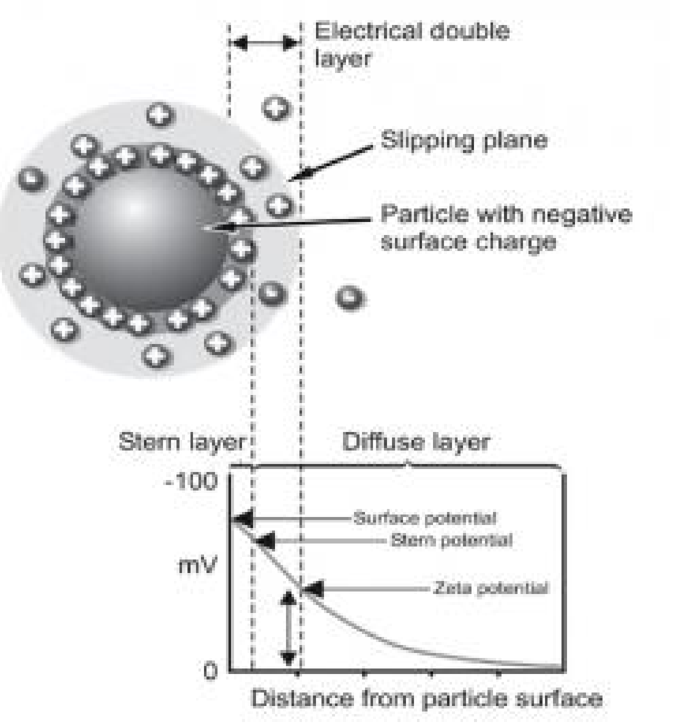


Figure 2.1 Diffuse Double Layer and Zeta Potential of the Particle Surface (Letterman and Yiacoumi, 2010)

There is significant variability in zeta potentials reported for *Cryptosporidium parvum* oocysts, ranging approximately from −40 mV to −10 mV (Brush, et al., 1998; Drozd and Schwartzbrod, 1996; Shaw, et al., 2000). Zeta potential is an indicator of effective coagulation. According to zeta potential theory, particles with large negative or positively zeta potential are electrically stabilized (e.g., > 30 mV or < -30 mV) (ASTM, 1985). They will tend to repel each other, and there is no tendency to flocculate. It has been shown that zeta potential values ranging between -10 mV and +10 mV are favorable condition for particle removal (McCurdy, et al., 2004; Tseng, et al., 2000). When the proper dosage of coagulant is added, zeta potential of particles should be approximate zero, theoretically. The point of zero charge (PZC) represents the proper dosage of coagulant added. For a specific coagulant, the PZC must be determined experimentally for a given water sample. The PZC will be the first assessment of the potential to underdose and overdose for each coagulant. However, zeta potential does not necessarily need to be zero for effective coagulation, since colloid destabilization occurs before complete neutralization of surface charge (Ratnaweers, et al., 1999).

Zeta potential is related to raw water pH. In general, zeta potential decreases (i.e., becomes more negative) as pH increases. It was found that for the dissolved organic carbon (DOC) concentration of 3.6 mg/L, zeta potential became more negative with increasing pH at pH values greater than pH 7 (Xagoraraki and Harrington, 2004). The impact of the background water conditions on the surface potentials of *Cryptosporidium parvum* through zeta potential measurements illustrated that the zeta potential of purified oocysts becomes more negative with increasing solution pH (Searcy, et al., 2005).

2.1.1.2 DLVO Theory

DLVO theory (Derjaguin, Landau, Verwey, and Overbeek) suggests that the stability of a colloidal system is determined by the sum of these Van der Waals attractive (E_V) and electrical double layer repulsive (E_E) forces that exist between particles as they approach each other due to the Brownian motion they are undergoing (Derjaguin and Landau, 1941; Haaland, 2008; Hunter, 2001). The net potential caused by addition of these two forces determines the strength and nature of the colloid interactions (Derjaguin and Landau, 1941).

Van der Waals forces result from attraction between positive and negative regions of neutral atoms due to fluctuations in charge distribution, including attractions between atoms, molecules, and surfaces, as well as other intermolecular forces, the formula for calculation is shown in Equation (2.1) (Hendricks, 2006; Letterman and Yiacoumi, 2010).

Electrostatic interactions occur due to the disproportionate amount of oppositely charged ions that collect near a charged surface in an aqueous medium. The two distinct regions of net charge are the electrical double layer and are depicted in Figure 2.1. The electrical double layer repulsive force is determined by Equation (2.2).

DLVO theory proposes that an energy barrier resulting from the repulsive force prevents two particles approaching one another and adhering together. But if the particles collide with sufficient energy to overcome that barrier, the attractive force will pull them into contact where they adhere strongly and irreversibly together. Therefore, if the particles have a sufficiently high repulsion, the dispersion will resist flocculation and the colloidal system will be stable. Oppositely, if a repulsion mechanism does not exist then aggregation will eventually take place.

$$E_v = \frac{AR}{6r} \tag{2.1}$$

$$E_E = 4\pi R \varepsilon \psi^2 \exp(-kr) \tag{2.2}$$

where, A is between 10^{-19} to 10^{-20} J (N·m) or 10^{-10} to 10^{-11} nJ (N·nm),
R is the radius of the particle (m, or nm),
r is the distance between the two particles (m, or nm),
ε is the permittivity constant, equals to $6.95 \cdot 10^{-7}$ nN/(mV^2),
ψ is zeta potential of the particle,
k is a function of the ionic composition.

2.1.1.3 Extended DLVO Theory

The classical DLVO theory has its limitation. When DLVO fails to explain experimental results, an extra term is often added, so called extended DLVO theory (i.e., hydration forces, hydrophobic forces, oscillaroty forces, water structure forces, etc.). Born repulsion force (E_B) from the resistance to overlap of electron clouds only occurs at extremely small separation distances as shown in Equation (2.3) (Haaland, 2008; Hunter, 2001).

$$E_B = \frac{A\sigma^6}{7560}\left[\frac{8R+r}{(2R+r)^7} + \frac{6R-r}{r^7}\right] \tag{2.3}$$

where σ is collision diameter, typically equals to 0.5 nm. Other parameters are as defined previously.

2.2.2 Destabilization Mechanisms

Suspension might be “destabilized”. The removal of dissolved natural organic matter (NOM) and colloidal particles is thought to occur via four primary mechanisms: double layer compression, surface charge neutralization, adsorption and precipitation, and interparticle bridging (Bratby, 2008; Edzwald and Tobiason, 1999; Letterman and Yiacoumi, 2010).

Polymers may function to charge neutralize colloids or other kinds of particles so that they may agglomerate as flocs and improve filter performance (Brown and Emelko, 2009; Chang, et al., 2005). Polymers are less pH dependent, have less sludge generation and disposal compared with metal-based coagulants (Polasek and Mutl, 2002; Wei, et al., 2010). As polymer addition generally does not impact the pH of the water being treated, pH adjustment is not necessarily required for optimum coagulation (Emelko and Huck, 2003). Polymers acting as coagulants usually contain materials with molecular weights (MW) generally less than 500,000 and high charge density (Bolto and Gregory, 2007).

Polydiallyl of dimethyl ammonium chloride (polyDADMAC) was found to be very effective for removing THM precursors, NOM, and color acting as a primary coagulant or coagulation aid (Chang, et al., 2005; Hankins, et al., 2006; Parsons, et al., 2007; Polasek and Mutl, 2002; Wei, et al., 2010). Chitosan has been used for the design of coagulation-flocculation processes applied to the treatment of particles and dissolved contaminates (Guibal, et al., 2006; Parsons, et al., 2007). Excellent turbidity and *Cryptosporidium parvum* oocysts reductions by chitosan coagulation at optimum dosages followed by filtration were comparable to those achieved when filtration was preceded by alum and $FeCl_3$ coagulation during optimized drinking water treatment operation with a filtration rate of 10.4 m/h (Brown and Emelko, 2009). The effectiveness of coagulation depends on dosage (Divakaran and Pillai, 2001). There is little information available in literature on coagulant dosage associated with *Cryptosporidium* coagulation.

2.2 Materials and Methods

2.2.1 Objectives

In this chapter, zeta potential of *Cryptosporidium* oocyst-sized microspheres corresponding to different dosages of six commercial coagulants were investigated to gain insight into the dose-response relationship between each coagulant and the surface charge of microspheres suspended in the pool waters. This study will test the coagulation performance of six coagulants on *Cryptosporidium*-sized microspheres. It will be the first assessment of the potential to underdose and overdose each coagulant associated with particle coagulation.

2.2.2 Experimental Material

2.2.1.1 Instruments

A zetasizer with an autotitrator (Malvern Instruments Ltd., Zetasizer Nano-ZS, Worcestershire, UK) was used as the zeta potential analyzer during the experiment. The disposable folded capillary cells were used, as shown in Figure 2.2. New tubing and circulation pump tubing were used for each experiment for quality control. The accuracy of the zetasizer was verified by zeta potential transfer standard (Malvern Instruments Ltd., DTS1230, Worcestershire, UK).

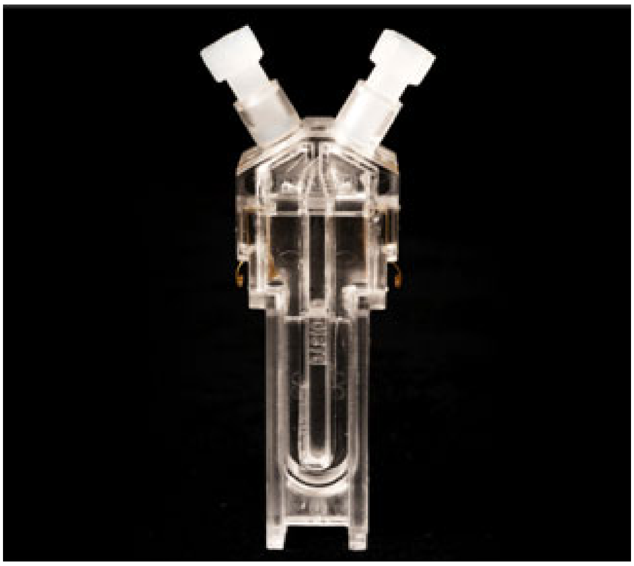


Figure 2.2 Disposable Capillary Cell (DTS1061)

2.2.1.2 *Cryptosporidium*-sized Polystyrene Microspheres

The use of polystyrene microspheres as oocysts surrogate has been done by multiple researchers, and it was used in this study (Amburgey, 2002; Amburgey, et al., 2004; Amburgey, et al., 2005; Dai and Hozalski, 2003). Microspheres with diameter of 4.5 μm were used as the surrogate since microspheres are virtually identical to

Cryptosporidium oocysts in size, shape, density, and surface charge in pool water (Fluorsebrite™ Carboxylate YG 4.5 micron microspheres, Cat. #16592, 4.5 µm, std.dev. 0.246 µm, Polysciences, Inc., Warrington, Pennsylvania, USA) (Amburgey, 2002; Amburgey, et al., 2004; Amburgey, et al., 2005; Dai and Hozalski, 2003). Stock suspensions microspheres concentration was 4.37×10^{11} #/L. A total of 10^7 microspheres was used in each of these experiments. The final concentration was 10^6 microspheres/mL (10^6 #/mL) for each experiment.

2.2.1.3 Coagulants

Six coagulants were used in pool water treatment. The coagulants are cationic coagulants. The detailed coagulants information is attached in Appendix C. Figure 2.3 shows the structure of polyDADMAC and chitosan.

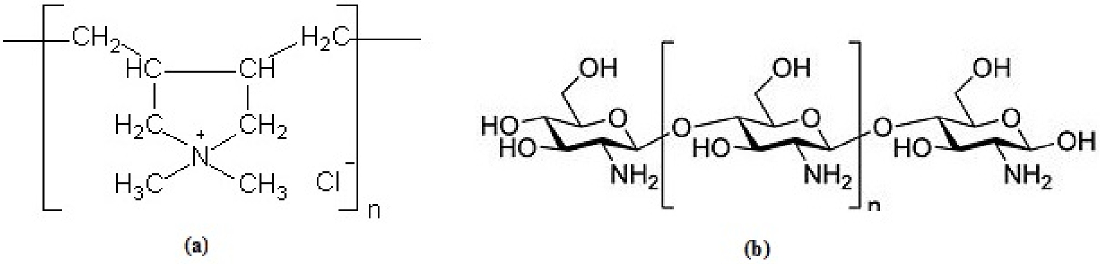


Figure 2.3 Structure of polyDADMAC and Chitosan ((a) is polyDADMAC, (b) is chitosan)

2.2.1.4 Synthetic Pool Water

The study made use of a body fluid analogue (BFA) solution, containing the primary endogenous organic amino compounds, as the organic carbon introduced into the simulated pool water. Recipe of BFA is shown in Appendix D. The synthetic pool water was generated based on previous swimming pool water quality investigation (Chapter 1). Chemical characteristics of the synthetic swimming pool water are summarized in in Appendix E. Chemicals including HCl, $CaCl_2$, $NaHCO_3$, $Ca(OCl)_2$, were added to the synthetic pool water to adjust chemical characteristic such as pH, alkalinity, hardness, and free chlorine. Recipe for the three representative pool waters is shown in Appendix F.

2.2.2 Experimental Method

Six coagulants were titrated into simulated pool water type-1, type-2, and type-3 with 10^6 #/mL microspheres. The corresponding zeta potential was measured to set benchmarks for each product. The benchmarks indicated the minimum, optimum maximum, and flexibility of the dosage for each chemical in terms of zeta potential. Zeta potential variation during each test was measured. Before starting the titration, it was necessary to fill the titrant container with a specific concentration of the titrant, and prime the titrant syringe pumps and tubes. An initial sample volume of 10 mL was used. Nitrogen was continuously added into the sample headspace to keep CO_2 out of sample and control pH. A measurement was not started until all the tubes were connected correctly and the capillary cell was filled. Computer-based standard operating procedures (SOPs) were created according for each experiment design. The titrant was added into sample controlled by SOP automatically. New connecting tubes, titrant pump tubing, titrant container, and sample container were replaced for each test as a quality control step to prevent carryover. The folded capillary cells, when reused, were washed by tap water three times and comet cleaner solution at least three times, and then rinsed by tap water. Simulated swimming pool water was used to rinse the cell before experiments. Zeta potential of samples was measured before titration for quality control. It was typically around – 30 mV ± 2 mV in this study.

2.3 Results and Discussions

2.3.1 Stability of Colloidal System

Figure 2.4 shows the impact of Van der Waals attractive (E_V), electrical double layer repulsive, and Born repulsion force (E_B) at different separation distances for 5 μm *Cryptosporidium*-sized microspheres. The minimum separation distance to attain a net attraction between microspheres is approximately 0.3 nm. The model demonstrated repulsion force dominated at separation distance above 0.3 nm, which implied the *Cryptosporidium*-sized microspheres colloidal system was stable prior to coagulant addition. Figure 2.5 shows the net forces for *Cryptosporidium*-sized microspheres before (-30 mV) and after coagulation (e.g., -10 mV and 0 mV). Results indicated attractive force dominated after coagulation with microspheres' zeta potentials of -10 mV, and 0 mV after coagulation; while repelling force dominated prior to coagulation. The maximum attractive force was obtained when zeta potential was 0 mV.

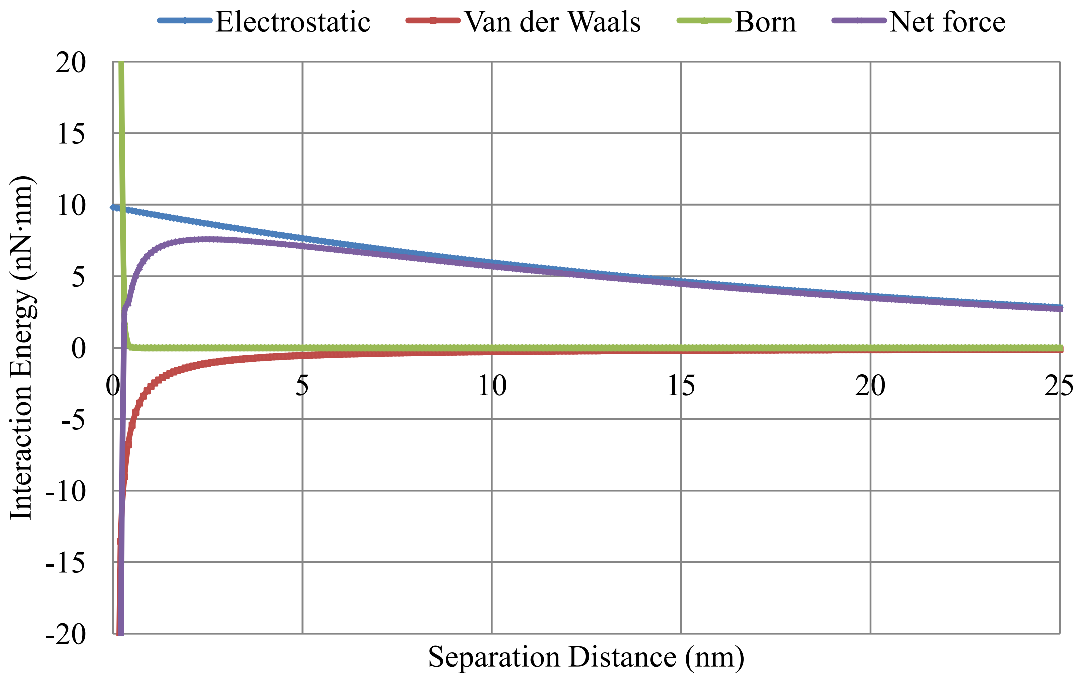


Figure 2.4 *Cryptosporidium*-sized Microspheres Interaction Forces Versus Separation Distance Prior to Coagulation

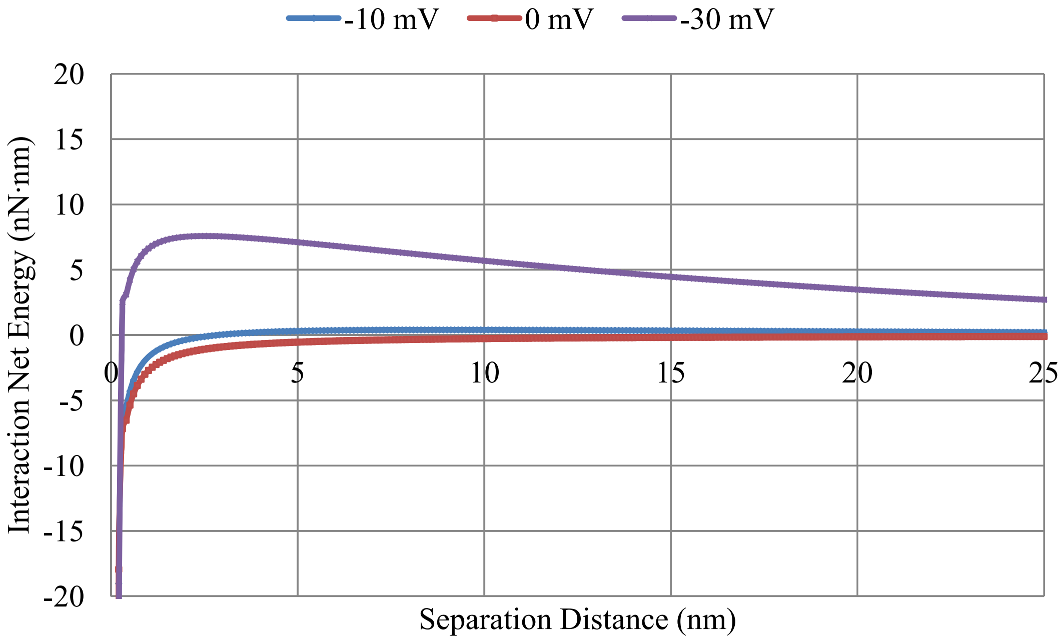


Figure 2.5 *Cryptosporidium*-sized Microspheres Interaction Net Forces Versus Separation Distance for Zeta Potential of -30 mV, -10 mV, and 0 mV

2.3.2 Titration Results for Simulated Swimming Pool Water

The zeta potential of simulated water type-1 with 10^6 #/mL versus coagulant concentration is plotted in Figure 2.6 for all six coagulants. Titration experiments suggested zeta potential of suspension increased in the positive direction as coagulant dosage increased. The recommended dosage were 1.56 mg/L for coagulant A, B, C, and F, 305 g/m^2 for coagulant D, and 1 mg/L as product (0.1 mg/L as Al) for coagulant E (Goodman, 2011). Previous study of drinking water revealed that achieving a zeta potential between -10 mV and 10 mV for the suspension being treated was the destabilized system (Tseng, et al., 2000). Coagulant A, B, and F dosage between 0.5 mg/L to 3 mg/L as product, coagulant D dosage between 6 mg/L and 12 mg/L as product, and coagulant E dosage between 1 and 20 mg/L as product (0.1 and 2 mg/L as Al) resulted in microsphere zeta potentials of -10 mV to 10 mV for water type-1. Coagulant C could not achieve microsphere zeta potential of -10 mV at recommended dosage (1.56 mg/L). Results indicated the reversal of charge was present as the coagulant concentrations increased. Overdose of coagulant A, B, and F were indicated by zeta potential above 10 mV.

A suspension of microspheres behaved as colloids and was coagulated readily by cationic coagulants. The differences in coagulation performance among different coagulants may be explained by the mechanism of coagulation and the configuration of the coagulants (Bolto and Gregory, 2007; Huang, et al., 2000; Pan, et al., 1999). The most likely mechanism of cationic coagulant coagulation is charge neutralization (Bratby, 2008; Letterman and Yiacoumi, 2010; Singley, 1970).

Figure 2.7 shows zeta potential titration results for water type-2, and Figure 2.8 shows zeta potential titration results for water type-3. Trends of microsphere zeta potential titration for the three water types were very similar. Different water types referred to the different pH, alkalinity, hardness, and ion concentration. Polymer tends to be less pH dependent (Hendricks, 2006; Huang and Yin, 1996; Huang, et al., 2000), which likely contributed to the similar trends of zeta potential in different water types.

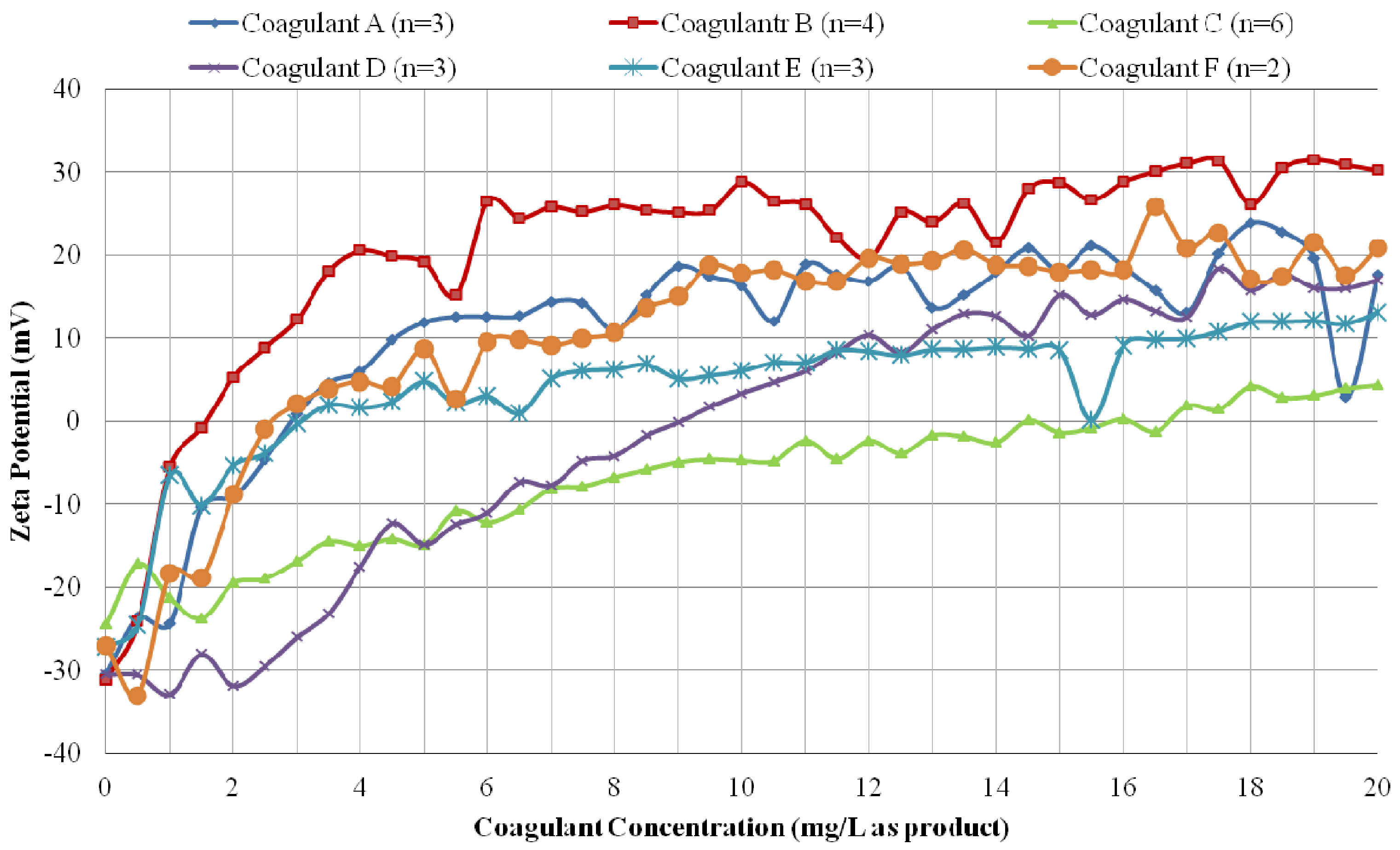


Figure 2.6 Zeta Potential Titration for Pool Water Type-1, 10^6 Microspheres/mL

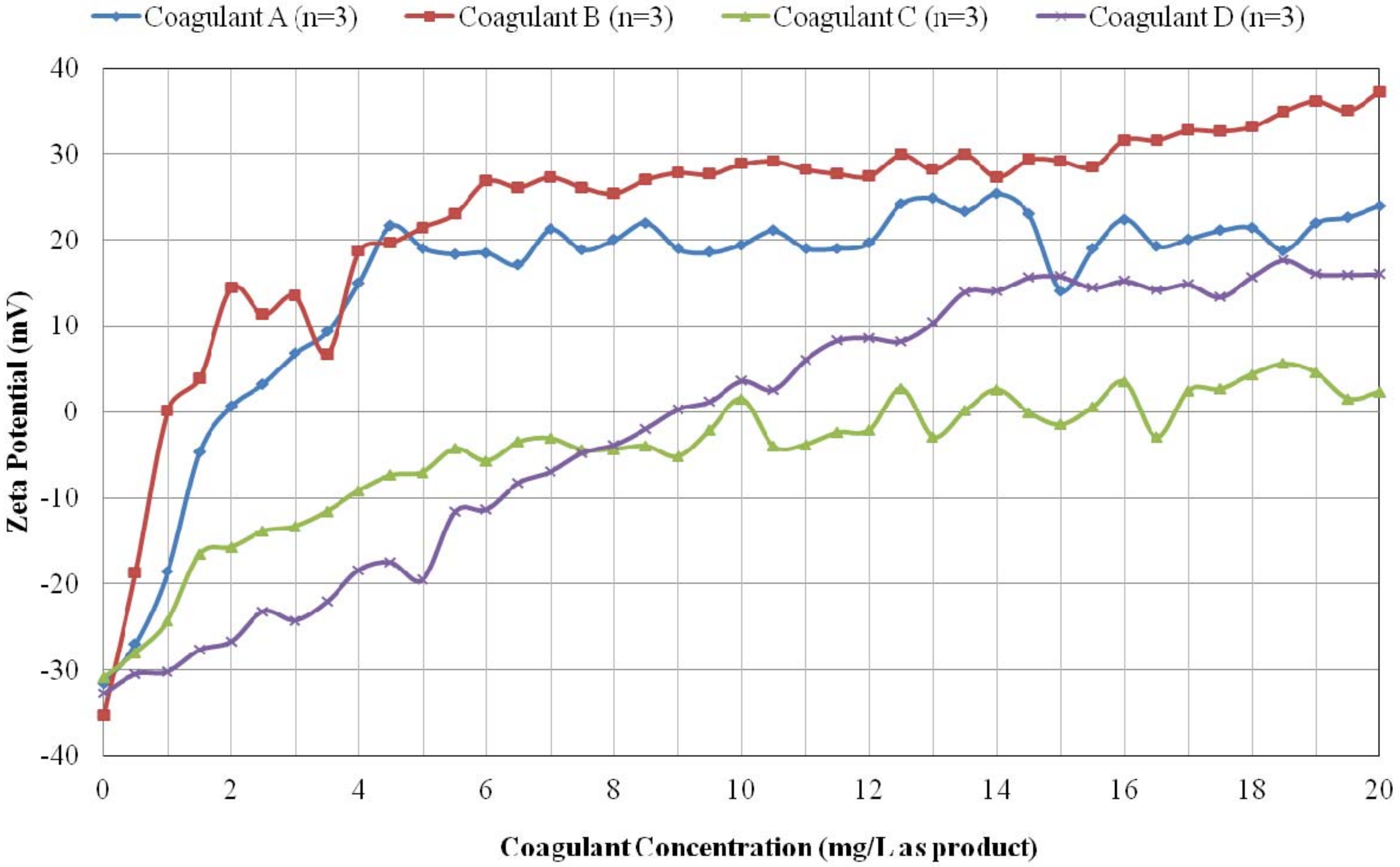


Figure 2.7 Zeta Potential Titration for Pool Water Type-2, 10^6 Microspheres/mL

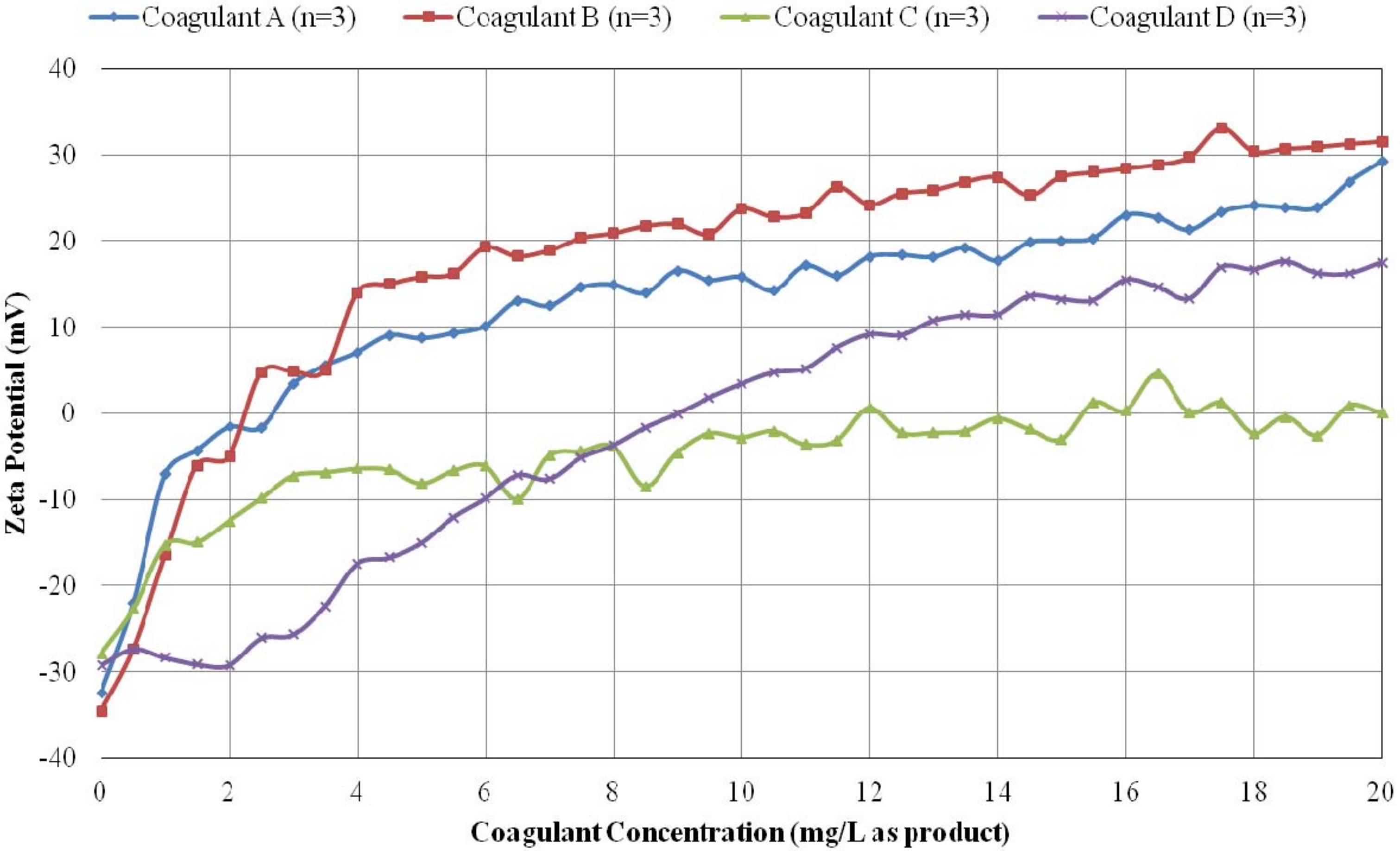


Figure 2.8 Zeta Potential Titration for Pool Water Type-3, 10^6 Microspheres/mL

Figure 2.9 shows zeta titration for the three water types by coagulant A. Figure 2.10 shows zeta titration for the three water types by coagulant B. Figure 2.11 shows titration results for the three water types by coagulant C. And Figure 2.12 shows the zeta titration results by coagulant D for the three water types. The negative zeta potential of microspheres decreases as the dosage of positively-charged coagulant increases. Results indicated in Figure 2.9 to Figure 2.12 also showed the three simulated swimming pool water types made no differences for the zeta potential of the microspheres titrated by coagulant A, B, C, and D.

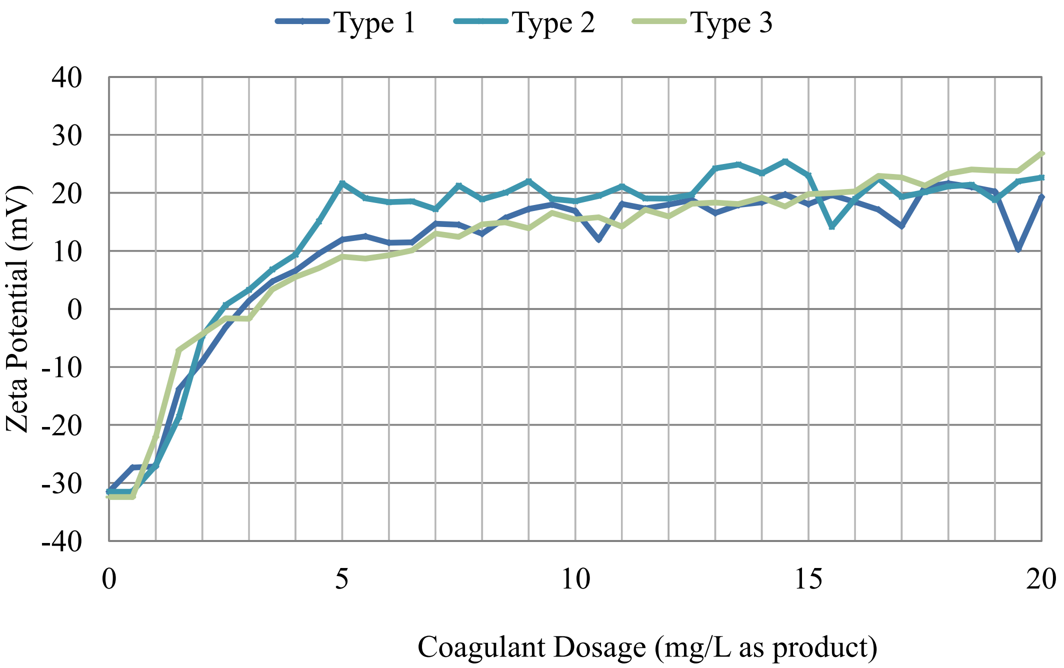


Figure 2.9 Comparison of Zeta Titration Results for Three Types of Swimming Pool Water, 10^6 Microspheres/mL, Coagulant A (n=3)

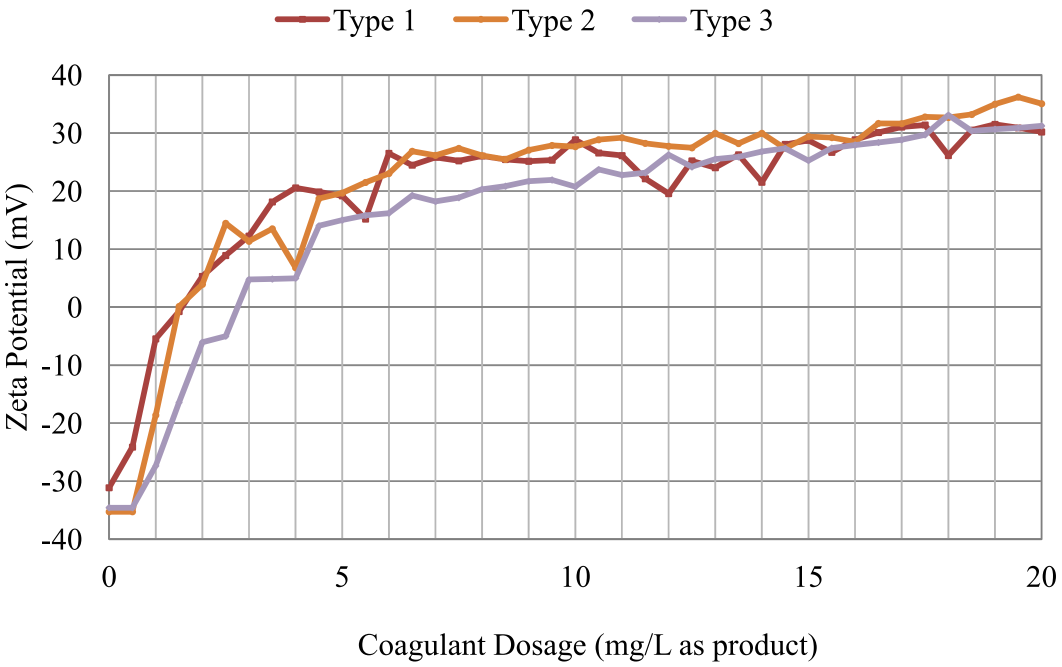


Figure 2.10 Comparison of Zeta Titration Results for Three Types of Swimming Pool Water, 10^6 Microspheres/mL, Coagulant B (n=3)

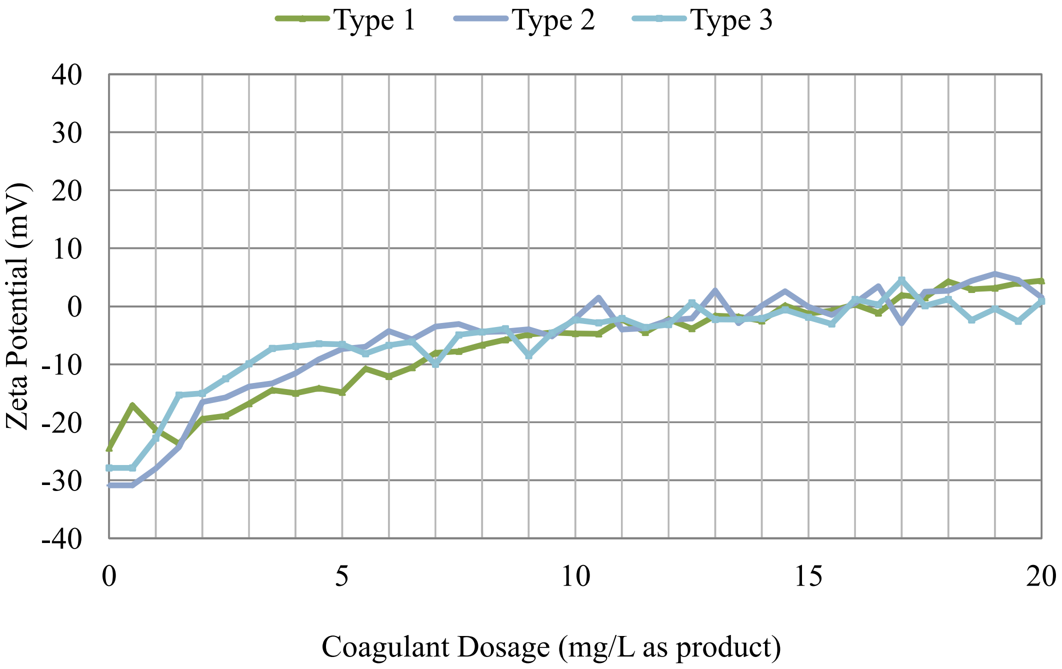


Figure 2.11 Comparison of Zeta Titration Results for Three Types of Swimming Pool Water, 10^6 Microspheres/mL, Coagulant C (n=3)

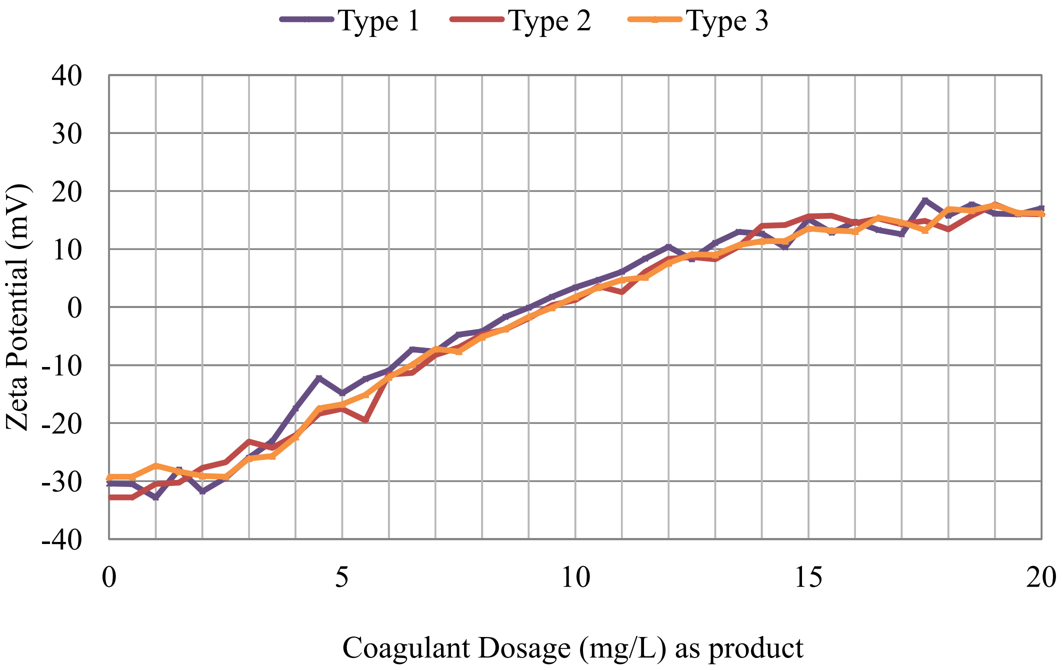


Figure 2.12 Comparison of Zeta Titration Results for Three Types of Swimming Pool Water, 10^6 Microspheres/mL, Coagulant D (n=3)

2.3.3 Coagulant Dosage Analysis

In theory, the zeta potential should be zero when the proper dosage of coagulant is added, which is called the point of zero charge (PZC). Thus, PZC may coincide with the critical coagulant concentration (CCC) level of the specific coagulant in that colloidal suspension, called CCC dosage or optimum dosage. The titration results showed the coagulant dosage required to achieve the PZC of a given microspheres concentration and raw water characteristic including DOC, pH, alkalinity, hardness, and free chlorine. The PZCs were 2.1 mg/L (standard deviation 0.6 mg/L), 1.4 mg/L (standard deviation 0.6 mg/L), 14 mg/L (standard deviation 2.6 mg/L), and 9.1 mg/L (standard deviation 0.4 mg/L) as product, for coagulant A, B, C, and D with 10^6 #/mL, respectively. The

PZC was 1 mg/L (standard deviation 0.2 mg/L) as product (0.1 mg/L as Al) for coagulant E and was 2.3 mg/L (standard deviation 0.7 mg/L) as product for coagulant F.

2.3.4 Effect of BFA on Zeta Potential Titration

BFA was titrated into water samples and led to the dissolved organic carbon (DOC) increasing from 0 to 20 mg/L, in order to study the DOC concentration effect on zeta potential. The water type-1 with coagulant A at the recommended dose and 10^6 #/mL microsphere was titrated by BFA. Figure 2.13 illustrates zeta potential versus DOC concentration. Zeta potential was not significantly reduced by DOC in the range anticipated in U.S. pools (< 16 mg/L, average of 5 mg/L). Again, the BFA effect on zeta potential was not significant (based on a two tailed t test: $P<0.05$).

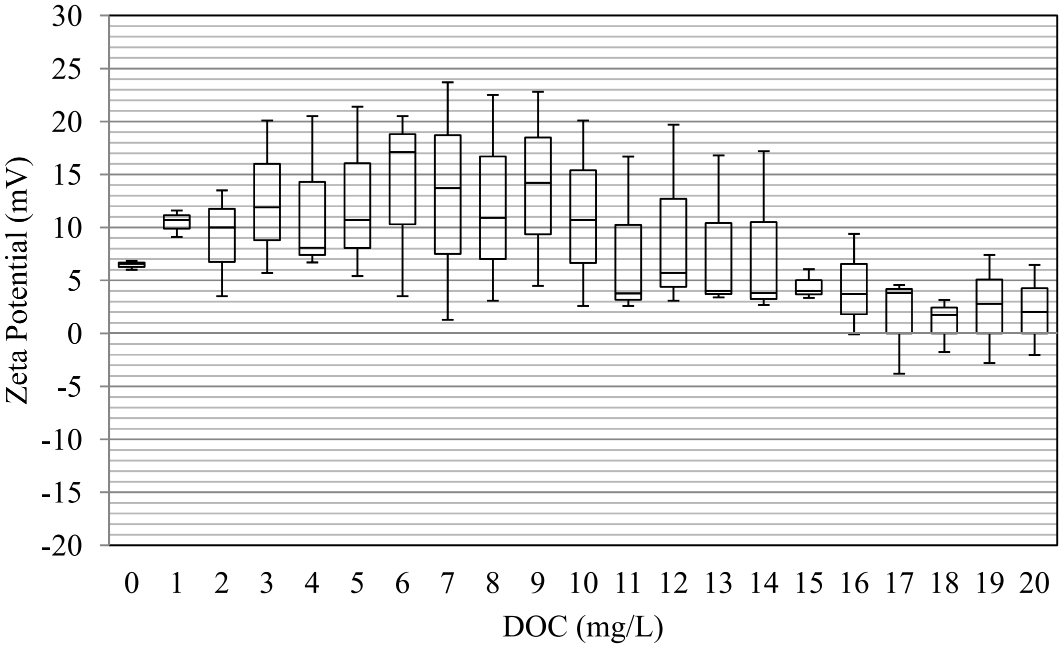


Figure 2.13 Zeta Potential of Suspension as Function of DOC Values (n=3, 1.56 mg/L Coagulant A)

2.4 Conclusions

Zeta potential titration results showed an upward trend of zeta potential with increased coagulant dosage for all six coagulants. Achieving desired zeta potential (-10 mV to 10 mV) required small dosage of coagulant A, B, E, and F compared with coagulant D for the representative simulated swimming pool water. Coagulant C did not appear to work well at the recommended dose. Overdosing of coagulant A, B, and F were indicated by zeta potential above 10 mV. No significant differences were observed for coagulant performance on different water types. The PZCs were 2.1mg/L (std. dev. 0.6 mg/L), 1.4 mg/L (std. dev. 0.6 mg/L), 14 mg/L (std. dev. 2.6 mg/L), and 9.1 mg/L (std. dev. 0.4 mg/L) as product for coagulant A, B, C and D, was 1 mg/L (std. dev. 0.2 mg/L) as product (or 0.1 mg/L as Al) for coagulant E, and was 2.3 mg/L (std. dev. 0.7 mg/L) as product for coagulant F with microspheres concentration of 10^6 #/mL, respectively. DOC (BFA) concentration did not appear to impact the zeta potential of coagulant A destabilized microspheres.

CHAPTER 3: METHOD DEVELOPMENT ON *CRYPTOSPORIDIUM*-SIZED MICROSPHERES REMOVAL FROM RECREATIONAL WATER VENUES

3.1 Introduction

3.1.1 Properties of *Cryptosporidium*

Cryptosporidium spp. are intracellular parasites that infect human epithelial cells of the small intestine (Fayer, et al., 1997). There are now 16 recognized species (Fayer, 2008). Most studies have been conducted on one species, *Cryptosporidium parvum*. It is geographically widespread, infecting many host species, and producing prodigious numbers of oocysts, thus making it more easily obtainable for study than other species of *Cryptosporidium*. Consequently, data derived from *Cryptosporidium parvum*, in some cases, have become generalized and extended to other members of the genus (Fayer, 2008). Another primary *Cryptosporidium* species of concern for human health is *Cryptosporidium hominis*. *Cryptosporidium parvum* and *Cryptosporidium hominis* have both been implicated in outbreaks associated with drinking and recreational water (Shields, et al., 2008).

Cryptosporidium is a one-celled parasite, with diameter of 4-6 µm, commonly found in lakes and rivers. It is surrounded by three distinct layers of the oocyst wall (Harris and Petry, 1999). *Cryptosporidium* oocysts are environmentally persistent and very resistant to many disinfectants, including cholorine, which is the major barrier to infectious disease transmission that has been used for the past several decades in the swimming pool water treatment (Korich, et al., 1990). Typical swimming pools in the

United States require at least 1 mg/L (ppm) free residual chlorine (NSPF, 2009; Perkins, 2000). This concentration free chlorine enables 99.9% of *Cryptosporidium* to inactive for over 11 days (Korich, et al., 1990; Shields, et al., 2008).

3.1.2 Cryptosporidiosis

Cryptosporidium has caused several large waterborne disease outbreaks of gastrointestinal illness, cryptosporidiosis, and emerged as a parasite of major public health concern in United States, United Kingdom, Australia, etc (Briancesco and Bonadonna, 2005; Karanis, et al., 2006; LeChevallier, et al., 1991; Lisle and Rose, 1995; PHLS, 2000; Puech, et al., 2001). The gastrointestinal illnesses include watery diarrhea, dehydration, fever, nausea, body fatigue, and abdominal cramps (Frost, et al., 1997). Cryptosporidiosis is a diarrheal illness caused by the infection of the gastrointestinal tract by the protozoan parasite *Cryptosporidium*. Infections caused by *Cryptosporidium* can last for days or up to 2-3 weeks (Mead, 2002). Multiple sources have indicated that weaker subpopulations (infants, young children, pregnant women and elderly people) are more susceptible, and the occasionally severe cases requiring hospitalization depends on individual immunity (Daniel, 1996; Ford, 1999; Hoxie, et al., 1997). Twenty four of 81 patients who developed cryptosporidiosis exhibited extraintestinal biliary infections on the Milwaukee outbreak (Mead, 2002). Immunocompromized individuals (AIDS) could die from cryptosporidiosis (Mead, 2002). In the Nevada outbreak of 1994, 32 out of 61 adults who developed cryptosporidiosis with AIDS died within 6 months, and cryptosporidiosis listed as a contributing cause on their death (Goldstein, et al., 1996). Many therapies are not effective against *Cryptosporidium,* since it has a natural resistance to drug therapy (Mead, 2002). Currently, no single or combined drug therapy has proven to be completely effective against cryptosporidiosis (Shahiduzzaman and Daugschies, 2012).

3.1.3 *Cryptosporidium* Sources and Transmission

Cryptosporidium oocysts are immediately infectious, and the parasites' infectious dosage is as low as 10 to 30 oocysts (DuPont, et al., 1995; Okhuysen, et al., 1999). The median infectious dosage for cryptosporidiosis is reported to be approximately 132 oocysts (DuPont, et al., 1995). One common source of infection is by swimming in a swimming pool with human contamination (Schets, et al., 2004). Most swimmers retain some level of feces on their perianal surface that can be rinsed into recreational water while swimming (Gerba, 2000). Relatively small amounts of fecal contamination per person, average 0.14 grams per person, have been documented, but large and heavily-used locations may receive a lot of daily fecal contamination (e.g., swimming pool with 20,000 visitors per day could receive 2.8 kg of fecal contamination) (Gerba, 2000). Infected humans excrete approximately 10^8 to 10^9 oocysts in stool per day (Goodgame, et al., 1995; Jokipii, et al., 1985). High levels of oocysts in stool make it possible for a single infected person's bowel movement to significantly contaminate beaches and artificial venues such as swimming pools (Chappell, et al., 2006; Jokipii, et al., 1985).

3.1.4 Outbreaks of Cryptosporidiosis

Numerous waterborne outbreaks of cryptosporidiosis have been linked to swimming pools (Briancesco and Bonadonna, 2005; Karanis, et al., 2006; LeChevallier, et al., 1991; Lisle and Rose, 1995; PHLS, 2000; Puech, et al., 2001). In May 1988, 60 cases of cryptosporidiosis outbreaks had been reported in Los Angeles County, United States (Joce, et al., 1991). The attack rate was about 73% for the swimmers exposed to pool water in which there had been a single accidental faecal release. In August 1988, the outbreak of cryptosporidiosis associated with a swimming pool in the United Kingdom was recognized (Joce, et al., 1991). The concentration of oocysts detected in the pool water samples was 50 oocysts per liter. The inspection of the potential pollution sources were sewage or infected swimmers. In 1990, an outbreak of cryptosporidiosis occurred in British Columbia, Canada (Bell, et al., 1993). Attack rates ranged from 8% to 78% for various groups of children's pool users. *Cryptosporidium* continues to pose a significant threat to public health in recreational water venues as more than 4,000 people were made aware in a summer 2005 outbreak in New York, nearly 2,000 more in Utah in the summer of 2007, and at least 378 others in the Dallas area in the summer of 2008. A study by Health Protection Agency in Britain has shown that *Cryptosporidium* remains a severe threat for swimming pools with more than 3,000 cases recorded before the end of 2009 (Health Protection Agency, 2009).

Cryptosporidiosis is widespread geographically in the United States. Data from 2006 to 2008 seem to indicate that cryptosporidiosis incidence has increased in almost all states in recent years (as shown in Figure 3.1). *Cryptosporidium*-related health issues increase significantly during summer and early fall due to the increasing number of visits to swimming pools. Past study indicated *Cryptosporidium* transmission goes up tenfold during the summer months as outdoor activities increase (as shown in Figure 3.2) (Aldras and Bitto, 2009; Jonathan S. Yoder and Michael J. Beach, 2007; Yoder and Beach, 2010).

Cryptosporidiosis outbreaks data from 1984 to 2008 in United States is shown in Figure 3.3. From 1984 through 2008, 172 waterborne cryptosporidiosis outbreaks have been reported to Centers for Disease Control and Prevention (CDC) as part of the national waterborne disease and outbreak surveillance system of the recreational water-associated outbreaks. From 2006 to 2008, the number of reported cases of cryptosporidiosis increased dramatically, from 6,479 for 2006 to 11,657 for 2007, and then decreased to 10,500 in 2008 (Jonathan S. Yoder, et al., 2010). The majority (52%) of infected people was less than 25 years old, among which, 20% were between 1 and 4 years old (as shown in Figure 3.4).

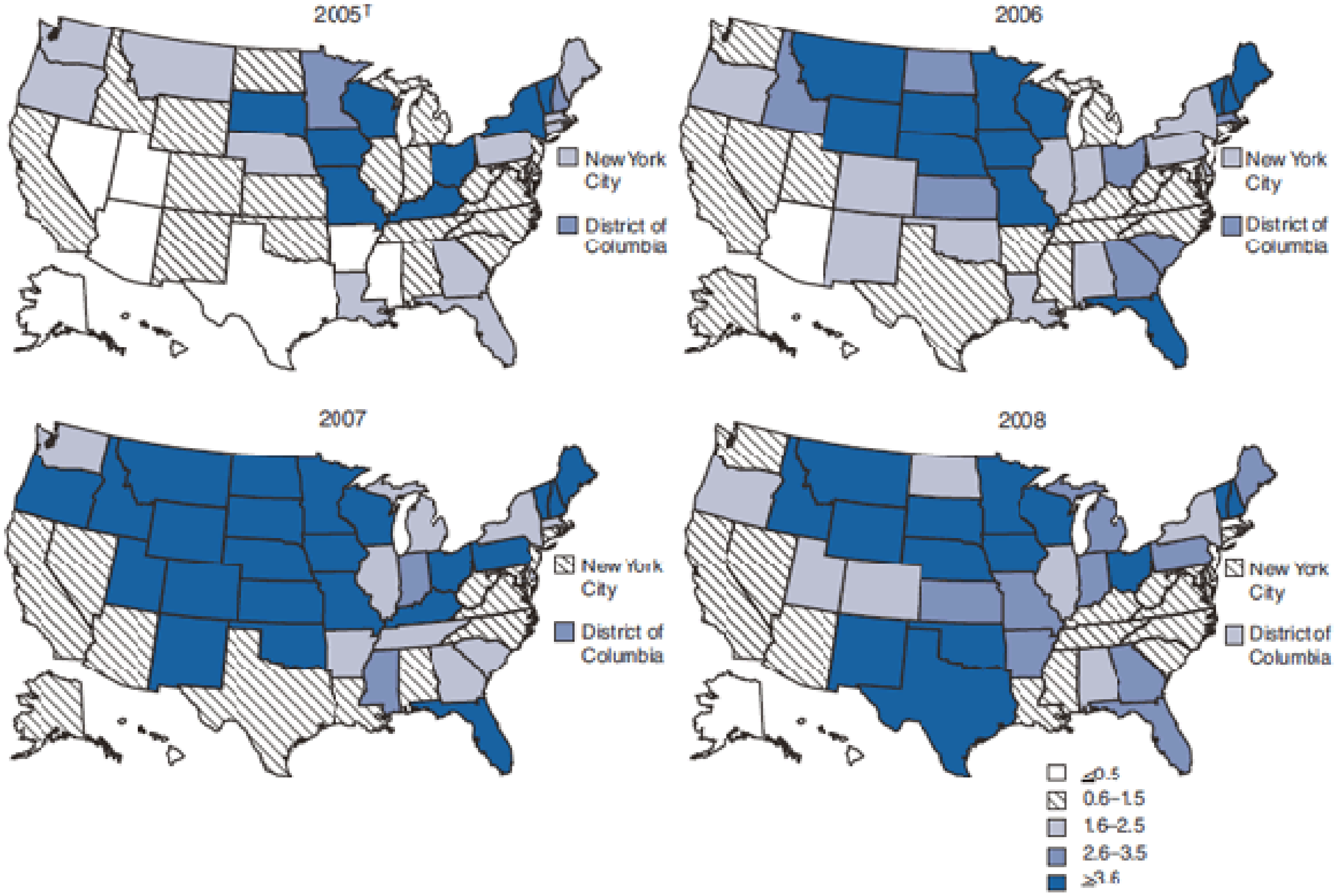


Figure 3.1 Incidence of Cryptosporidiosis, by State, United States (2005-2008)

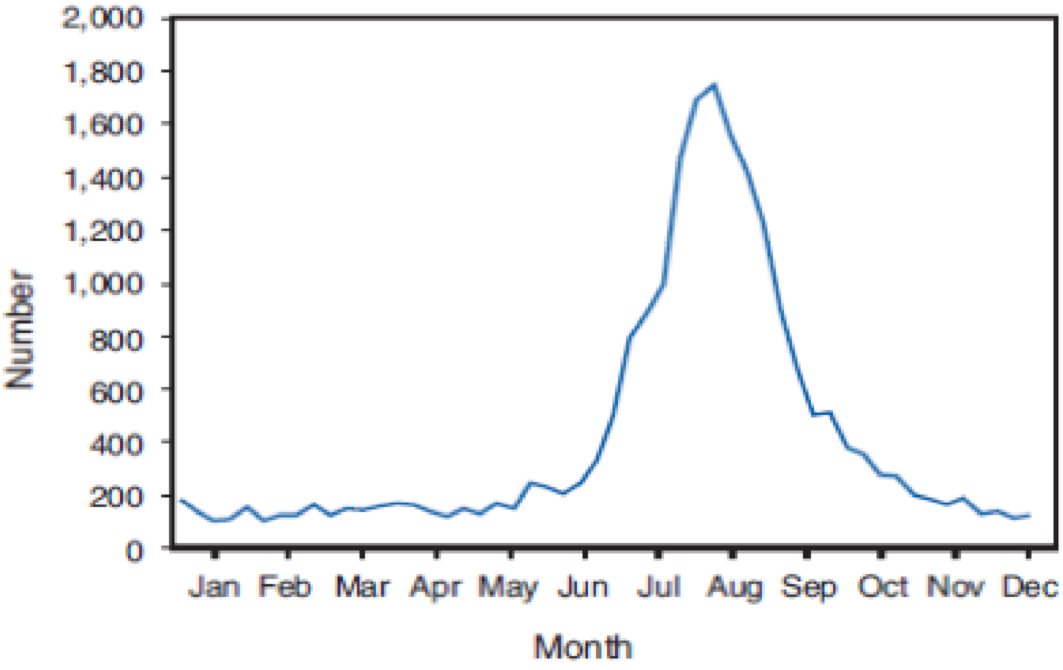


Figure 3.2 Number of Cryptosporidiosis Case Reports – United States (1995 – 2007, n = 37,995) (Jonathan S. Yoder, et al., 2010; Yoder and Beach, 2010)

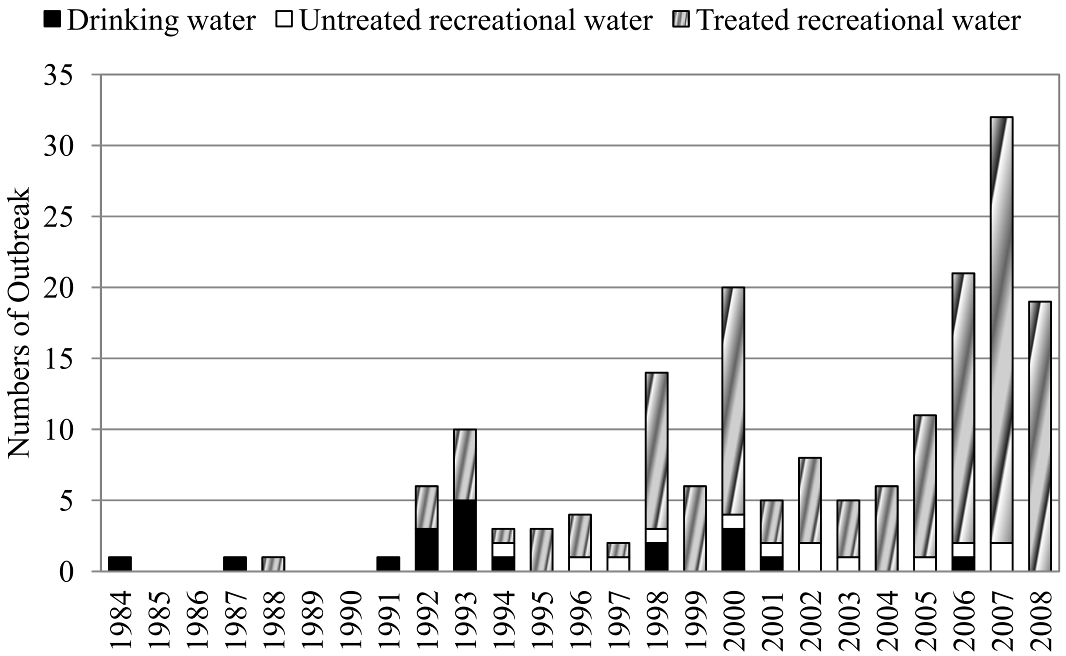


Figure 3.3 Number of Cryptosporidiosis Case Reports, 1984-2008 (n= 172, Data for 2007 and 2008 are provisional) (Jonathan S. Yoder, et al., 2010; Yoder and Beach, 2010)

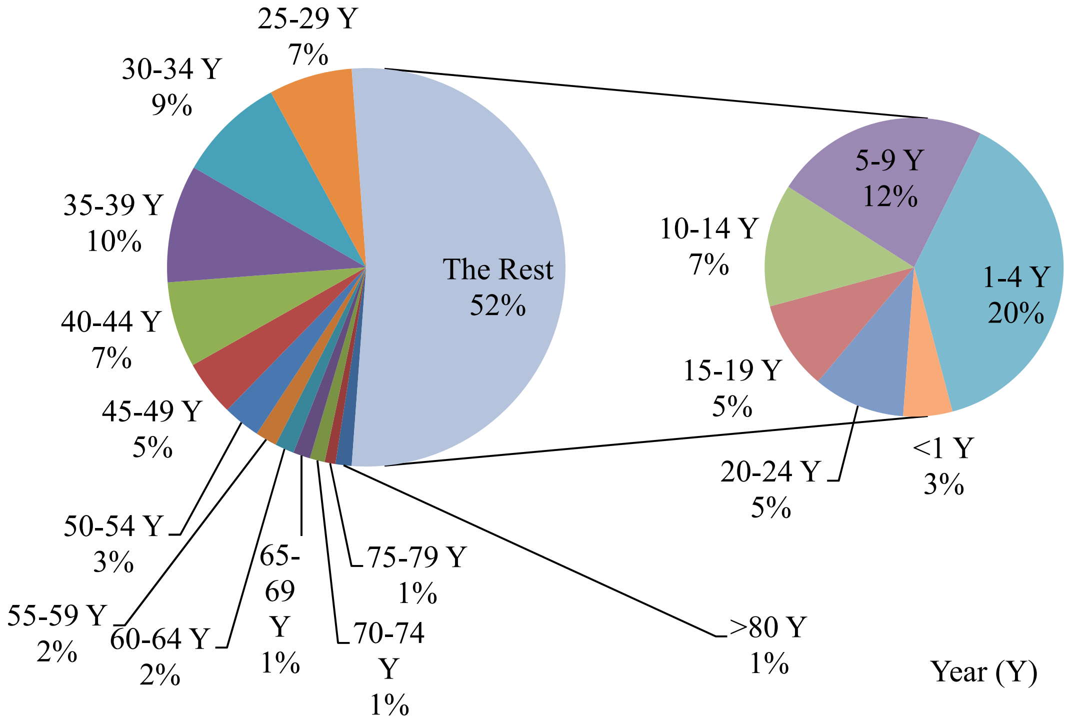


Figure 3.4 Number of Cryptosporidiosis Case Reports, by Selected Age Group — United States, (1995–2007, n = 37,995) (Yoder and Beach, 2010)

3.2 Materials and Methods

3.2.1 Research Objective

This chapter considered the performances of the representative operation in swimming pools in order to develop a novel evaluation procedure for coagulants that will produce reliable results applicable in field-relevant swimming pools. Decisions will be made regarding whether to add coagulant or microspheres first, whether to add coagulant and microspheres as continuous inputs or as intermittent inputs, and whether or not coagulant build-up occurs in the system after extended dosing causing impaired performance. Experiments will be performed to determine whether the concentration of microspheres seeded into the pool system impact the overall microsphere removals.

Calculations will be made to determine the ratio of filter media surface area to total system water volume, and experiments will be conducted to determine the potential impact of filter surface area on microsphere removal. Further experiments will be conducted to determine the impact of DOC on *Cryptosporidium*-sized microsphere removals.

3.2.2 Experiment Setup

A 5,500 L swimming pool was built with filtration system and chemical control system. Pool water can be pumped through the filter (either granular filter or precoat filter) as shown in Figure 3.5. Appendix G contains detailed information about the materials used in this research (i.e., instruments, pumps, flow meters, and filters). The smaller sand filter was made from transparent polyvinyl chloride (PVC) pipe. It utilized an integral media support cap (Leopold, ITT) as support for filter media as well as backwash flow distribution. The filter had a diameter of 15 cm and the sand depth of 30 cm. The effective size of the sand was 485 µm. Hydraulic loading rates (HLR) for the sand filter was 37 m/h, which is a typical high-rate filter loading rate used in the US swimming pools. All chemicals and microspheres were fed using peristaltic or metering pumps. The pool's pH and oxidation reduction potential (ORP) sensors were mounted in a bypass line shown in Figure 3.5. These sensors were connected to a controller (CAT 5000, Poolcomm, Rockville, MD, USA) for monitoring and chemical feed control. Coagulant and microspheres were fed into the pipe ahead of the pump and pre-filtration for a rapid coagulant mixing. Streaming current meter (Micrometrix, Suwanee, Georgia, USA) was installed in sample influent line to measure the surface charge of the water. Turbidimeter (HF scientific, Fort Myers, Florida, USA), particle counter (Chemtrac, Norcross, Georgia), UV transmission monitor (HF scientific, Fort Myers, Florida, USA, and Real Tech INC, Canada) were installed both on filter influent and effluent line. On-line data can be record and download from a computer. Particle counters collect the particle size in the following range, 2 µm-3 µm, 3 µm-6 µm, 6 µm-10 µm, 10 µm-20 µm, 20 µm-50 µm, 50 µm-100 µm, and the total particles from 2 µm to 100 µm.

Brown particles, thought to be sediment particles from the water distribution system, were intermittently observed in the tap water used to make the simulated swimming pool water. To remove the majority of these particles and provide a consistent base for the pool water recipe, tap water was circulated through a sand filter without coagulant addition for one pool turnover time (large sand filter = 25 mins, precoat filter = 30 mins) prior to each experiment. Swimming pool turnover is theoretical hydraulic detention times of the pool. The particles were then removed by backwashing prior to all experiment.

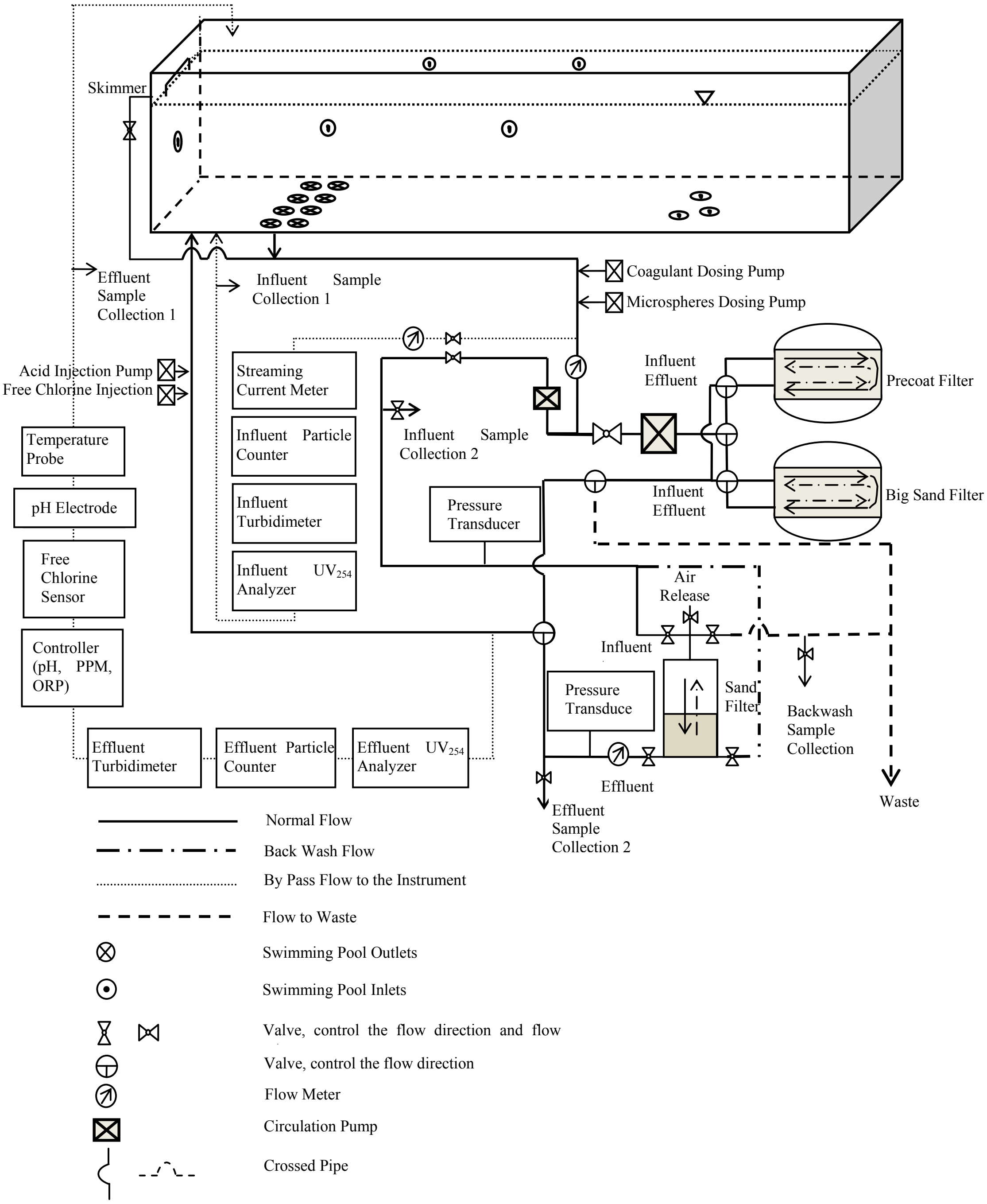


Figure 3.5 Pilot-Scale Swimming Pool Set-up

3.2.3 Synthetic Pool Water

The simulated swimming pool water type-1 was applied in all the experiments. The body fluid analog (BFA) solution, containing the primary endogenous organic amino compounds, as the organic carbon was introduced as DOC into the simulated pool water. Appendix D shows the ingredient of the BFA solution. Chemical characteristics of the pool water samples are summarized in Appendix E. Amount of 5,500 L of Charlotte, NC tap water with total organic carbon (DOC) of 1 mg/L was supplemented with $NaHSO_4$, $CaCl_2$, and $NaHCO_3$ to adjust pool water chemical characteristic. Appendix F shows the recipes for simulated swimming pool water.

3.2.4 Experimental Approach

3.2.4.1 Order of Feeding Coagulant and Microspheres

The order of adding coagulant and microspheres may impact the overall removal. Three scenarios are possible in practice and were evaluated to produce reliable results, “adding coagulant first”, “adding microsphere first”, and “adding coagulant and microsphere simultaneously”. The recommended dosage of coagulant and 1.8 #/mL microspheres was seeded for each experiment. The experiment with adding coagulant and microspheres simultaneously were conducted in one turnover time (8 hr), which was named as “normal” experiment. Samples were collected at 0.5, 1, 2, 4 6, and 8 hr, respectively.

A “coagulant first” experiment was conducted by feeding 1.56 mg/L coagulant A for 8 hrs, following by 10 hrs without coagulant feeding. Samples were taken at the 0.5 hr, 1.5 hr, 4 hr, 6 hr, 8 hr, and 10 hr since stop the coagulant feed. Microspheres were only fed 15 mins before each sample collection, and feeing stopped after each sample collection.

A "microspheres first" experiment was conducted by feeding 1.8 #/mL microspheres for 30 mins (experiment was started at 0 hr, and microspheres were fed during 0-0.5 hr). One recommended dosage of coagulant (1.56 mg/L) was fed for 8 hrs since stop feeding microspheres (coagulant was fed during 0.5 – 8.5 hr). The first sample was collected at 1 hr after feeding coagulant (first sample was taken at 1.5 hr). The rest of samples were taken over the time of feeding coagulant.

3.2.4.2 Feeding Modes of Coagulants and Microspheres

"Intermittent feeding of coagulant" and "continuous feeding of coagulant" was evaluated. "Intermittent feeding" experiment was conducted for approximately 64 hrs. Coagulant was fed as 1.56 mg/L for 8 hrs followed by no coagulant feeding for 8 hrs, which was called a cycle (one cycle time = 16 hrs). Four cycles were conducted. Amount of 10^7 microspheres (1.8 #/mL) was seeded and samples were taken at the second and eighth hour during the 8 hrs without coagulant feeding. The experiment with continuous feeding coagulant was conducted by continuously feeding 1.56 mg/L/8hrs coagulant A by coagulant pump, which was the same as the "normal" experiment.

3.2.4.3 Extended Feeding Coagulants

Excessive use of coagulant could lead to impaired microsphere removals as well as inefficient use of resources. Extended feeding coagulant with the same filter media and water were evaluated at 1.56 mg/L/8 hrs. Samples were collected every turnover.

3.2.4.4 Microspheres Concentration versus Coagulant Dosages

Multiple experiments with different coagulant dosages (from 0.03 mg/L to 1.56 mg/L) and microsphere concentrations (the amount of 10^5, 10^7, and 10^8 microspheres, correlated with concentration of 1.8×10^{-2} #/mL, 1.8 #/mL, and 18 #/mL, representatively) were performed. Coagulant was fed from high dosage to low dosage to determine the dosages corresponding to 99%, 95%, and 90% microspheres removals. Coagulant was also fed from low dosage to high dosage to further evaluate the relationship between microspheres concentration and coagulant dosage.

3.2.4.5 Filter Media Surface Area

Experiments were conducted to determine the potential impact of filter media surface area on microsphere removal using the large filter with diameter of 48 cm (0.18 m^2) and the small filter with diameter of 15 cm (0.018 m^2) at 37 m/h (15 gpm/ft^2). The media surface area was 2.8 m^2 and 0.03 m^2.

3.2.4.6 Body Fluid Analogue (BFA) Concentration

Experiments were performed to evaluate the impact of BFA on microsphere removals. Experiments were conducted under “normal” condition, feeding recommended dosage of coagulant A per turnover with or without addition of BFA. BFA was applied into the pool water and led to the dissolved organic carbon (DOC) increasing.

3.2.5 Enumeration of *Cryptosporidium*-sized Polystyrene Microspheres

The use of polystyrene microspheres as an oocyst surrogate has been done by multiple researchers and was used in this study (Amburgey, 2002; Amburgey, et al., 2004; Amburgey, et al., 2005; Dai and Hozalski, 2003; Li, et al., 1997). Microspheres with diameter of 4.5 μm were used as the surrogate (Fluorsebrite™ Carboxylate YG 4.5 micron microspheres, Cat. #16592, 4.5 μm, std.dev. 0.246 μm, Polysciences, Inc., Warrington, Pennsylvania, USA) since microspheres are virtually identical to *Cryptosporidium* oocysts in size, shape, density, and surface charge in water (Amburgey, 2002). Stock suspensions microspheres concentration was 4.37×10^{11} #/L. The diluted suspension with microspheres concentration of 4.37×10^{8} #/L was prepared by 1 to 1,000 dilutions of stock solution. Microsphere samples were mixed by vortexing and hand shaking for at least two minutes each before analyzing. Samples were passing through 3.0 µm pore size polycarbonate filters (Product # K30CP02500, GE Osmonics, Minnetonka, Minnesota, USA). Each polycarbonate filter was mounted on a glass microscope slide with a polyvinyl alcohol-DABCO solution, covered with a glass cover slip (25-mm square, No. 1.5, Corning, Inc., Corning, New York, USA), and counted under an epifluorescence microscope (Zeiss Standard 25 microscope, Carl Zeiss MicroImaging, LLC, Thornwood, New York, USA) (Freer, 1984). For ease of counting and to obtain statistically valid data, microscope slides needed to contain between 10 and 150 microspheres. Removal efficiency was calculated by comparing the concentrations between influent and effluent samples.

3.2.6 PolyDADMAC Measurement

PolyDADMAC was analyzed using a method based on that of Parazac et al (Parazak, et al., 1987). The method involves the formation of an insoluble complex between the cationic polymer and the anionic dye Ponceau S. The complex precipitates out of solution and is collected at the interface between the aqueous layer and a solvent. The aqueous layer is collected, and the concentration of dye remaining in solution is measured by a Varian Cary 100 BIO UV Spectrophotometer at 520 nm (Agilent Technologies, Santa Clara, California, USA). Ponceau S (200 mg/L)

(Fisher BioReagents), 0.5 M sulfuric acid (Fisher BioReagents), and dichloromethane (Fisher BioReagents) were used. The detailed experimental description could be found in Analytical methods for polymers and their oxidative by-products (Fielding, 1998). The absorbance of the standards versus polyDADMAC concentration calibration plot is shown in Figure 3.6. Standards with known polyDADMAC concentrations were made of tap water and polyDADMAC polymer (coagulant A). Calibration plot was created and the regression is shown in Equation (3.1).

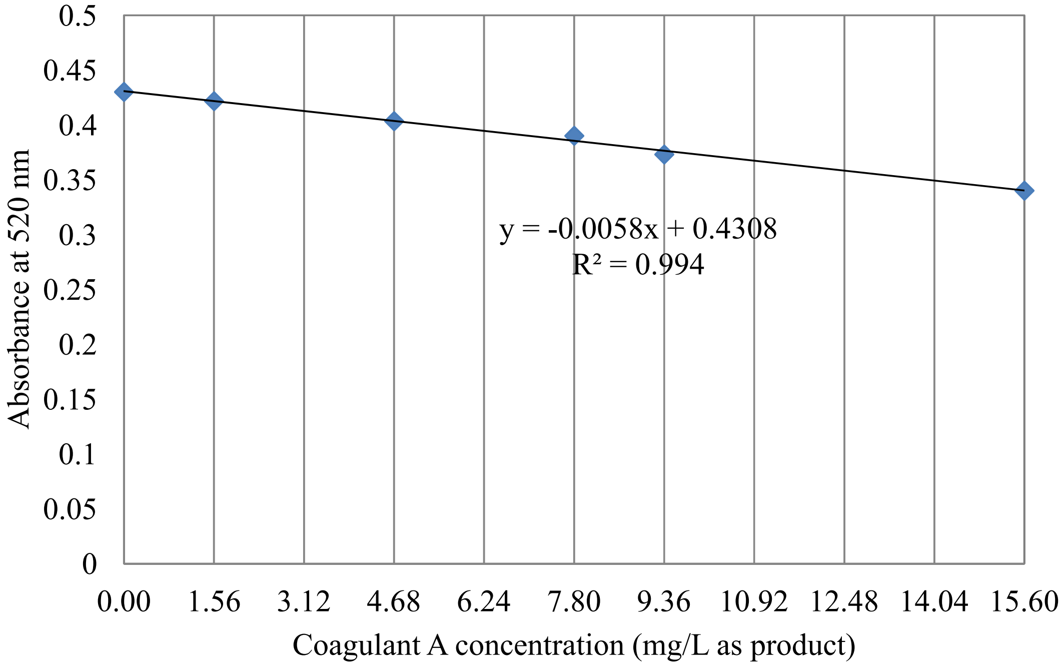


Figure 3.6 Absorbance versus coagulant A concentration calibration curve (10 mm cell)

$$y = -0.0058x + 0.4308 \quad (3.1)$$

where y is absorbance at 520 nm for standard; x is coagulant A concentration of standard.

3.2.7 Data Analysis

A box plot was applied to evaluate the benchmarks for each coagulant. In statistics, a box plot is a convenient way of graphically depicting groups of numerical data through their five-number summaries: the smallest observation (sample minimum), lower quartile, median, upper quartile, and largest observation (sample maximum).

3.2.8 Quality Assurance and Quality Control

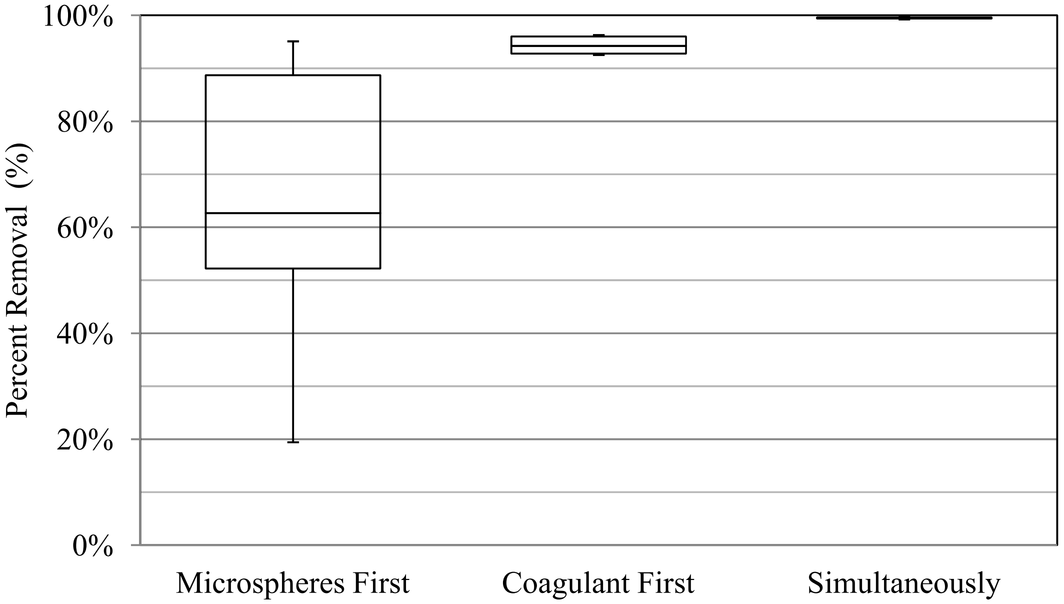
A control experiment was conducted without filter media to test if there are microsphere losses in the system. The average 1% removal (approximately zero) was obtained and demonstrated close to no significant system losses. A sand filter experiment without coagulation was conducted as another control experiment indicating 20% - 63% (0.1 - 0.4 log) *Cryptosporidium*-sized microspheres removal. Duplicate experiments were conducted. Triplicate samples were taken (only one experiment was conducted with triplicate samples for some of the experiment and indicated by n=1). The swimming pool was rinsed, filled, and drained with tap water at least three times between experiments to limit the amount of cross-contamination between experiments. Fresh sand was used for each experiment. Sand filter was backwashed with simulated pool water for 5 minutes to ensure the sand was clean and sand grain restratified (fine grains on top and coarse grains on bottom).

3.3 Results and Discussions

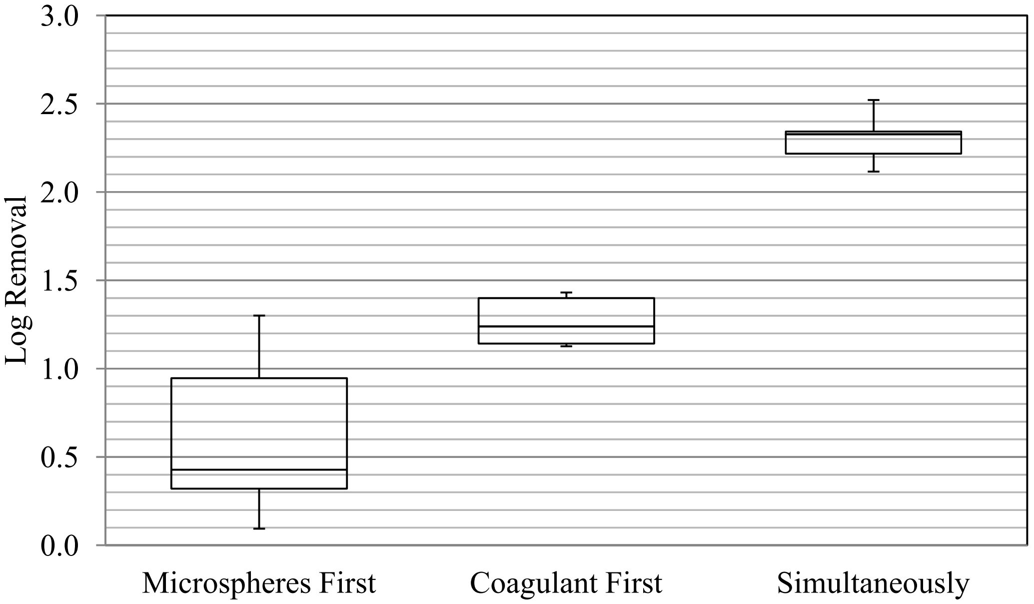
3.3.1 Orders of Seeding Microspheres and Coagulant

In swimming pools, there are three possible *Cryptosporidium* contamination scenarios, such as their releases into the pool while no coagulant residual exists in the pool (corresponding to the experimental procedure adding microspheres first), or there is coagulant residual in the pool when microspheres are released (corresponding to adding coagulant prior to microspheres), or microsphere contamination occurs during active coagulant addition (corresponding to adding microspheres and coagulant simultaneously). The order of adding coagulant and microspheres might impact the overall removal. Figure 3.7 shows the percent removal and log removal of *Cryptosporidium*-sized microsphere referring to the three scenarios. The percent removal, 99.5% (2.3 log), was achieved by feeding coagulant and microspheres simultaneously. Adding coagulant first averaged 94% removal (1.3 log). The average removal was only 65% (0.5 log), for ‘adding microspheres first’ experiment.

Figures 3.8, 3.9, and 3.10 display the microsphere removals over time for the three scenarios. Figure 3.8 shows removals for feeding coagulant and microspheres simultaneously. Removals were above 99% if feeding coagulants and microspheres simultaneously over the 8 hrs as shown in Figure 3.8. Removals decreased from 98% to 92% over time when feeding coagulant first as shown in Figure 3.9. Figure 3.10 shows microspheres removals and particle counts in 3-6 µm for “feeding microspheres first” experiment. The microsphere removals were increased over time for “feeding microspheres first” experiment. The effluent particle counts (3-6 µm) were significant higher than the influent particle counts (3-6 µm) in the first 1 hr after feeding microspheres as shown in Figure 3.10.



(a. Percent Removal for Three Scenarios)



(b. Log Removal for Three Scenarios)

Figure 3.7 Performances of the Three Scenarios Referring to Sequence of Adding 10^7 Microspheres (1.8 #/mL), 1.56 mg/L coagulant A, 30 cm Sand, and 37 m/h Filtration Rate *("Coagulant first" — seeding of microspheres as well as collecting samples after feeding 1.56 mg/L coagulant for 8 hrs; "Microspheres first" — seeding microspheres 30 mins prior to coagulant addition, followed by feeding coagulant for 8 hr and taking samples over this time; "Simultaneously" — feeding microspheres and coagulants simultaneously.)*

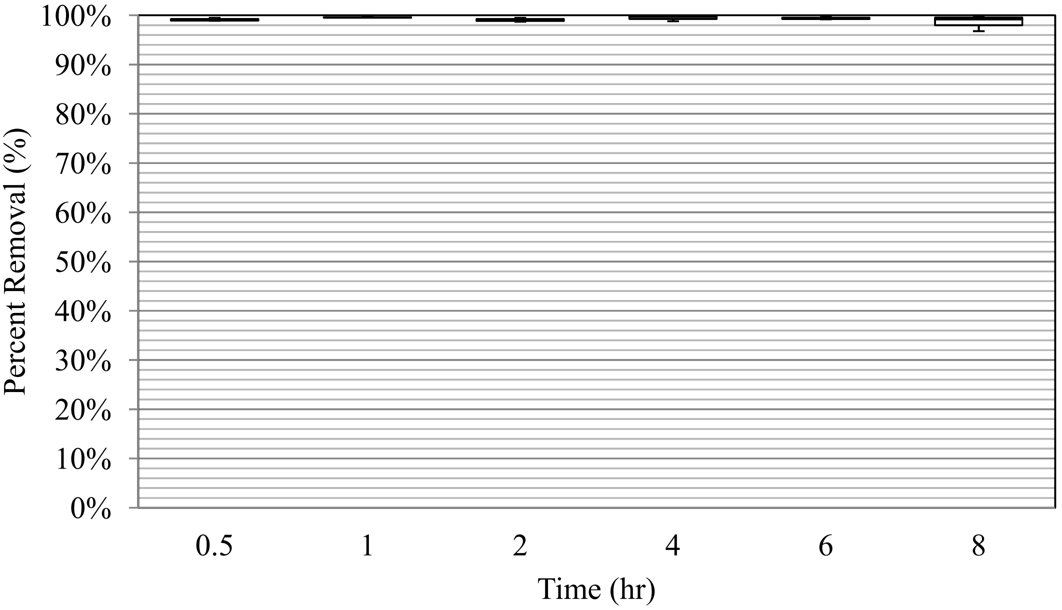


Figure 3.8 “Simultaneously Feeding of coagulant and Microspheres” Test, Microspheres Removals over Time, 30 cm Sand, and 37 m/h Filtration Rate ─ *(feeding of 1.56 mg/L coagulant, and seeding 1.8 #/mL microspheres over 8 hrs)* (number of experiments =1, number of samples = 3)

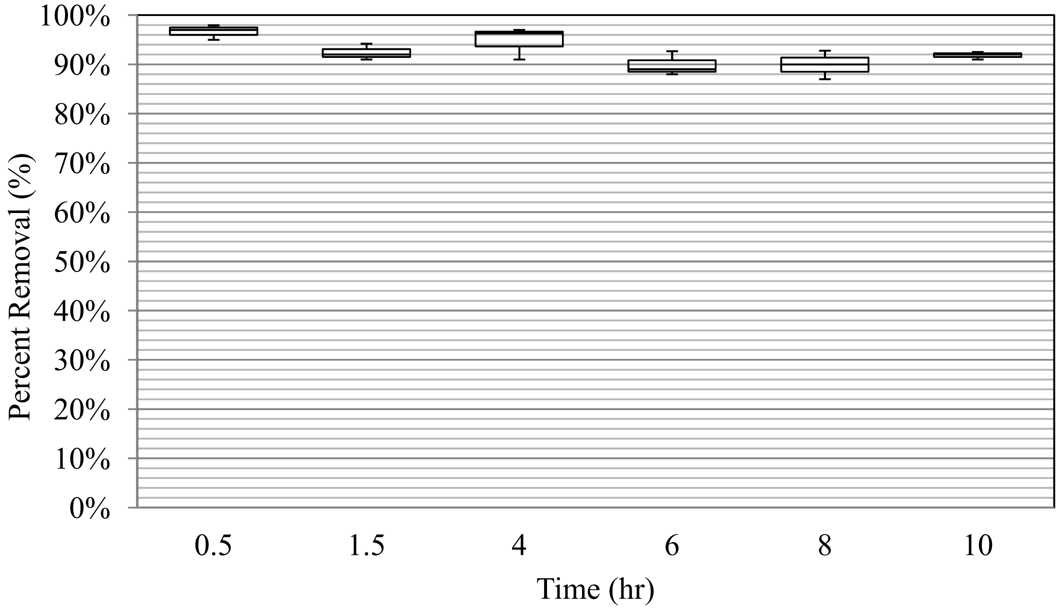


Figure 3.9 “Coagulant First” Test, Microspheres Removals over Time, 30 cm Sand, and 37 m/h Filtration Rate ─ *(feeding of 1.56 mg/L coagulant for 8 hrs, then seeding 1.8 #/mL microspheres without coagulant feeding and collecting samples)* (number of experiments =1, number of samples = 3)

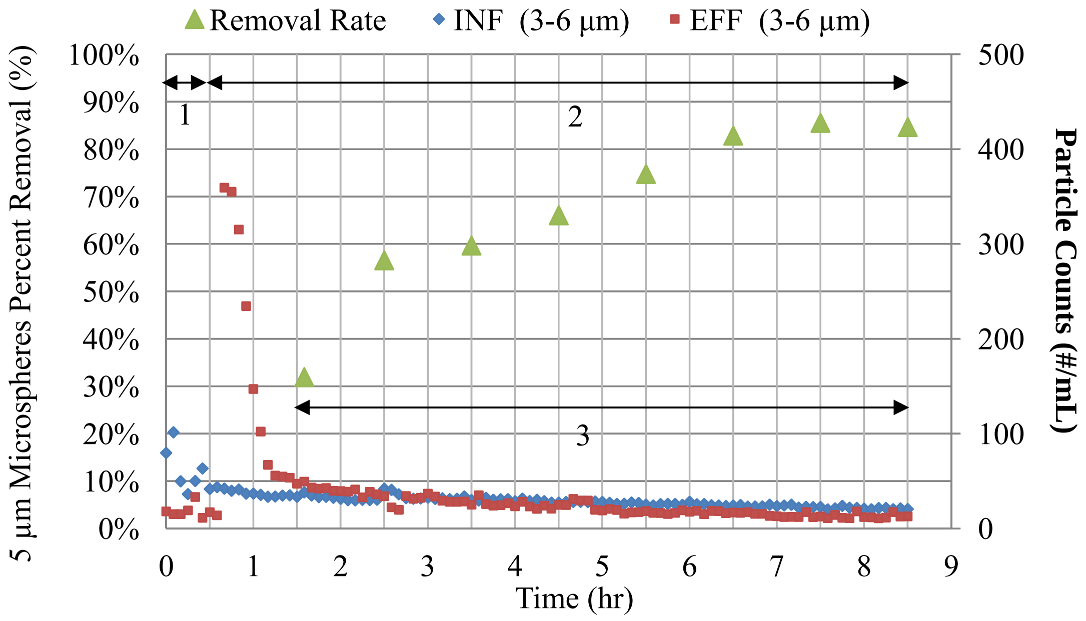
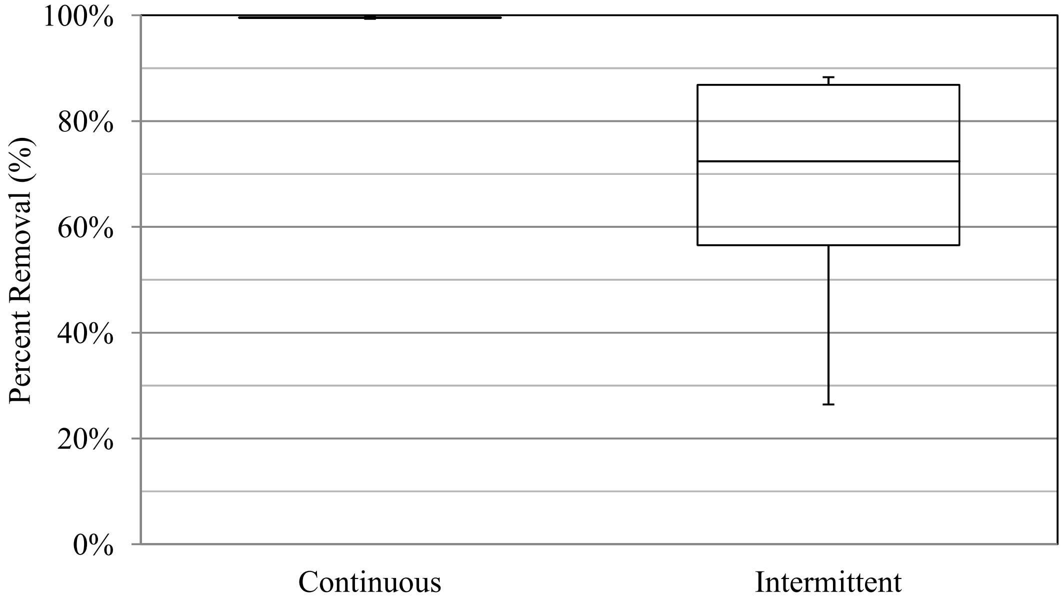


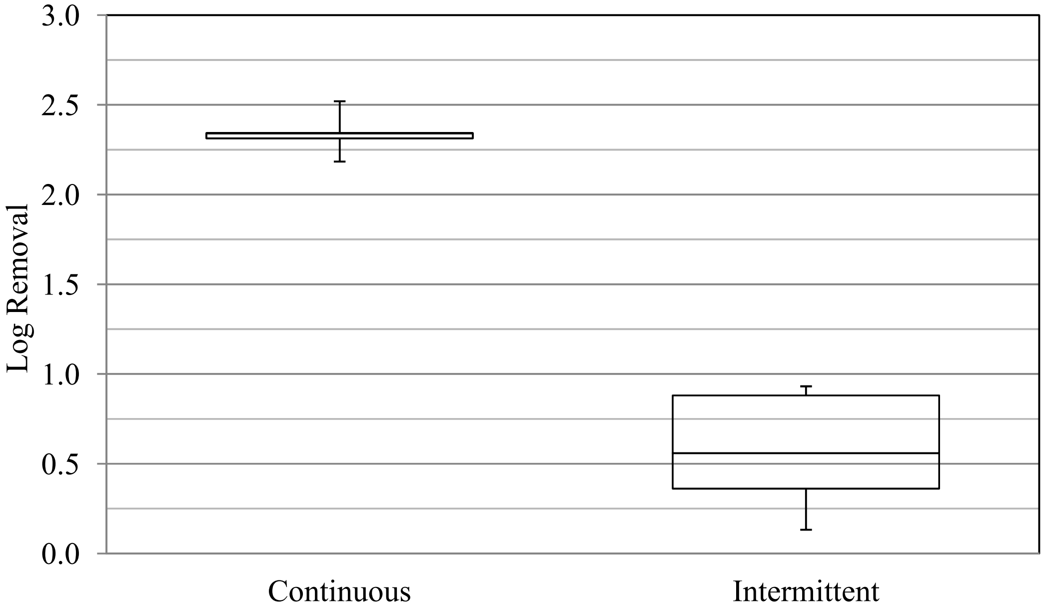
Figure 3.10 "Microspheres First" Test, Microsphere Removal and Filter Influent and Effluent Particle Counts, 30 cm Sand, and 37 m/h Filtration Rate (*seeding 1.8 #/mL microspheres 30 mins prior to 1.56 mg/L coagulant addition*) (Microspheres were fed in period '1'; Coagulant was fed continuously in period '2'; Samples were collected in period '3' with intermittent microsphere seeding) (number of experiments =1, number of samples = 3)

3.3.2 The Mode of Feeding of Coagulants

Experiments with continuous inputs or intermittent input of coagulant were conducted. One cycle of "Intermittent feeding" was 16 hrs. Four cycles, 64 hrs, were performed. Coagulant was fed for 8 hrs in each cycle. Samples were collected at the second and eighth hours after coagulant feeding stopped in each cycle. "Continuously" feeding of coagulant was conducted by feeding coagulant continuously without stop for 8 hrs. Samples were collected during the 8 hrs. For both experiments, microspheres were only fed 15 mins before sample collection, and were stopped feeding after collection samples. Figure 3.11 shows the removals for continuous and intermittent feeding. Microsphere removal of 99.5% (2.3 log) was achieved by continuously feeding coagulant and microsphere. While only 74% (0.6 log) of microspheres were removed by intermittent feeding. The mechanism of "intermittent feeding" is similar to the "coagulant first". Differences between these two experiments operations were: (1) "coagulant first" experiment was only conducted in 2 turnovers (16 hrs), with feeding of coagulants for 8 hrs, seeding microspheres and collecting samples during the next 8 hrs, while the "intermittent feeding" experiments were conducted over 8 turnovers (64 hrs); (2) Microspheres residual from the last cycle would impact the microspheres removals for "intermittent feeding" experiment, and this was similar to "feeding microspheres first" (i.e., low microspheres removals in last cycle led to microspheres exist before coagulant fed in this cycle). The same as "coagulant first" experiment, coagulant was fed for 8 hrs and samples were collected in the next 8 hrs. Two samples were collected in the following 8 hrs, 2 hrs samples and 8 hrs samples since stop feeding of coagulant in each cycle. Figure 3.12 displays the microsphere removals for "intermittent feeding" over 64 hrs. The removals at the eighth hour since stopping feeding of coagulant were typically less than that at the second hour. Removals at the second hour decreased over time, which perhaps because of the similar mechanism of "feeding microspheres first" (as shown in Figure 3.10) and the excessive dosing coagulant (will be discussed in 3.3.3 Extended Dosing of Coagulant). All these results indicated the coagulant should be fed continuously to maximize the removals of *Cryptosporidium*-sized microsphere from the pool.



(a. Percent Removal Rate)



(b. log Removal Rate)

Figure 3.11 Performances of Continuous Feeding and Intermittent Feeding, 10^7 Microspheres (1.8 #/mL), 1.56 mg/L coagulant A, 30 cm Sand, and 37 m/h Filtration Rate (“Intermittent” ─ 1.56 mg/L coagulant A was fed in 8 hrs, and samples were taken after the coagulant addition after 2 hrs and 8 hrs delay; “Continuous” ─ feeding microspheres and coagulant A continuously and simultaneously)

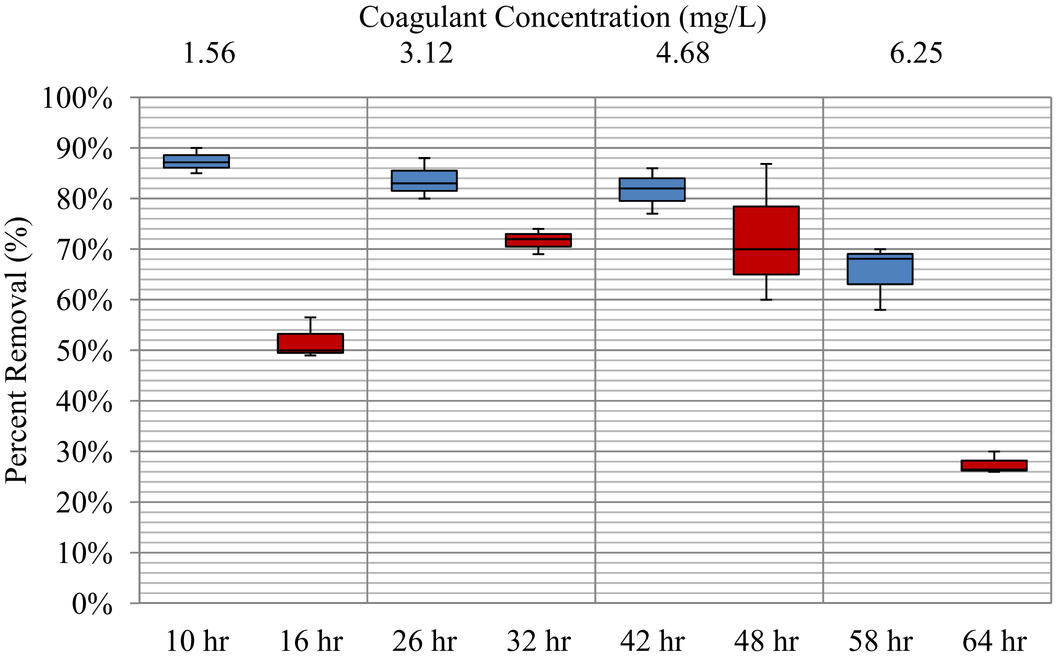


Figure 3.12 Performances of Intermittent Feeding over Time, 1.8 #/mL Microspheres, 1.56 mg/L coagulant A, 30 cm Sand, and 37 m/h Filtration Rate (Blue column— removals at the second hour since stopping feeding of coagulant; red column — removals at the eighth hour since stopping feeding of coagulant) (One cycle was 16 hrs, coagulant was fed in the first 8 hrs, and followed by samples collection at the second and eighth hour without coagulant feeding in the next 8 hrs) (number of experiments =1, number of samples = 3)

3.3.3 Extended Dosing of Coagulant

Performance of extended dosing of coagulant was evaluated. Coagulant was fed as one recommended dosage per turnover for five days, streaming current data and removals are shown in Figure 3.13. Streaming current started from -200 streaming current unit (SCU), which was the streaming current of Charlotte tap water after adding chemicals to get pH of 7.5, alkalinity of 100 mg/L as $CaCO_3$, hardness of 200 mg/L as $CaCO_3$, and free chlorine of 2 mg/L. The streaming current meter was installed at the filter influent line after the coagulant feeding point. Streaming current values increased with addition of coagulant. Figure 3.14 shows the streaming current trends with feeding

0.1 times of the recommended dosage coagulant every turnover. The negatively charged microspheres were neutralized by positively charged coagulant, and this led to the increasing of streaming current at first. Streaming current tended to be saturated by the overdose of coagulant as shown in Figure 3.13 and 3.14. Removals of microsphere decreased with the continued coagulant addition, because of the coagulant accumulated in the system. Coagulant concentration in the pool at each turnover is shown in Table 3.1. Results indicated coagulant A concentration increased over time and approximately was multiple of 1.56 mg/L with differences between 3% to 12%. The removal data indicated excessive use of coagulant led to impaired microsphere removal.

Table 3.1 Measured and Estimated Coagulant A Concentration in Each Turnover

Time (hr)	Influent Concentration (mg/L)[a]	Effluent Concentration (mg/L)[b]	Average of 'a' and 'b' (mg/L)[c]	Estimated Concentration (mg/L)[d]	Differences between 'c' and 'd'
8	1.40	1.38	1.39	1.56	12%
16	2.76	3.03	2.90	3.12	7%
24	4.36	4.41	4.39	4.68	6%
32	5.86	6.07	5.97	6.24	4%
40	7.36	7.72	7.54	7.8	3%
48	9.16	9.09	9.12	9.36	3%

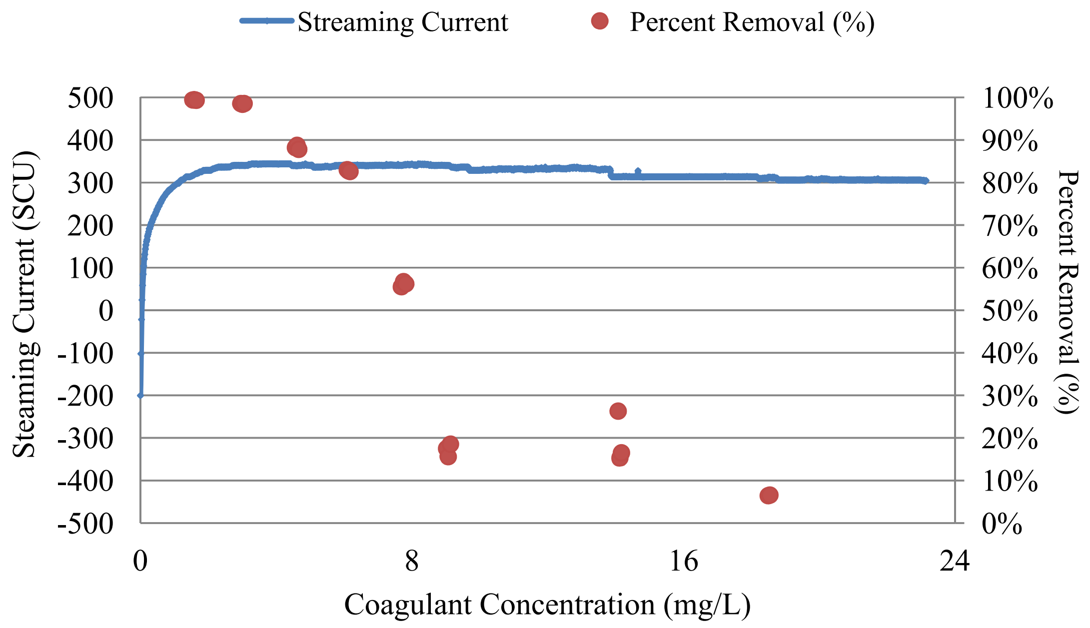


Figure 3.13 Streaming Current Variation and Microsphere Removal versus coagulant Concentration, 10^7 Microspheres (1.8 #/mL), 1.56 mg/L coagulant A, 30 cm Sand, and 37 m/h Filtration Rate (n=1)

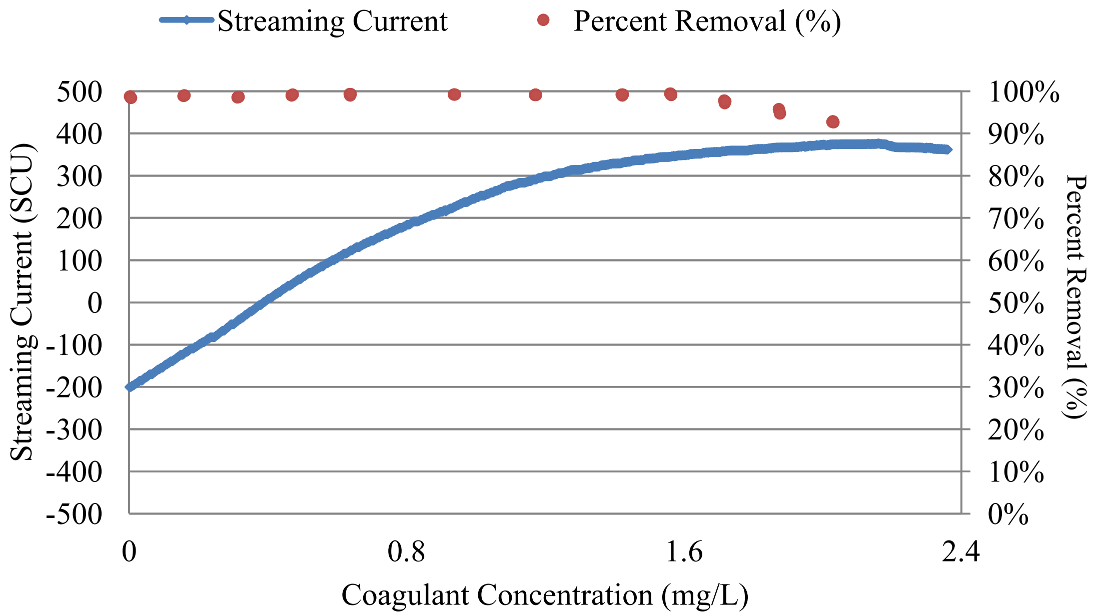


Figure 3.14 Streaming Current Variation and Microsphere Removal versus coagulant Concentration, 10^7 Microspheres (1.8 #/mL), 0.156 mg/L coagulant A, 30 cm Sand, and 37 m/h Filtration Rate (n=1)

Streaming current measured the surface charge of microspheres in the pool water. The streaming current value obtained with microsphere feeding and continuous coagulant feeding was defined as active streaming current. Streaming current data shown in Figure 3.13, Figure 3.14, and Figure 3.15 were active streaming current. Figure 3.15 shows microsphere removals corresponding to different active streaming current values. The streaming current value obtained with microsphere feeding but without coagulant feeding (only coagulant residual existed in the pool) was defined as passive streaming current. Figure 3.16 shows microsphere removals under different passive streaming current. Microsphere removals were not always the same for the same active and passive streaming current, and they were much agreed for active and passive streaming current at 0 SCU.

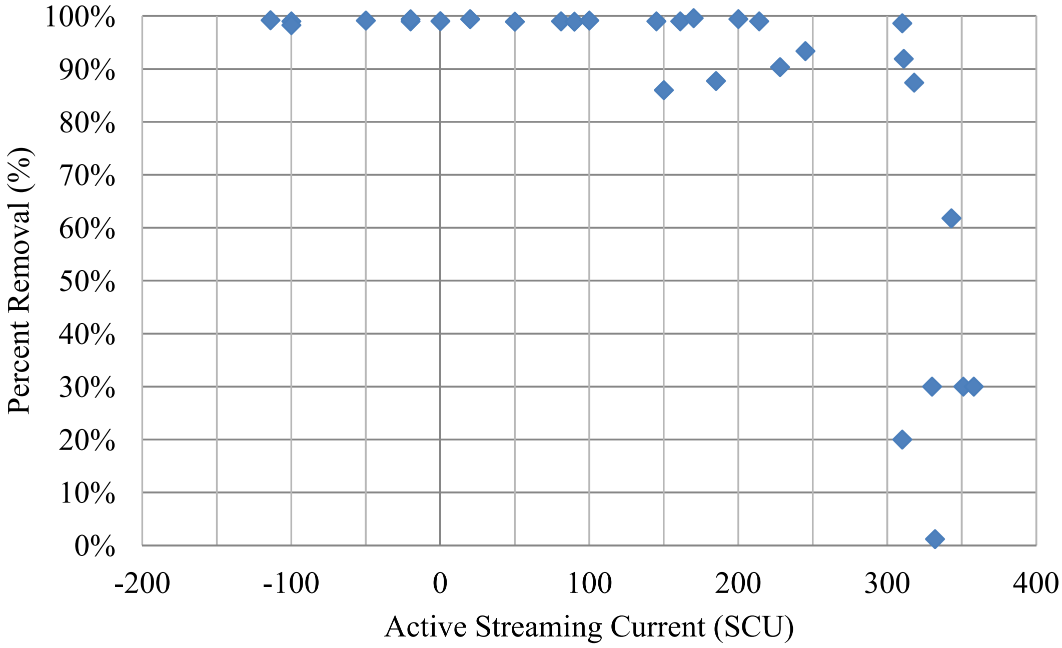


Figure 3.15 Active Streaming Current versus Microsphere Removal, 10^7 Microspheres (1.8 #/mL), 1.56 mg/L coagulant A, 30 cm Sand, and 37 m/h Filtration Rate (n=1)

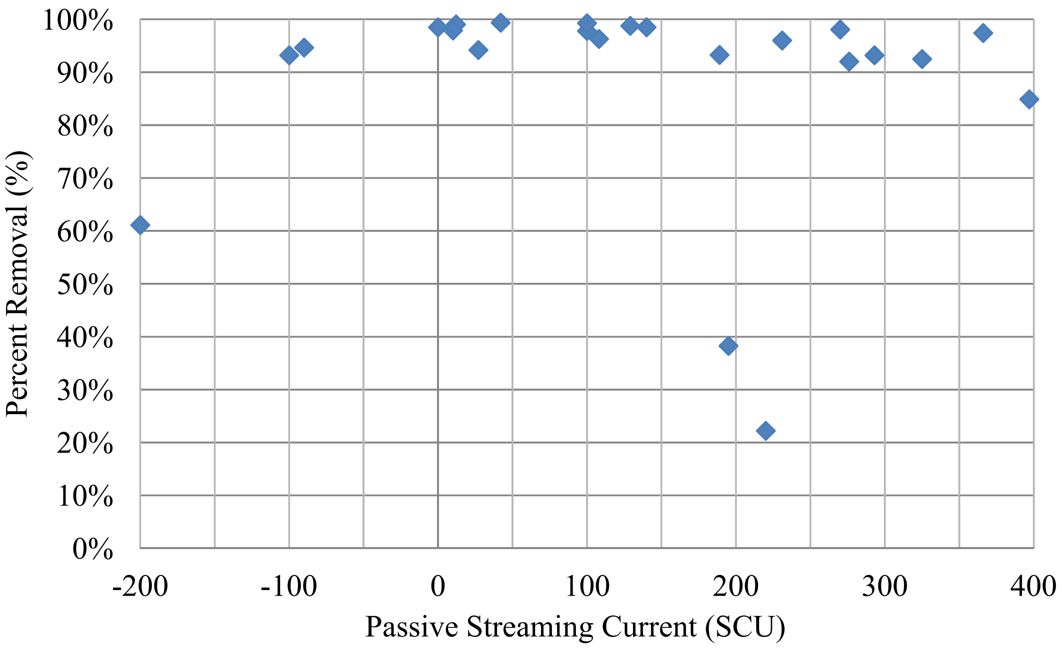


Figure 3.16 Passive Streaming Current versus Microsphere Removal, 10^7 Microspheres (1.8 #/mL), 1.56 mg/L coagulant A, 30 cm Sand, and 37 m/h Filtration Rate (n=1)

3.3.4 Microsphere Concentration

The removals of *Cryptosporidium* have been reported to be dependent on the oocyst concentration in the source water (Assavasilavasukul, et al., 2008; Betancourt and Rose, 2004). Multiple experiments were conducted with multiple microsphere concentrations and multiple coagulant dosages in order to determine whether the concentration of microsphere seeded into the pool system impacted the overall microsphere removals. Figure 3.17 shows 1.8×10^{-2} #/mL microsphere removals at different coagulant concentrations. Figure 3.18 shows 1.8 #/mL microsphere removals at different coagulant concentrations. And Figure 3.19 shows 18 #/mL microsphere removals at different coagulant concentrations. Coagulant was fed from high dosage to low dosage in order to discover the dosages corresponding to 99%, 95% and 90%

microsphere removals for each microsphere concentration. Figure 3.20 displays the removal at 99%, 95% and 90% for the microsphere with concentrations of 1.8×10^{-2} #/mL, 1.8 #/mL, and 18 #/mL (magnitude of 1×10^{5}, 1×10^{7}, and 1×10^{8} microsphere) versus the coagulant dosage to achieve those percent removals. Results indicated microspheres concentration impacted the overall percentage of microsphere removals. The relationship between coagulant dosage and microsphere removals was stoichiometric (Tenny and Stumm, 1965), which was indicated by the coefficient of determination (R^2) in Figure 3.20. Raw water coagulant demand was not considered in this study.

Coagulant demand to neutralize one microsphere (4.5 μm) is determined to be 1.63×10^{-7} mg. 10^{5} microspheres will need 1.63×10^{-2} mg coagulant; 10^{7} microspheres will need 1.63 mg coagulant; 10^{8} microspheres will need 16.3 mg coagulant as shown in Appendix H.

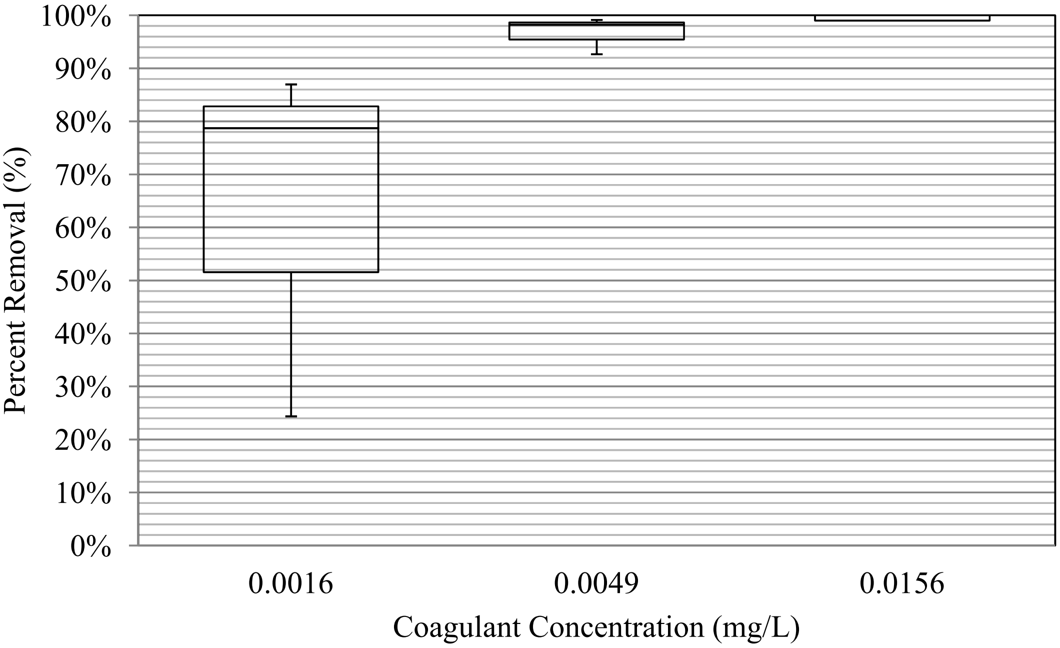


Figure 3.17 Microspheres (1.8 × 10^{-2} #/mL) Removal versus coagulant B Concentration, 30 cm Sand, 37 m/h Filtration Rate *(coagulant was fed beginning with high dosage and reduced to low dosage)* (number of experiments =1, number of samples = 3)

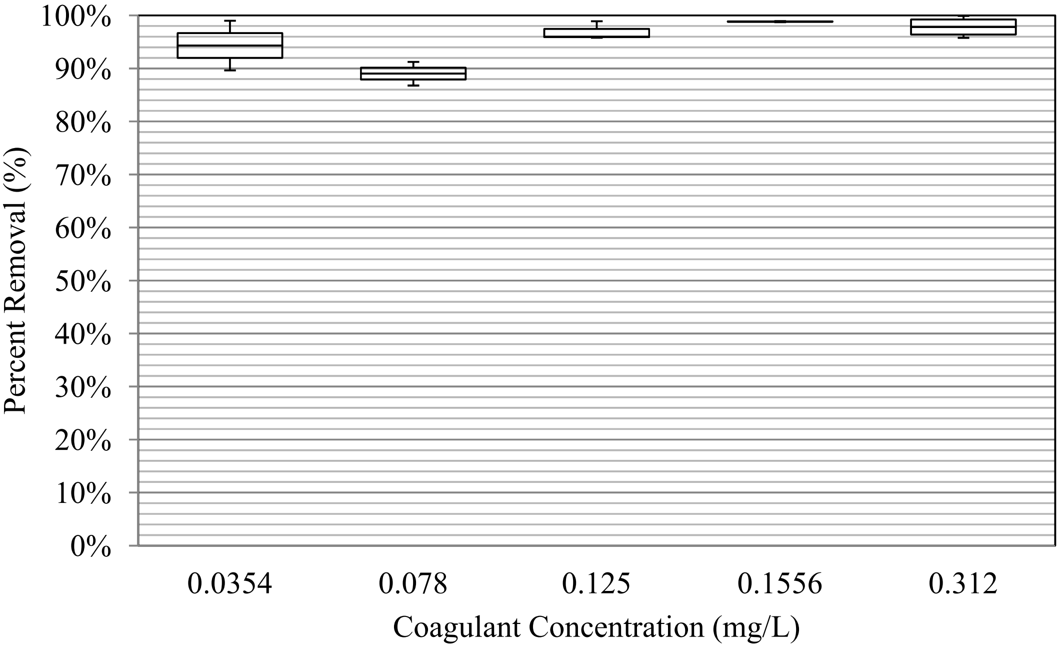


Figure 3.18 Microspheres (1.8 #/mL) Removal versus coagulant B Concentration, 30 cm Sand, 37 m/h Filtration Rate *(coagulant was fed beginning with high dosage and reduced to low dosage)* (number of experiments =1, number of samples = 3)

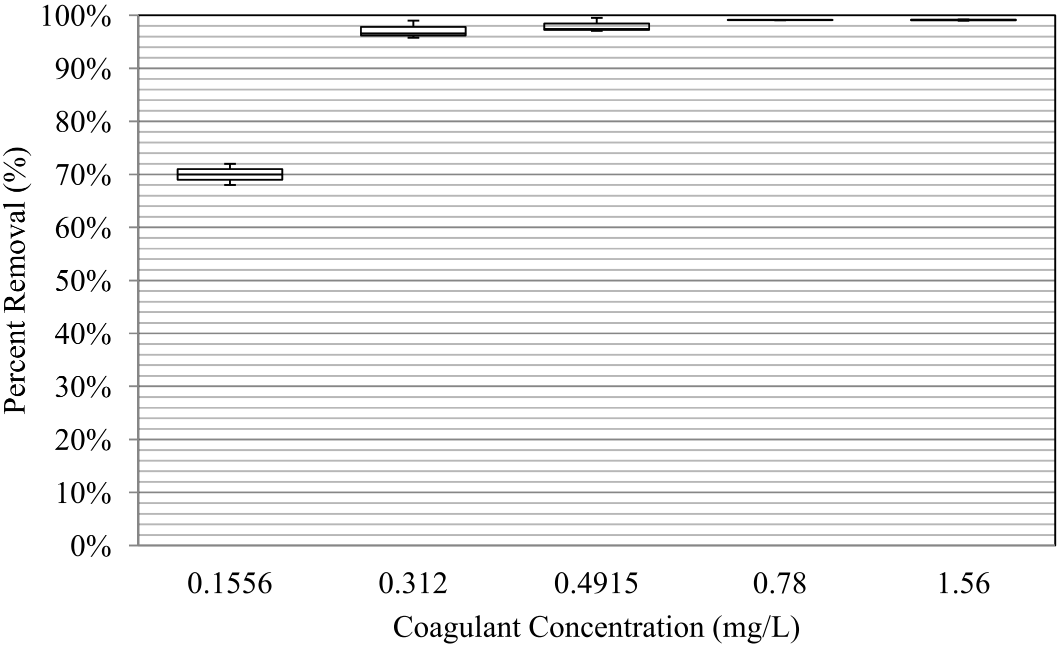


Figure 3.19 Microspheres (18 #/mL) Removal versus coagulant B Concentration, 30 cm Sand, 37 m/h Filtration Rate *(coagulant was fed beginning with high dosage and reduced to low dosage)* (number of experiments =1, number of samples = 3)

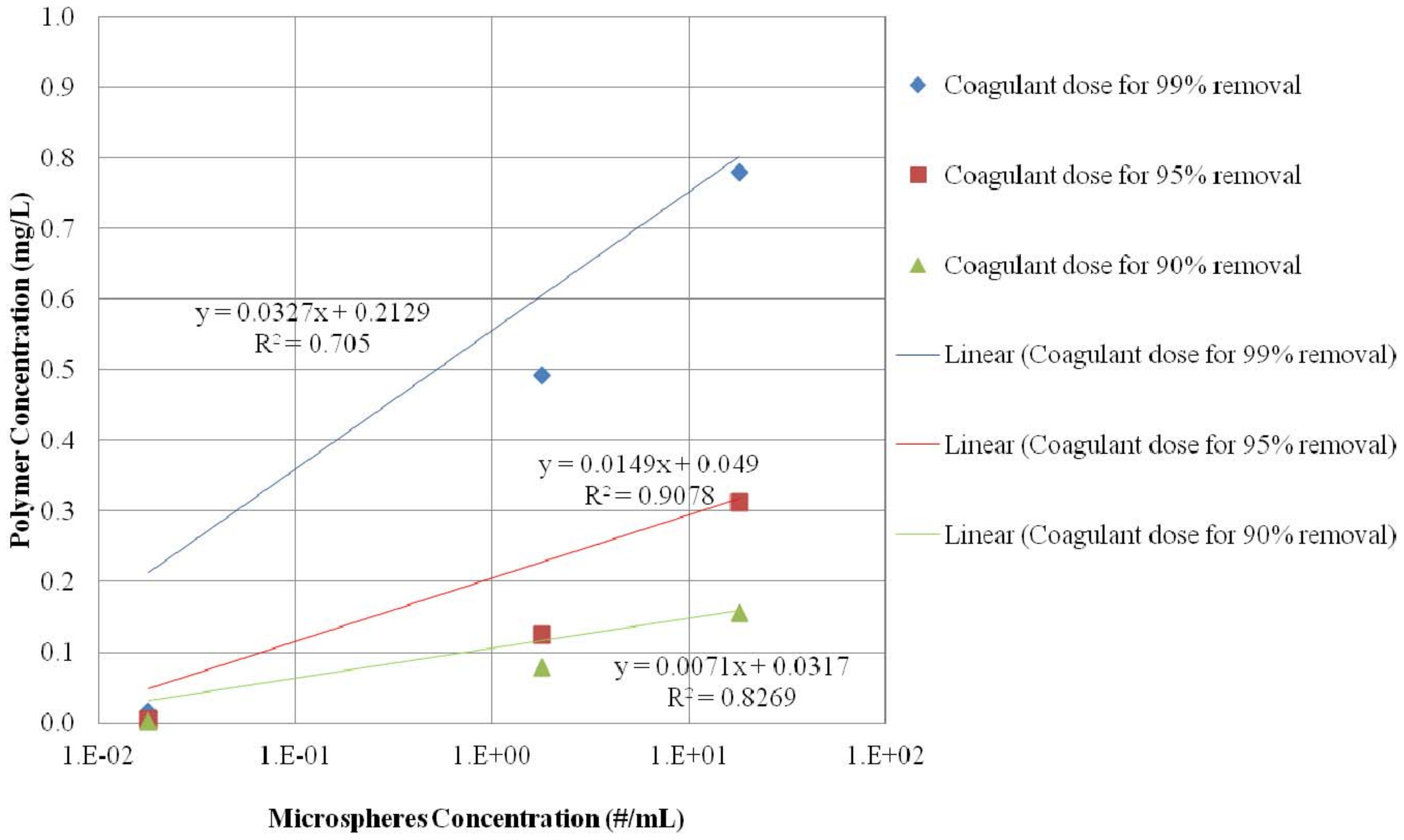


Figure 3.20 Coagulant B Dosage versus Microspheres Concentration at Microsphere Removal of 90%, 95%, and 99%, 30 cm Sand, 37 m/h Filtration Rate (n=3) *(data points from Figures3.17, 3.18, and 3.19)*

Coagulants were also fed with low dosage and increased to higher dosage to determine the relationship between the microsphere concentration and coagulant dosage. Microsphere concentration of 1.8×10^{-2} #/mL, 1.8 #/mL, and 18 #/mL (total microspheres of 10^5, 10^7, and 10^8) were evaluated. Results are illustrated in Figure 3.21. Significant differences of the removal performance were observed for different microsphere concentrations. The 96% of microsphere removals, which was the highest removals obtained (for microsphere concentration of 1.8×10^{-2} #/mL) was achieved at 0.016 mg/L. The 98% of microsphere removals, which was the highest removals obtained (for microsphere concentration of 1.8 #/mL) was achieved at 0.78 mg/L. The 97% of microsphere removal, which was the highest removals obtained (for microsphere concentration of 18 #/mL) was achieved at 1.56 mg/L. None of these experiments achieved 99% removals as observed in previous experiments. Since the coagulant dosage went from low to high, this was thought to be similar to "feeding microspheres first" (i.e., feeding microspheres before an effective dose of coagulant was started). The "feeding microspheres first" results appear in Figure 3.10 with removals never exceeding 90%. Removals decreased with the increased coagulant dose after achieved the highest microsphere removals for microspheres concentration of 1.8×10^{-2} #/mL and 1.8 #/mL, perhaps because of the overfeeding of coagulant.

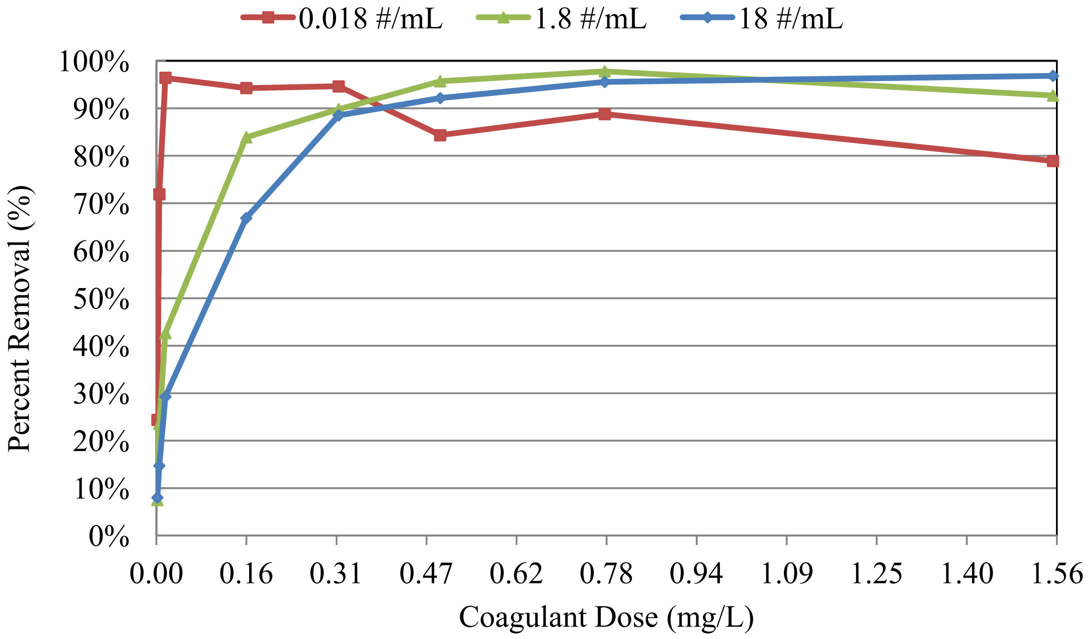


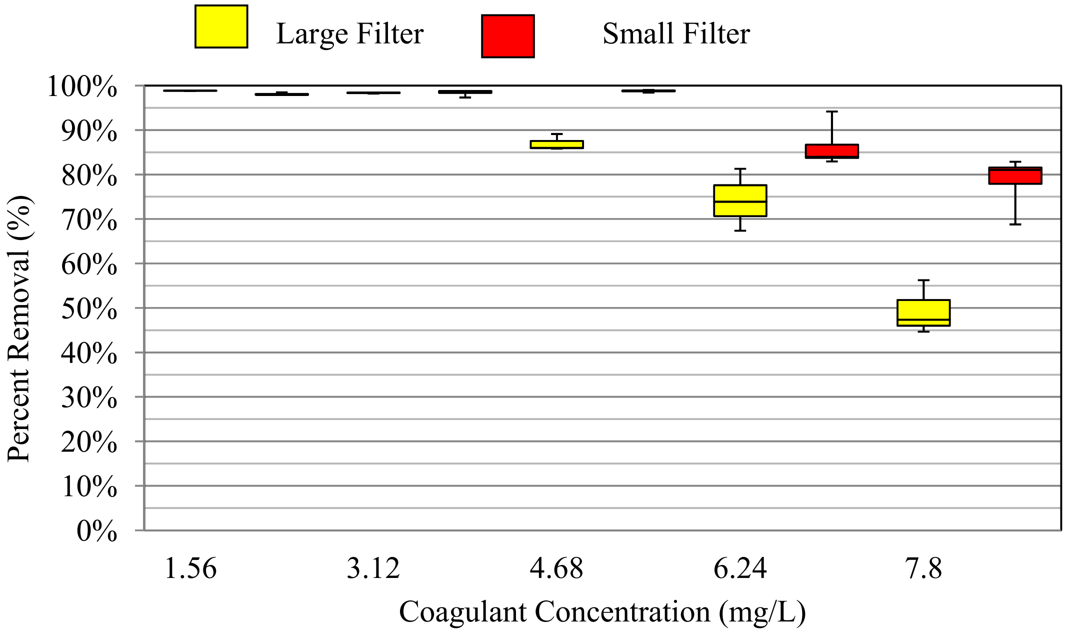
Figure 3.21 Removals of Microspheres concentration of 1.8 × 10^{-2} #/mL, 1.8 #/mL, and 18 #/mL at Different Coagulant A Dosage, 30 cm Sand, 37 m/h Filtration Rate (coagulant was fed from low to high dosage) (n=1)

3.3.5 Ratio of Filter Media Surface Area to Pool Volume

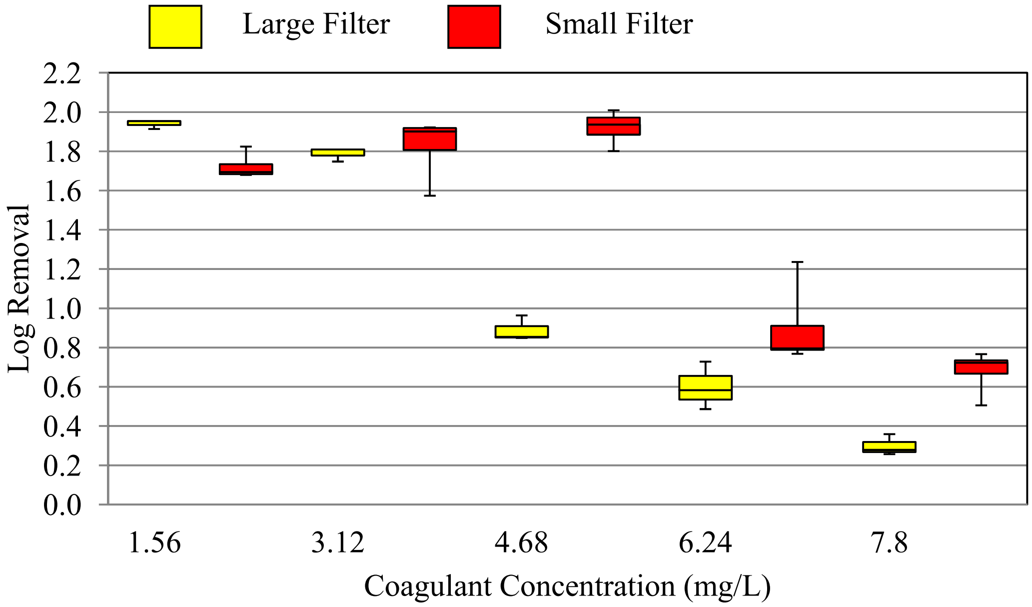
Microsphere removals by sand filtration with two different sand surface areas were compared. The large sand bed surface area was 0.18 m^2 (1.9 ft^2), and the small sand bed surface area was 0.018 m^2 (0.19 ft^2). Swimming pool turnover time was 50 min for the large sand filter and 8 hrs for the small sand filter. The hypothesis was that the surface area of the sand might exert a greater coagulant demand, which was not supported by the result obtained under experimental condition.

Large sand filter bed failed first compared with small sand filter (as shown in Figure 3.22). Large sand filter media depth was 25.4 cm (10 inch), and small sand filter depth was 30 cm (12 inch). Previous study indicated media depth made differences in microspheres removal by comparing 30 cm and 60 cm sand filters with the same filtration rate (Goodman, 2011). Large sand filter was operated at 114 L/m (30 gpm), and small sand filter was operated as 11.4 L/m (3 gpm). Perhaps mixing was also different with the higher flow for large sand filter versus the lower flows for large sand filter.

The ratio of the pool volume to sand filter media surface area was calculated as 148,209 L/m^2 (3,638 gal/ft^2) for the small bed filter, 1,959 L/m^2 (48 gal/ft^2) for the big bed filter, and 69,638 L/m^2 (1,709 gal/ft^2) for one full scale swimming pool located on the University of North Carolina at Charlotte campus. Appendix I gives the parameters and the calculations for the ratio of pool volume to the sand surface area of the swimming pools.



(a. Percent Removal)



(b. log Removal)

Figure 3.22 Removals Corresponding to Different Filter Bed Surface Areas, 1.8 #/mL Microspheres, 1.56 mg/L coagulant A, 30 cm Sand, 37 m/h Filtration Rate *(Yellow color box — 0.18 m^2 filter surface area; Red color box — 0.018 m^2 filter surface area)* (number of experiments =1, number of samples = 3)

3.3.6 BFA Concentration Impact on Removal of Microspheres

The study made use of a BFA solution, containing artificial sweat and urine. Removals of microsphere with and without BFA addition over 8 hrs are shown in Figure 3.23. No differences were observed between with and without BFA addition. The results agreed with the zeta titration results that BFA had no significant impact on microspheres surface charge.

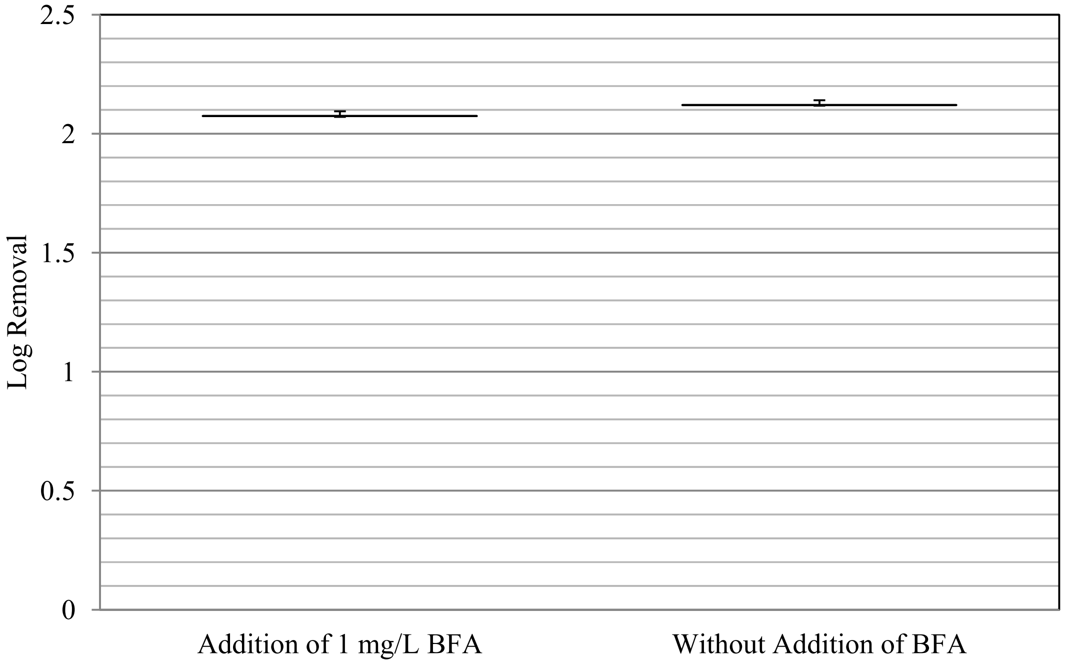


Figure 3.23 Log Removal of Microspheres With or Without BFA addition, 1.8 #/mL Microspheres, 1.56 mg/L coagulant A, 30 cm Sand, 37 m/h Filtration Rate, Continuous and Simultaneous Feeding (number of experiments =1, number of samples = 3)

3.4 Conclusion

The microsphere removals for feeding microspheres and coagulant A simultaneously were over 99% (2 log), compared with 94% removal (1.3 log) for “feeding coagulant first”, and 65% (0.5 log) for ‘adding microsphere first’. Continuously feeding of coagulant A achieved over 99% (2 log) removals, compared with 74% (0.6 log) by “intermittent feeding”. All of these experiments indicated that the maximum microsphere removals were achieved by continuously feeding coagulant by using coagulant pump. Microspheres concentration impacted the system performance. Higher microsphere concentration required higher coagulant dosage to achieve the same microsphere removals. No significant differences of microsphere removals were observed between large sand filter and small sand filter. No significant differences between microsphere removals with and without addition of BFA were observed either. However, extended periods of feeding coagulant led to coagulant accumulation in the system and reduced removal efficiency under these experimental conditions (coagulant A was the only coagulant used in this part of the study).

CHAPTER 4: PILOT-SCALE STUDY ON ENHANCED *CRYPTOSPORIDIUM*-SIZED MICROSPHERE REMOVALS FROM RECREATIONAL WATER THROUGH FILTRATION

4.1 Introduction

4.1.1 Conventional Drinking Water Treatment on *Cryptosporidium*

The removal of *Cryptosporidium* in drinking water industry has been widely researched for decades. It has been demonstrated that *Cryptosporidium* removal throughout all stages of the classical treatment process is largely influenced by the effectiveness of coagulation pretreatment (Amburgey, 2002; Amburgey, et al., 2004; Cummins, et al., 2010; Dugan, et al., 2001; Hankins, et al., 2006; Karim, et al., 2010; Lopez, et al., 2010).

4.1.1.1 Drinking Water Treatment Process

Conventional drinking water treatment includes the coagulation, rapid mixing, flocculation, sedimentation, and filtration (Hendricks, 2006). Particles tend to repel each other and there is no natural tendency to flocculate. Coagulation is the process destabilizing the particles (Edwards, 1997; Gao, et al., 2002).

4.1.1.2 Coagulation of *Cryptosporidium*

Inorganic trivalent metal ions such as aluminum and ferric iron, and water-soluble organic polymer coagulants are widely used for particle and NOM coagulation (Bolto and Gregory, 2007; Polasek and Mutl, 2002). Charge neutralization and sweep flocculation are the predominant mechanism for *Cryptosporidium* coagulation (Butkus, et al., 2003;

Okuda, et al., 2006; Xagoraraki and Harrington, 2004). The best removals have been shown to occur at high alum doses where aluminum hydroxide precipitation was observed to be extensive (Xagoraraki and Harrington, 2004). Coagulation pH has impact on coagulation through its effect on particle zeta potential and chemical speciation. One investigation suggested that lowering coagulation pH could improve removal of *Cryptosporidium* (States, et al., 2002). The effect of pH on metal-based coagulants is more significant than for polymeric organic coagulants (Hendricks, 2006).

Polymeric organic coagulants (polymers) are less pH dependent, have less sludge generation and sludge disposal associated secondary pollution compared with metal-based coagulants (Hendricks, 2006). They may function to charge neutralize colloids or other types of particles so that they may agglomerate as flocs. Since polymer addition generally does not impact the pH of the water being treated, pH adjustment is not necessarily required for optimal coagulation (Emelko and Huck, 2003). Polymers acting as coagulants usually contain materials with high charge density (Bolto and Gregory, 2007). Polymerisation of diallyl dimethyl ammonium chloride (polyDADMAC) is a water-soluble polymer. It was found to be very effective for removing disinfection by-product (BDPs) and natural organic matter (NOM) acting as a primary coagulant or coagulation aid (Chang, et al., 2005; Hankins, et al., 2006; Polasek and Mutl, 2002; Wei, et al., 2010). The elimination of pathogenic organisms like *Giardia* and *Cryptosporidium* can be achieved by combination of alum salts as coagulant and polymer as coagulation aid (Bernhardt and Clasen, 1991; Narkis, et al., 1990). The natural cationic polymer such as chitosan was reported to coagulate with particle and enhance the particle removals (Bolto and Gregory, 2007; Fabris, et al., 2010; Guibal, et al., 2006). Chitosan has the characteristic of low charge density (Parsons, et al., 2007). *Cryptosporidium parvum* oocysts were removed by chitosan coagulation at optimal dosages followed by filtration were comparable to those achieved when filtration (at 10 m/h) was preceded by alum or iron coagulation during optimized operation (Brown and Emelko, 2009).

The effectiveness of coagulation depends on dosage (Divakaran and Pillai, 2001). Investigation indicated chitosan coagulation at dosage less than 1.0 mg/L did not result in appreciable improvements in *Cryptosporidium* parvum oocyst removal (Brown and Emelko, 2009).

4.1.2 Direct Filtration Removal of *Cryptosporidium*

Direct filtration is similar to conventional treatment in that a coagulant is used to form larger particles, but coagulated water is applied directly to the filters without settling or sedimentation step. It is generally used for low and consistent turbidity water.

The removals of *Cryptosporidium* in direct filtration is usually lower than that in the conventional water treatment (Amburgey, 2002; Nieminski and Ongerth, 1995; Nieminski, et al., 1995). A two year evaluation of *Cryptosporidium* was conducted at a full-scale treatment plant and a pilot plant operating under coagulation and direct filtration (Nieminski and Ongerth, 1995). Consistent of 2.9 log removal of *Cryptosporidium* were achieved when the treatment plant produced water of consistently low turbidity (0.1–0.2 NTU). Although the direct filtration was applied in a water treatment plant, a cryptosporidiosis outbreak was reported in 1994 (Nieminski and Ongerth, 1995; Roefer, et al., 1995; Roefer, et al., 1996).

4.1.3 Granular Media Filtration Removal of *Cryptosporidium*

Granular media filters alone were unable to stop the flow of *Cryptosporidium* oocysts. Laboratory experiments have shown only approximately 0.1 to 0.3 log removal (20% to 50%) of *Cryptosporidium* oocysts following a single pass through a filter without coagulation (Amburgey, et al., 2001; Amburgey, 2002; Amburgey, et al., 2009; Croll, et al., 2007).

4.1.4 Precoat Filtration Removal of *Cryptosporidium*

Diatomaceous earth (DE) filtration used in drinking water treatment can achieve approximately 3-6 log removal of *Cryptosporidium* depending on DE grades and operating conditions (Ongerth and Hutton, 1997; Ongerth and Hutton, 2001; Schuler, et al., 1988; Schuler and Ghosh, 1990). DE for *Cryptosporidium* and *Cryptosporidium*-sized microspheres removals were from 2.25 log (99.44%) to 4.44 log (99.996%) from 757 L (200 gal) swimming pool (Amburgey, et al., 2012). Straining is one of the removal mechanisms in precoat filtration, and when an appropriate grade of DE is selected, the pore structure of the filter cake physically blocks the passage of oocysts into filtered water (Letterman and Yiacoumi, 2010). The finer-graded media provides smaller pores between the grains and removes smaller particles more efficiently, but finer media also leads to faster head loss (Letterman and Yiacoumi, 2010).

Bumping is the act of intentionally stopping the precoat filter and forcing the precoat media and collected contaminants to be removed from the filter septum. It may impair pathogen removal and could facilitate the release of pathogens previously trapped in the filter, but the impact has not been clearly determined for swimming pool applications.

4.1.5 Cartridge Filter Removal of *Cryptosporidium*

Cartridge filters consist of surface filter media wrapped or constructed around a hollow core, wherein the feed water contacts the outer perimeter and, with pressure, moves across the filter to the core. Media is often pleated to increase the effective filter surface area; in some cartridges, media of differential porosity is used, the outer depth being of higher pore size to trap larger particles, while the inner media is tighter, to capture finer material.

4.2 Materials and Methods

4.2.1 Research Objectives

This chapter determined the approximate level of *Cryptosporidium* oocyst-sized microsphere removals that can be achieved in a swimming pool system through high-rate sand filtration with six coagulants. Microsphere removals, particles counts, turbidity, UV_{254}, and filter pressure loss were evaluated.

The performance of perlite/sand filter on *Cryptosporidium*-sized polystyrene microspheres removal was evaluated in a 5,500 L (1,450 gal) swimming pool. Sand and sand with an added top-layer of perlite filter media performances was tested without coagulation. *Cryptosporidium*-sized microsphere removals by DE without coagulation at different amount of precoat (DE) and filtration rates, as well as DE filtration with coagulation were evaluated. The bumping impact on DE filter performance was evaluated.

4.2.2 Experimental Setup

A 5,500 L swimming pool was built with filtration system and chemical control system. Pool water can be pumped through the filter (either granular filter or precoat filter) as shown in Figure 4.1. Detailed information about the materials used in this research is shown in Appendix G (i.e., instruments, pumps, flow meters, and filters). The small sand filter was made from transparent polyvinyl chloride (PVC) pipe. It utilized an integral media support cap (Leopold, ITT) as support for filter media as well as backwash flow distribution. The filter had a diameter of 15 cm and the sand depth of 30 cm. The effective size of the sand was 485 µm. Hydraulic loading rates (HLR) for the sand filter was 37 m/h, which is a typical high-rate filter loading rate used in the US swimming pools. All chemicals and microspheres were fed using peristaltic or metering pumps. The pool's pH and oxidation reduction potential (ORP) sensors were mounted in a bypass line shown in Figure 4.1. These sensors were connected to a controller (CAT 5000, Poolcomm, Rockville, MD, USA) for monitoring and chemical feed control. Coagulant and microspheres were fed into the pipe ahead of the pump and pre-filtration for a rapid coagulant mixing. Streaming current meter (Micrometrix, Suwanee, Georgia, USA) was installed in sample influent line to measure the surface charge of the water. Turbidimeter (HF scientific, Fort Myers, Florida, USA), particle counter (Chemtrac, Norcross, Georgia), UV transmission monitor (HF scientific, Fort Myers, Florida, USA, and Real Tech INC, Canada) were installed both on filter influent and effluent line. On-line data can be record and download from a computer. Particle counters collect the particle size in the following range, 2 µm - 3 µm, 3 µm - 6 µm, 6 µm - 10 µm, 10 µm - 20 µm, 20 µm - 50 µm, 50 µm - 100 µm, and the total particles from 2 µm to 100 µm.

Brown particles, thought to be sediment particles from the water distribution system, were intermittently observed in the tap water used to make the simulated swimming pool water. To remove the majority of these particles and provide a consistent base for the pool water recipe, tap water was circulated through a sand filter without coagulant addition for one pool turnover time (large sand filter = 25 mins, precoat filter = 30 mins) prior to each experiment. The particles were then removed by backwashing prior to all experiment.

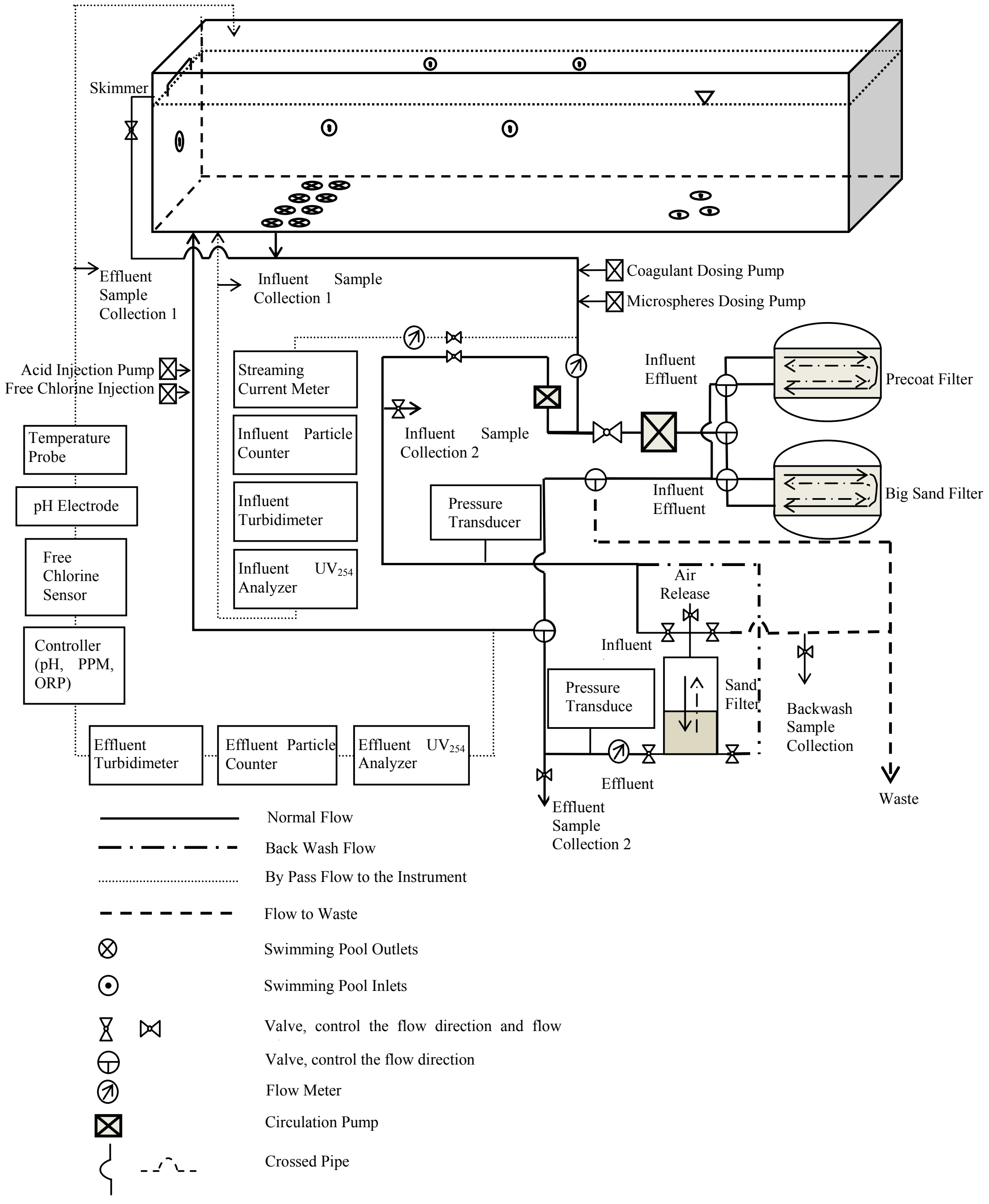


Figure 4.1 Pilot-Scale Swimming Pool Set-up

4.2.3 Filter Design

A sand filter was filled with 30 cm (12 inch) of dry sand. The single collector efficiency predicting model, shown in Equation (4.1) and (4.2) were applied (Tufenkji and Elimelech, 2004). Calculated single collector efficiency, η, and removal efficiency are shown in Figure 4.2. Single collector efficiency is the ratio of 'total rate at which particles strike a media grain' and 'total rate at which particles approach a media grain', including efficiency for transport by diffusion, gravity and interception (Tobiason, et al., 2010; Tufenkji and Elimelech, 2004). The 30 cm sand filter could remove only approximated 50% of *Cryptosporidium*-size microspheres according to this model (as shown in Figure 4.2), and 250 cm (100 inch) sand would be used for a required 99% removal, which might be impractical. However, it indicated with the increasing of particle size (due to aggregation), removal efficiency also increased (as shown in Figure 4.3).

$$\eta_T = 2.4A_S^{1/3}N_R^{-0.081}N_{pe}^{-0.715}N_{vdw}^{-0.052} + 0.55A_S N_R^{1.675}N_A^{0.125} + 0.22N_R^{-0.24}N_G^{1.11}N_{vdw}^{-0.053} \qquad (4.1)$$

$$r_e = 1 - \exp[\frac{3(1-\varepsilon_p)}{-2d_c} L_d \alpha \eta_T] \qquad (4.2)$$

where η_T is single collector efficiency,

N_{Pe} is peclet number,

N_R is aspect ratio,

N_{vdw} is van der Waals number,

N_A is determined as '$H/3\pi\mu d_p^2V$' (H is Hamaker constant, V is filtration rate, d_p is particle diameter),

N_G is determined as '$dp^2(\rho1-\rho)g/18\mu V$' ($\rho1$ is density of particle, ρ is density of water),

A_s is porosity-dependent parameter of Happel's model,

r_e is removal efficiency, L_d is filter media depth, ε_p is porosity, α is coagulation efficiency, and dc is sand grains.

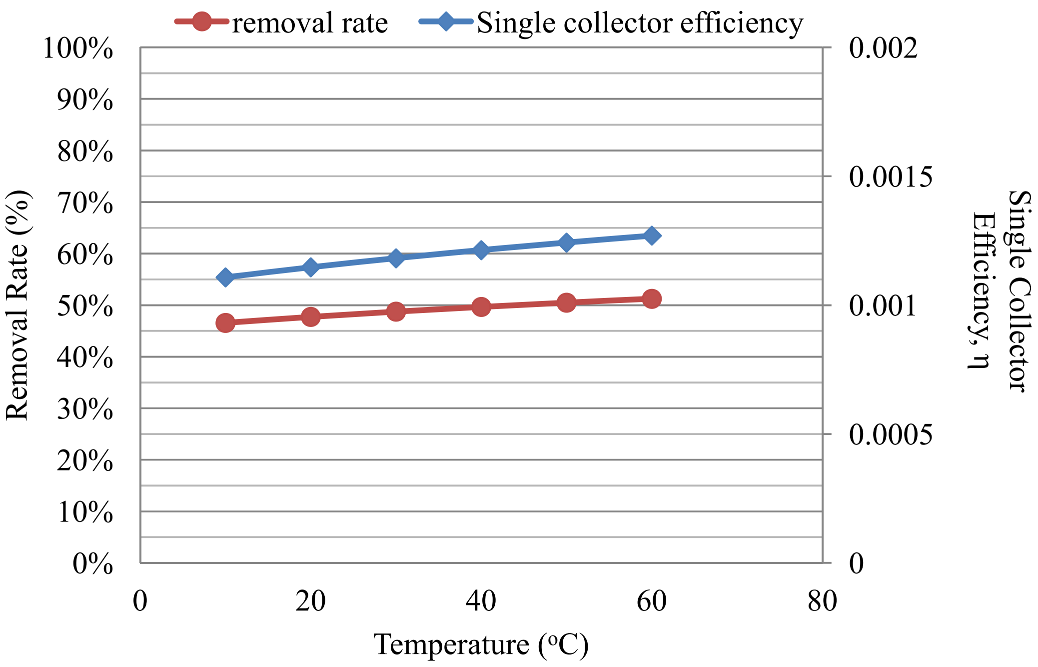


Figure 4.2 Microsphere (5 μm) Removals and Single Collector Efficiency Using 30 cm Sand Filter at Different Temperature, b. different sizes of microspheres at 20 °C)

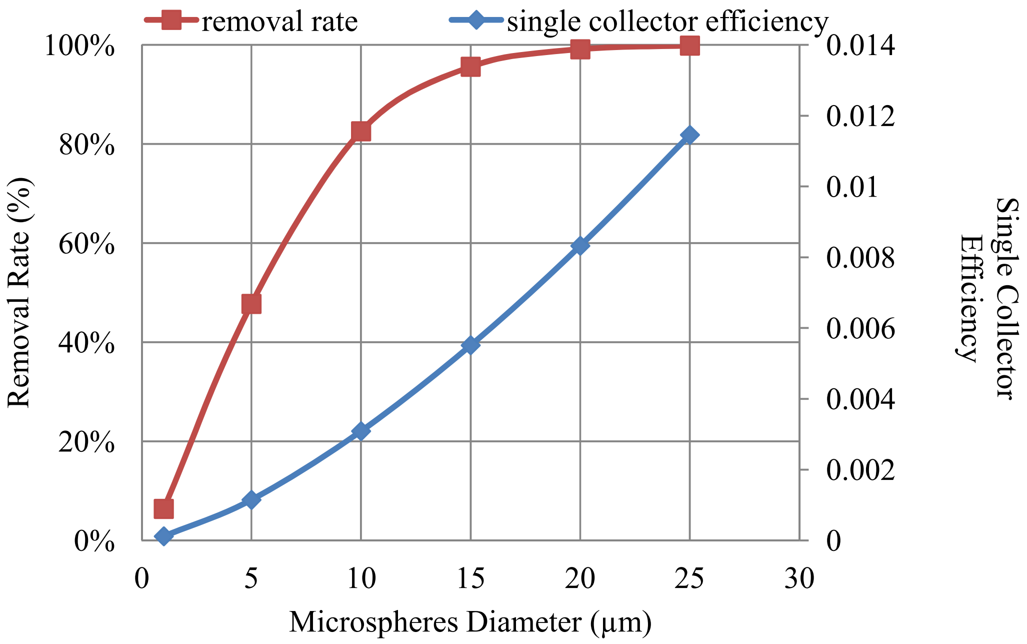


Figure 4.3 Different Sizes of Microsphere Removals and Single Collector Efficiency Using 30 cm Sand Filter at 20 °C

4.2.4 Synthetic Pool Water

The synthetic pool water was generated based on previous swimming pool water quality investigation (simulated swimming pool water type-1). Chemical characteristics of the water samples are summarized in Table 4.1. Amount of 5,500 L of Charlotte, NC tap water with dissolved organic carbon (DOC) of approximate 1 mg/L was supplemented with $NaHSO_4$, $CaCl_2$, $NaHCO_3$, $Ca(OCl)_2$, to adjust pool water chemical characteristics to those listed in Table 4.1.

Table 4.1 Chemical characteristic of experiment water samples

DOC (mg/L)	pH	Alkalinity (mg/L as $CaCO_3$)	Hardness (mg/L as $CaCO_3$)	Free chlorine	Oxidation reduction potential (ORP)
1.0	7.5	100	200	2	770-800

4.2.5 *Cryptosporidium*-sized Polystyrene Microspheres and Coagulants

The use of polystyrene microsphere as an oocyst surrogate has been done by multiple researchers and was used in this study (Amburgey, 2002; Amburgey, et al., 2004; Amburgey, et al., 2005; Amburgey, 2011; Amburgey, et al., 2012; Dai and Hozalski, 2003; Li, et al., 1997). Microspheres with diameter of 4.5 µm (Fluorsebrite™ Carboxylate YG 4.5 micron microspheres, Cat. #16592, Polysciences, Inc., Warrington, Pennsylvania, USA) were used as the surrogate since microspheres are virtually identical to *Cryptosporidium* oocysts in size, shape, density, and surface charge in pool water (Amburgey, 2010). Stock suspensions microspheres concentration was 4.37×10^{11} #/L. The diluted suspension with microspheres concentration of 4.37×10^{8} #/L was prepared by 1 to 1,000 dilutions of stock solution. Microsphere samples were mixed by vortexing and hand shaking for at least two minutes each before analyzing. Samples were passing through 3.0 µm pore size polycarbonate filters. Each polycarbonate filter was mounted on a glass microscope slide with a polyvinyl alcohol-DABCO solution, covered with a glass cover slip and counter under an epifluorescence microscope (Freer, 1984). For ease of counting and obtaining statistically valid data, microscope slides needed to contain between 10 and 150 microspheres. Removal efficiency was calculated by comparing the concentrations between influent and effluent samples. Six coagulants were used as primary coagulants in pool water treatment. Chemical characteristic of coagulants are summarized in Appendix C. "Material safety sheets" for each coagulant are shown in Appendix Q.

4.2.6 Granular Media

Table 4.2 illustrates the sand and perlite media properties. Table 4.3 shows the DE characteristic and the filter operation details (IIG, 2011). Sand (Pavestone®, Grapevine, Texas, USA), perlite (IIG, Brunswick, GA, USA) and DE (EpMinerals®Reno, Nevada, USA) were used as filter media in experiment. A sieve analysis of the filter sand was performed to determine the grain size distribution of the filter sand. The D_{90}, D_{60}, and D_{10} for the sand were 993, 726, and 485 µm, respectively. The D_{10} is also known as the effective size (0.49 mm). The sand was approximately a 20/40 mesh size.
This means that most of the sand passed through a #20 sieve, but was retained on a #40 sieve. The uniformity coefficient for the filter sand was 1.50. This is calculated by dividing the D_{60} by the D_{10}. The results of this analysis can be seen in Figure 4.2.
Perlite size distribution was obtained from datasheet by Microtrac
(as shown in Appendix J), and DE characteristics were obtained by datasheet from EP Minerals (as shown in Appendix K) (IIG, 2011).

Table 4.2 Filter Media and Filter Operating Details

Filter media materials	Sand	Perlite
Effective Size (d_{10}, µm)	485	16.9
d_{60} (µm)	726	50.37
d_{90} (µm)	993	92.3
Uniformity coefficient (UC, d_{60}/d_{10})	1.50	2.98
Filter bed depth (cm)	30	*varied among experiments*
Filter surface area	0.018 m^2 (0.196 ft^2)	0.018 m^2 (0.196 ft^2)
Hydraulic loading rate (HLR)	37 m/h (15.3 gpm/ft^2)	37 m/h (15.3 gpm/ft^2)

Table 4.3 DE Media Characteristics

Grain density (kg/m^3)	Permeability (µm^2)	Filter surface area (m^2)
320	3.6	2.23

4.2.7 General Experimental Approach

4.2.7.1 High-Rate Sand Filtration

Experiments were performed over multiple turnovers (theoretical hydraulic detention times) of the swimming pool (turnover time was 8 hr). Coagulants were fed at one recommended dose per turnover. Extended feeding of coagulants was evaluated. Samples were taken at each turnover. High-rate sand filtration control experiments without coagulant addition were conducted. A backwash was conducted after each experiment. Mass balance calculation for each experiment was performed. The mass balance calculation for the filter was shown as below (Equation 4.3, Equation 4.4, and Figure 4.4),

$$\text{Mass In} - \text{Mass Out} = \text{Accumulated} \qquad (4.3)$$

$$\text{Percent of Total Added} = \text{Out} / \text{In} \cdot 100\% \qquad (4.4)$$

where “Mass In” includes total added microspheres; “Mass Out” includes microspheres in backwash flow, backwash remnant water flow out of the filter, and flow to the pool; “Accumulated” refers to accumulated mass in the filter.

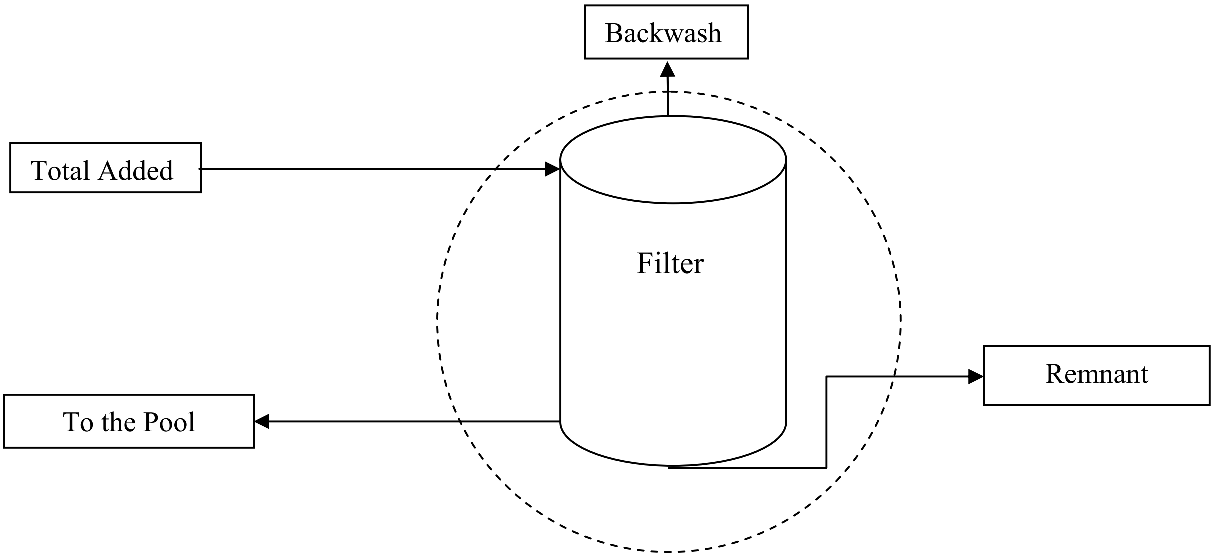


Figure 4.4 Filter Mass Balance Sketch

4.2.7.2 Precoat Filtration

Amount of precoat is the amount of perlite or DE media loaded on unit filter surface area, with the unit of kg·perlite/m^2 or kg·DE/m^2. Four levels of perlite were tested at 0.24 kg·perlite/m^2 (0.05 lbs·perlite /ft^2), 0.37 kg·perlite /m^2 (0.075 lbs·perlite /ft^2), 0.49 kg·perlite /m^2 (0.1 lbs·perlite /ft^2), and 0.61 kg·perlite /m^2 (0.125 lbs·perlite /ft^2), respectively. Experiments were conducted to compare single sand media and perlite/sand media on *Cryptosporidium*-sized microsphere removals under swimming pool conditions. The four levels of amount of precoat were separately added onto the filter through the skimmer.

The precoating of the DE was done in a closed loop with DE slurry. Water was pumped through the filter at rates of 182 L/min for the precoat filter. Studied HLRs for the precoat filter were 6 m/h, 5 m/h, and 3.6 m/h. DE was added via the skimmer to the precoat filter, corresponding to 0.5 kg·DE/m^2, 0.7 kg·DE /m^2 and 1.0 kg·DE /m^2.

Bumping was conducted by restarting the filter after a 5-minute, 15-minute, or 30-minute stop of the filter.

4.2.7.3 PolyDADMAC Measurement

PolyDADMAC was analyzed using a method based on that of Parazac et al (Parazak, et al., 1987). The method involves the formation of an insoluble complex between the cationic polymer and the anionic dye Ponceau S. The complex precipitates out of solution and is collected at the interface between the aqueous layer and a solvent. The aqueous layer is collected, and the concentration of dye remaining in solution is measured by a Varian Cary 100 BIO UV Spectrophotometer at 520 nm (Agilent Technologies, Santa Clara, California, USA). Ponceau S (200 mg/L) (Fisher BioReagents), 0.5 M sulfuric acid (Fisher BioReagents), and dichloromethane (Fisher BioReagents) were used. The detailed experimental description could be found in Analytical methods for polymers and their oxidative by-products (Fielding, 1998). The absorbance of the standards versus polyDADMAC concentration calibration plot is shown in Figure 4.5. Standards with known polyDADMAC concentrations were made of tap water and polyDADMAC polymer (coagulant A). Calibration plot was created and the regression is shown in Equation (4.5).

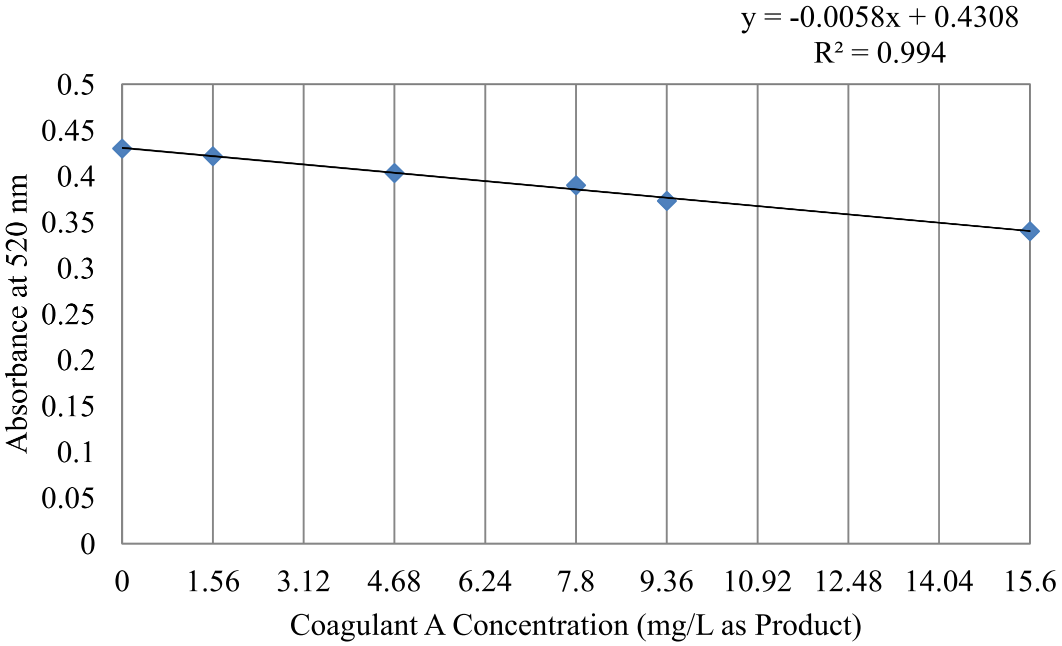


Figure 4.5 Absorbance versus coagulant A concentration calibration curve (10 mm cell)

$$y = -0.0058x + 0.4308 \qquad (4.5)$$

where y is absorbance at 520 nm for standard; x is coagulant A concentration of standard.

4.2.8 Data Analysis

A box plot was applied to evaluate the benchmarks for each coagulant.

In statistics, a box plot is a convenient way of graphically depicting groups of numerical data through their five-number summaries: the smallest observation (sample minimum), lower quartile (Q1), median (Q2), upper quartile (Q3), and largest observation (sample maximum). Removal of microspheres through the treatment process was expressed either as percent removal (i.e., 99%) or in terms of the logarithmic reductions (base 10). Log reductions are currently calculated as the difference between the $\log_{10}$ of the influent concentration and the $\log_{10}$ of the effluent concentrate. Log removals that incorporated non-detects (i.e., no particles detected in filtrate) are prefixed with the > symbol with one particle assumed in the effluent (Dugan, et al., 2001). (Pool water pH, free chlorine, oxidation reduction potential (ORP), conductivity, and temperature are shown in Appendix L. Raw data for microsphere removals from pilot-scale pool are shown in Appendix M.)

4.2.9 Quality Assurance and Quality Control

A control experiment was conducted without filter media to test if there are microsphere losses in the system. The average 1% removal (approximately zero) was obtained and demonstrated no significant system losses. A sand filter experiment without coagulation was conducted as another control experiment indicating 20% - 63% (0.1 - 0.4 log) *Cryptosporidium*-sized microsphere removals (as shown in Figure 4.6). Duplicate experiments were conducted. Triplicate samples were taken. The swimming pool was rinsed, filled, recirculated, and drained with tap water at least three times between experiments to limit the amount of cross-contamination between experiments. Fresh sand was used for each experiment. Sand filter was backwashed with simulated pool water for 5 minutes to ensure the sand was clean and sand grain restratified (fine grains on top and coarse grains on bottom).

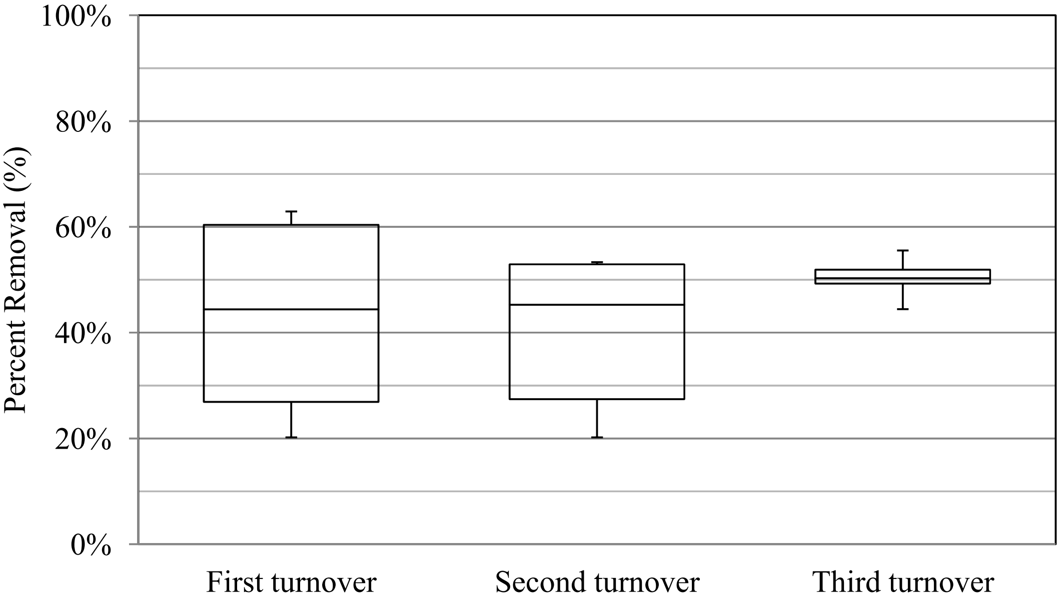
4.3 Results and Analysis

4.3.1 Sand Filtration Control

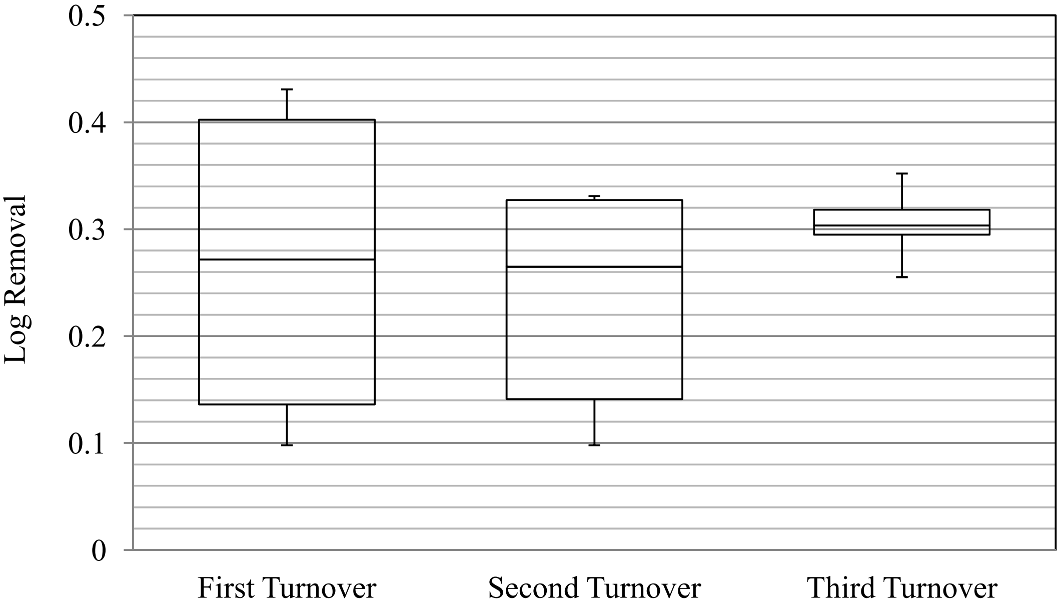
Figure 4.6 shows the removals of microspheres in control experiment without coagulation. Control experiments were conducted over 24 hrs and followed by a backwash. Microsphere removals were consistent during the 24 hrs and only between

20% - 63% (0.1 - 0.4 log). The pore size of the sand filter was larger than the 4.5 µm microspheres. The negatively charged *Cryptosporidium*-sized microspheres repel each other and cannot efficiently attach on the negatively charged sand media (Amburgey, 2002). Figure 4.7 shows UV_{254} data. Influent and effluent UV_{254} was very close. Figure 4.8 illustrates the turbidity and particle counts for influent. The swimming pool influent water turbidity average was 0.12 NTU. The upper-limit guideline for turbidity was 0.5 NTU for swimming pool (ISO, 1999). Peaks of turbidity and particle counters were associated with microspheres seeded into the system, especially in 3 µm - 6 µm particle counters as shown in Figure 4.8. Figure 4.9 illustrates along with increased turbidity, particle counter also increased. No pressure variation was observed during the 24 hr as shown in Figure 4.10.

Filter mass balance was conducted. Mass flow into the filter included total added microspheres. Mass flow out of the filter included microspheres in backwash water, in backwash remnant, and to the pool in the filter effluent. The accumulated microspheres in filter could then be calculated based on the mass balance as shown in Equation (4.3). The "percent of total added" averaged was 60% for the control as shown in Table 4.4.



a. Percent removal



b. Log removal

Figure 4.6 Microspheres Removal by Sand Filter during 24 hr *(1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)(number of experiments = 2, number of samples = 3)*

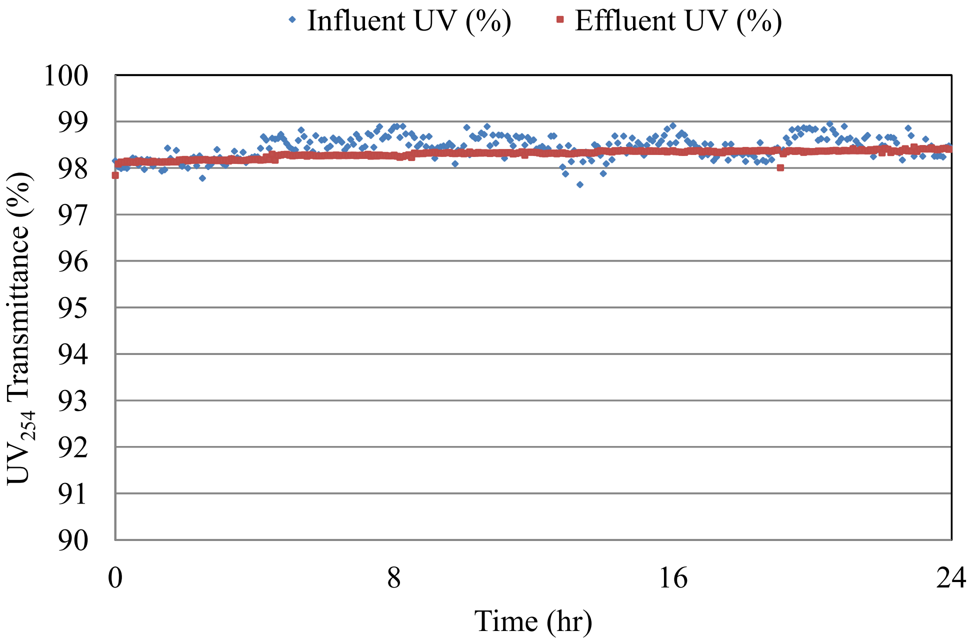


Figure 4.7 Filter Influent and Effluent UV Transmittance Variation *(1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

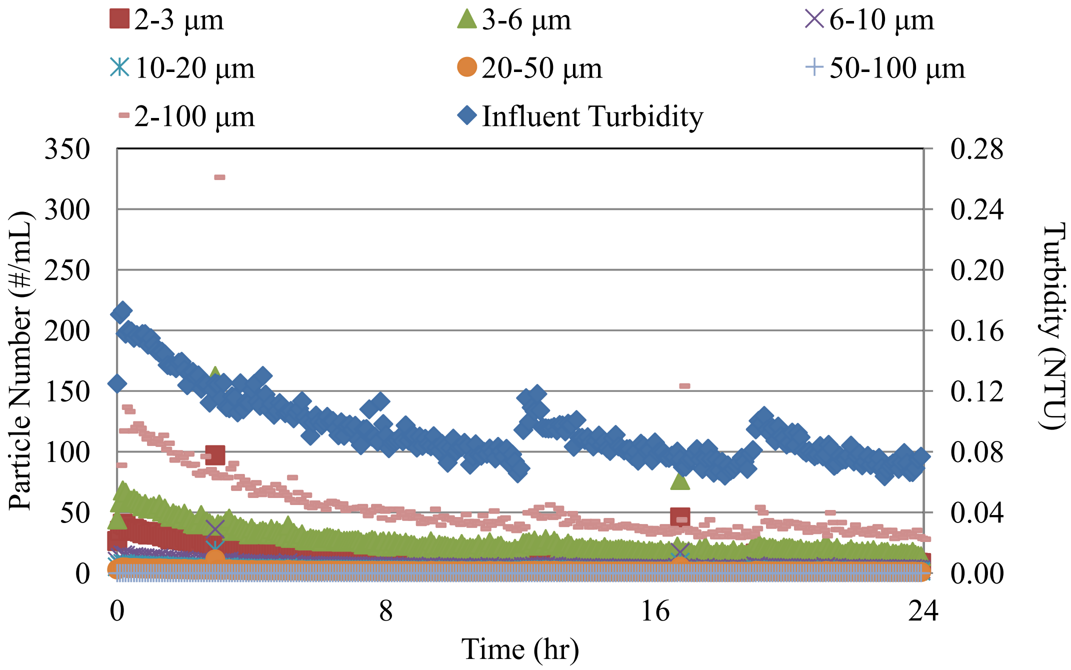


Figure 4.8 Influent Turbidity and Particle Counter Variation *(1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

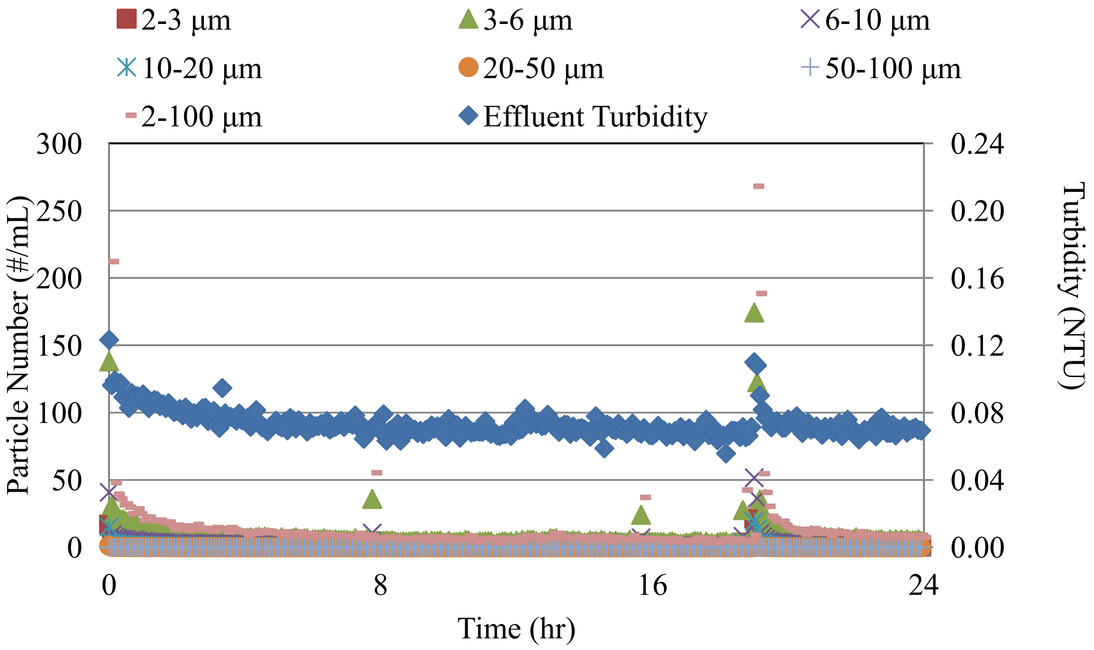


Figure 4.9 Effluent Turbidity and Particle Counter Variation *(1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

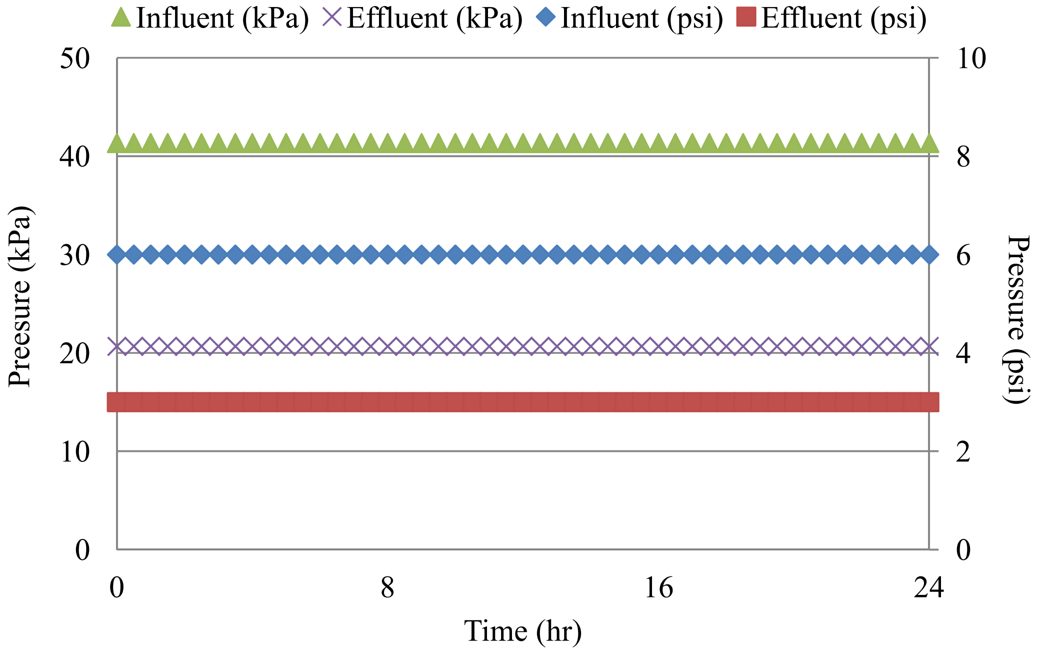


Figure 4.10 Filter Influent and Effluent Pressure *(1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

Table 4.4 Mass Balance and Overall Removal Rate for Coagulant A, B, C, D, and F

	Total Added		Backwash		Remnant in Filter		To the Pool		Percent of Total Added[i]	Removal From System[j]
	Conc. (#/mL)[a]	Vol. (L)[b]	Conc. (#/mL)[c]	Vol. (L)[d]	Conc. (#/mL)[e]	Vol. (L)[f]	Conc. (#/mL)[g]	Vol. (L)[h]		
Control 1	1.9	1402	10	57	2.4	34	0.200	5488	65.1%	23.7%
Control-2	2.1	1402	8	57	2.2	34	0.200	5488	54.7%	17.4%
Polymer A-1	1.9	2162	59	57	0.6	34	0.002	5488	84.3%	84.0%
Polymer A-2	2.0	1835	54	57	0.7	34	0.001	5488	84.3%	84.2%
Polymer B-1	1.8	1853	48	57	0.3	34	0.000	5488	82.6%	82.6%
Polymer B-2	1.7	1483	40	57	0.4	34	0.000	5488	87.3%	87.3%
Polymer C-1	1.8	3838	63	57	1.7	34	0.304	5488	77.5%	53.0%
Polymer C-2	1.8	3892	63	57	1.6	34	0.398	5488	83.0%	51.8%
Polymer D-1	2.0	2780	80	57	0.2	34	0.000	5488	81.8%	81.8%
Polymer D-2	1.9	9857	257	57	0.2	34	0.020	5488	78.4%	77.8%
Coagulant F	2.0	2100	61	57	0.7	34	0.001	5488	83.1%	83.0%

Percent of Total Added=(Backwash + Remnant in Filter + To the Pool) / (Total Added) = $(c \cdot d+e \cdot f+g \cdot h) / (a \cdot b) \cdot 100\%$

Removal From System=Backwash / Total Added = $(c \cdot d)/(a \cdot b) \cdot 100\%$

No backwash samples were colleced for coagulant E

4.3.2 High-Rate Sand Filtration

4.3.2.1 Particle Removals

(1) *Cryptosporidium*-Sized Microsphere Removals

Particle removals were evaluated by microsphere removals, filter influent and effluent particle counts, and turbidity. Coagulant A and B were polyDADMAC products, coagulant C was chitosan, coagulant D was an aluminum based coagulant, and coagulant E was polyaluminum chloride (BioGraud, 2001; Kemira, 2012; Robarb, 2000; SeaKlear, 2008; Vantage, 2009). Formulation of coagulant F is proprietary. Coagulants were continuously fed into the system at the rate of one recommended dose per turnover.

Table 4.4 illustrates the mass balance calculation for each coagulant except for coagulant E (no backwash samples were collected for coagulant E). Control experiments listed in Table 4.4 were sand filtration without a coagulant. No system loss was demonstrated as 1% removals (roughly zero removal) obtained in control experiment without filter media. The "percent of total added" for all of the experiments were between 55% and 87%. Some of microspheres could remain attached to the sand media that were not detected. The "percent removals from the system" by backwashing were from 83% to 87% for coagulant A and B, were average of 52% for coagulant C, were approximately 80% for coagulant D, and were 83% for coagulant F. While these numbers may contain some error, it appears that at least 13% of the microspheres could remain attached to the media following a water only backwash.

Box plots of *Cryptosporidium* oocyst-sized microsphere removals by high-rate sand filtration preceded by coagulation A at one recommended dosage per every 8 hrs (i.e., one turnover) are shown in Figures 4.11. Up to 99% (2 log) microsphere removals were obtained by filtration with coagulant A. Microsphere removals decreased with continuous feeding of coagulant A. Table 4.5 shows coagulant A concentration in each turnover. The concentration of coagulant A in the pool water after 24 hrs of feeding was approximately 3 times of recommended dose of 4.68 mg/L. Based on the data in Table 4.5, it appears that polyDADMAC rapidly accumulated in the bulk water, which appears to explain the rapid decline in removals over time as the effective coagulant dosage is exceeded. Figure 4.12 shows microsphere removals at each turnover for coagulant B. Coagulant B performed similar to coagulant A, because they both contained polyDADMAC polymers. Microspheres removals by coagulant C were always less than 80% as shown in Figure 4.13. Figure 4.14 shows microsphere removals in each turnover by coagulant D. Up to 99% removals were achieved by coagulant D in the first 56 hrs by continuously feeding coagulant D. Microsphere removals were in the range of 35% to 70% with coagulant E at 37 m/h as shown in Figure 4.15. The same results were found previously (Goodman, 2011). Figure 4.16 shows the microsphere removals with filtration rate of 30 m/h by coagulant E (0.1 mg/L as Al). Experiments were conducted 3 days, and backwashes were conducted after that. The microsphere removals were increased to as high as 99% by reducing the filtration rate to 30 m/h by coagulant E. Above 90% of microspheres were removed at the second and third day by coagulant E. Figure 4.17 shows microsphere removals by coagulant F. Coagulant F performed similar to coagulant A and B, with up to 99% removals achieved. The removals decreased over time since coagulants continuously feeding led to the overdose of coagulants A, B, and F (as shown in Figures 4.11, 4.12, and 4.16). Removals decreased for coagulant D and E were caused by filter pressure build-up/filter pore clogging (as will be discussed subsequently). The removal data could be interpreted based on the zeta titration data, which indicated coagulants A, B, D, E, and F achieved -10 mV at recommended dosage while coagulant C did not.

The highest 99% (2 log) removals obtained from experiments was higher than predicted single filtration removal efficiency (approximate 50%) for 5 μm microspheres according to single collector efficiency as shown in Figure 4.2. The potential reasons included (1) the single collector efficiency model was theoretically based on clean bed media; (2) single collector efficiency model assumed the spherical media, which was different from the shape of the sand used in this study; (3) suspended media grain that did not touch were also assumed in the model, while the sand media grain contacted each other; and (4) 5 μm microspheres might collide and attach each other to form larger microsphere aggregates in coagulation process (Tufenkji and Elimelech, 2004). The removal for larger microsphere aggregates is predicted in Figure 4.3, which illustrated >95% removal was predicted for 15 μm microsphere aggregates.

Table 4.5 Measured and Estimated Coagulant A Concentration in Each Turnover

Time (hr)	Influent Concentration (mg/L)[a]	Effluent Concentration (mg/L)[b]	Average of 'a' and 'b' (mg/L)[c]	Estimated Concentration (mg/L)[d]	Differences between 'c' and 'd'
8	1.40	1.38	1.39	1.56	12%
16	2.76	3.03	2.90	3.12	7%
24	4.36	4.41	4.39	4.68	6%
32	5.86	6.07	5.97	6.24	4%
40	7.36	7.72	7.54	7.8	3%
48	9.16	9.09	9.12	9.36	3%

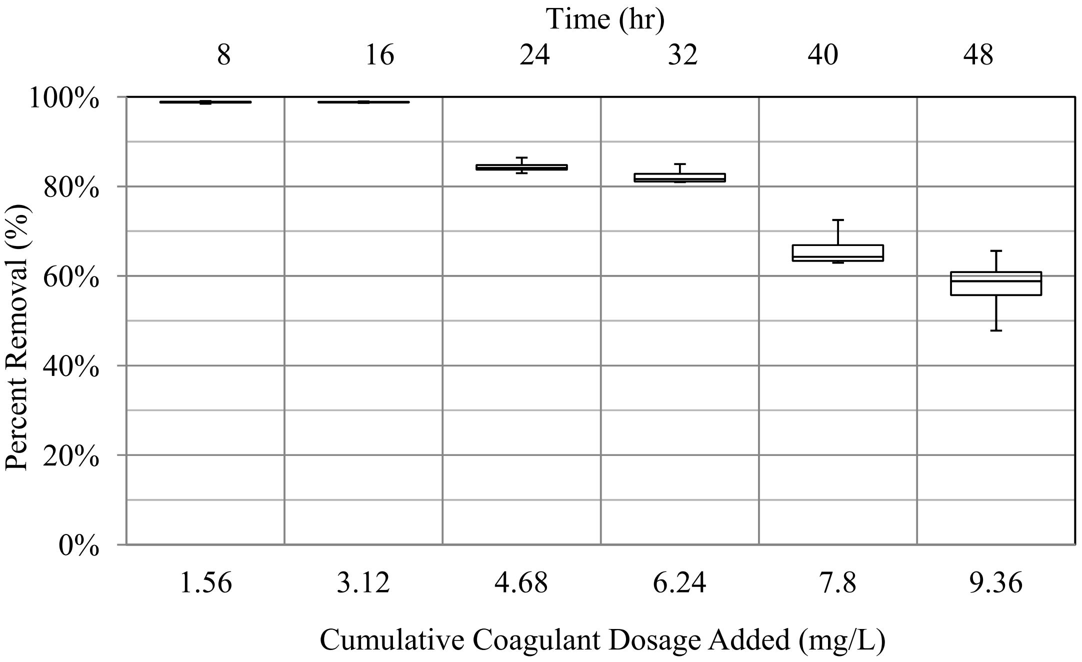


Figure 4.11 *Cryptosporidium*-sized Microsphere Removals through Filtration *(1.56 mg/L Coagulant A, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate) (number of experiments = 2, number of samples = 3)*

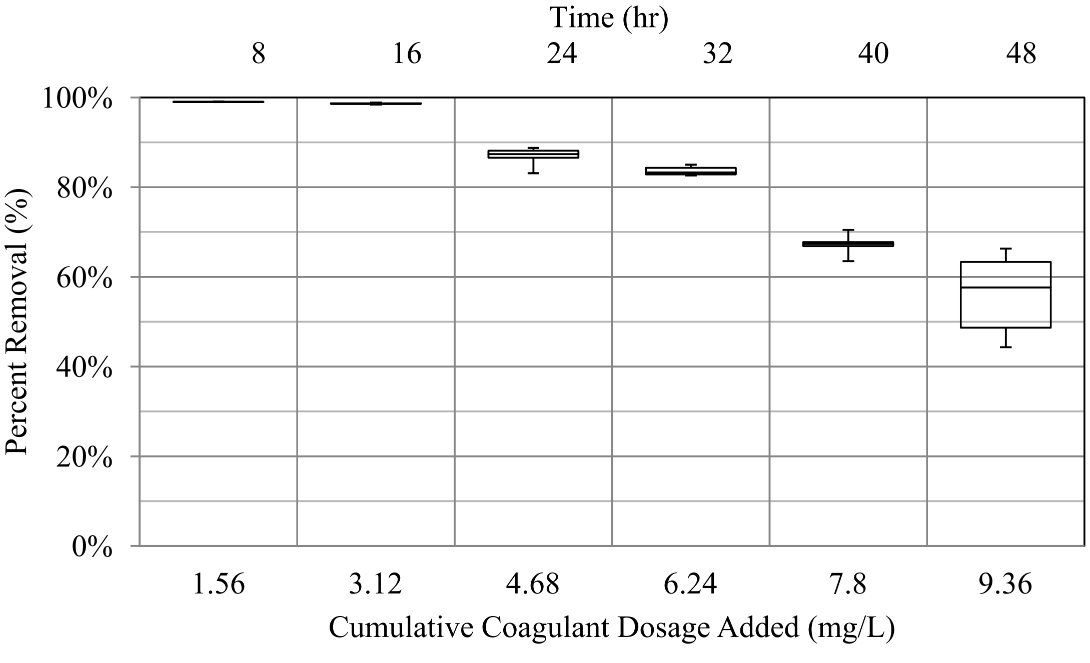


Figure 4.12 *Cryptosporidium*-sized Microsphere Removals through Filtration *(1.56 mg/L Coagulant B, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate) (number of experiments = 2, number of samples = 3)*

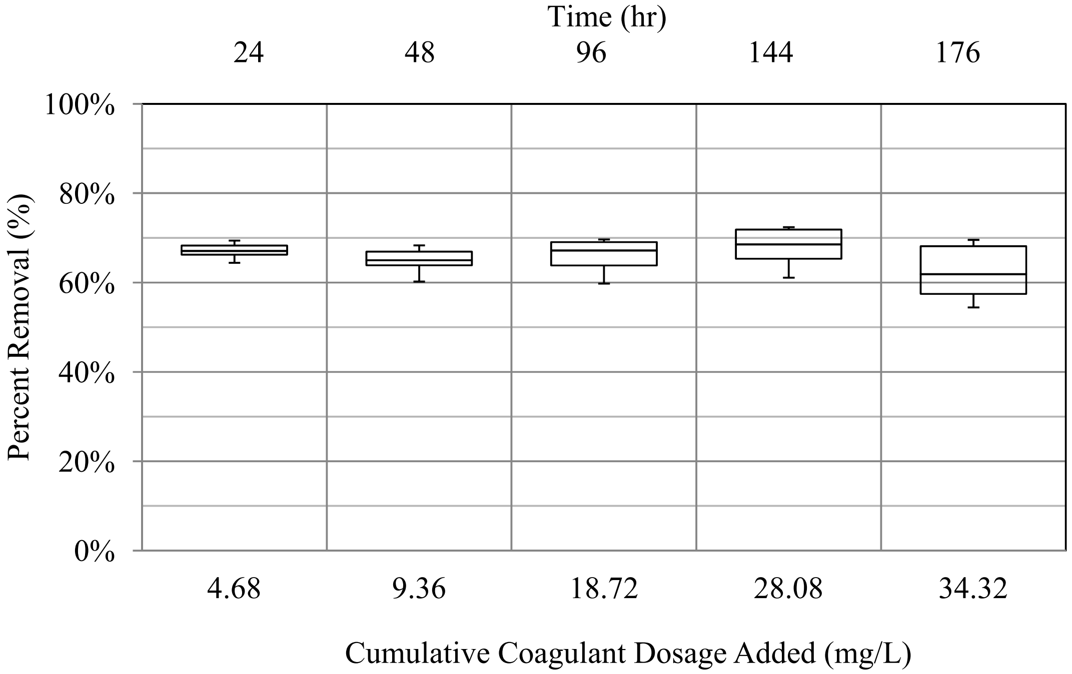


Figure 4.13 *Cryptosporidium*-sized Microsphere Removals through Filtration *(1.56 mg/L Coagulant C, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate) (number of experiments = 2, number of samples = 3)*

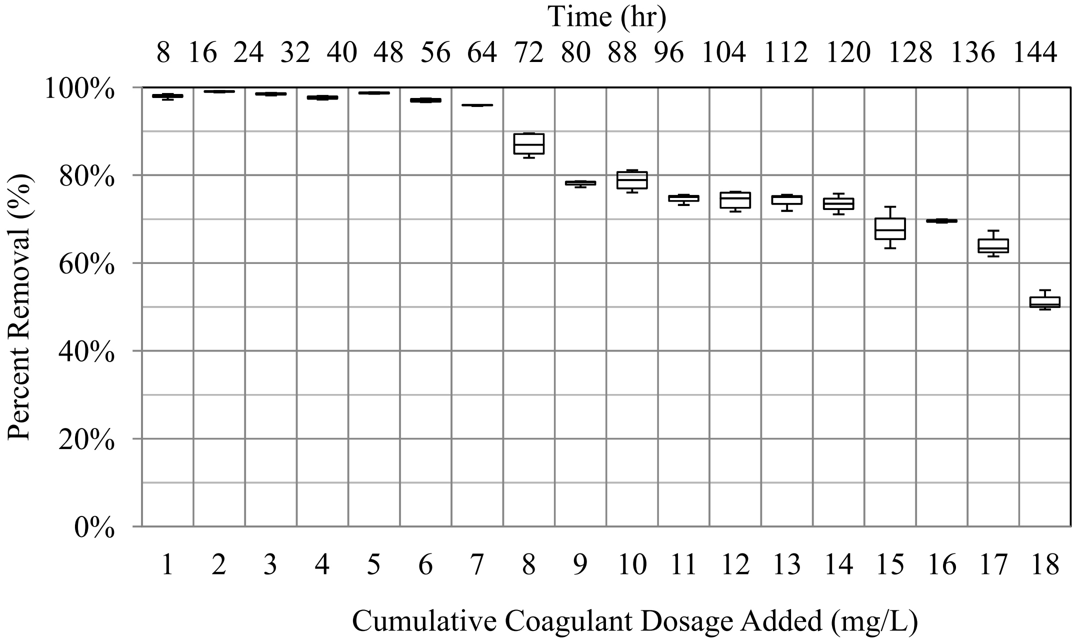


Figure 4.14 *Cryptosporidium*-sized Microsphere Removals through Filtration *(305 g/m^2 Coagulant D, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate) (number of experiments = 2, number of samples = 3)*

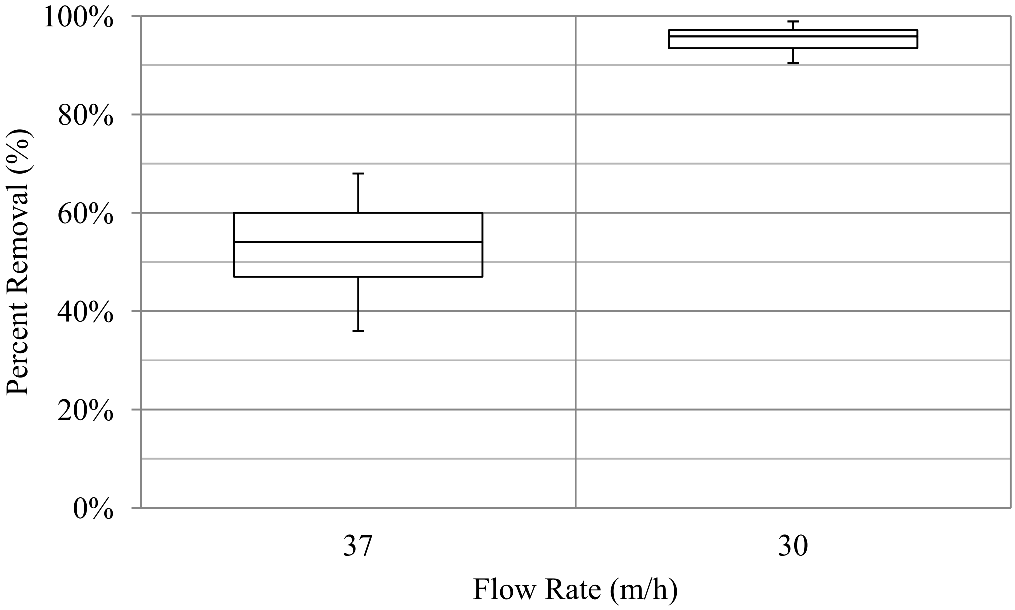


Figure 4.15 *Cryptosporidium*-sized Microsphere Removals through Filtration *(0.1 mg·Al/L Coagulant E, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate) (number of experiments = 2, number of samples = 3)*

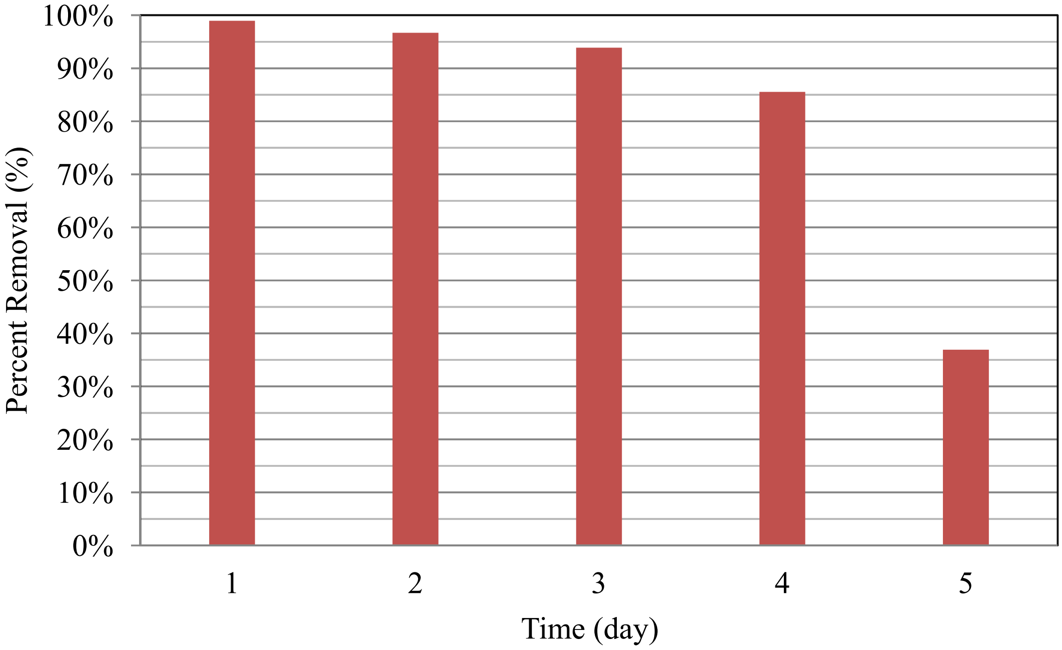


Figure 4.16 *Cryptosporidium*-sized Microsphere Removals through Filtration, *(0.1 mg·Al/L Coagulant E, 1.8 #/mL Microsphere, 30 cm Sand, 30 m/h Filtration Rate) (number of experiments = 2, number of samples = 3)*

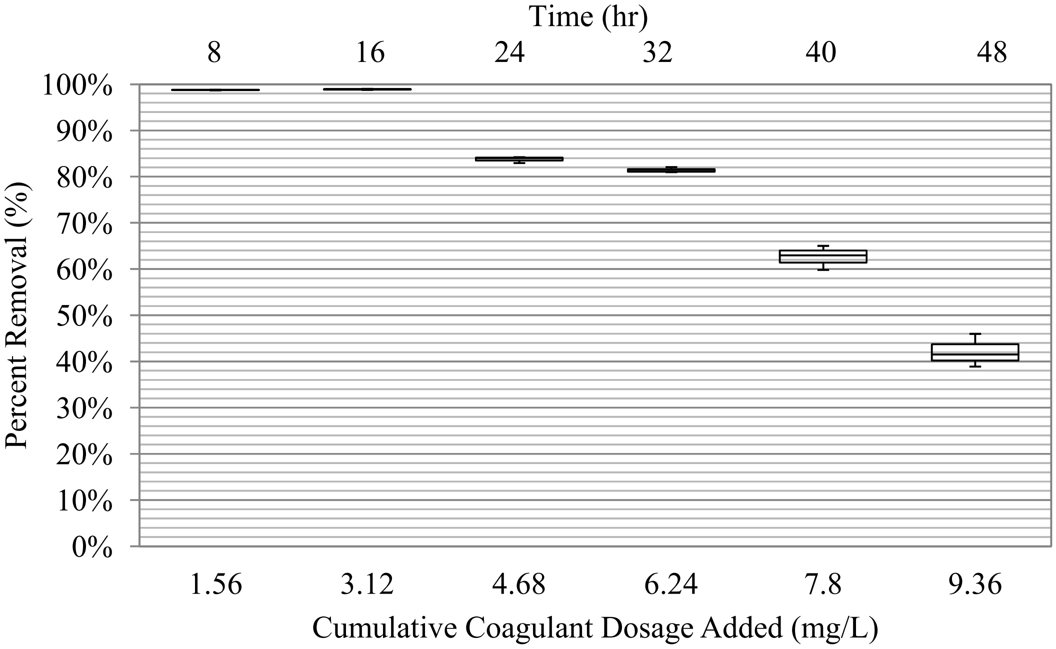


Figure 4.17 *Cryptosporidium*-sized Microsphere Removals through Filtration *(1.56 mg/L Coagulant F, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate) (number of experiments = 2, number of samples = 3)*

(2) Particle Counts

Filter influent particle count for coagulant A is shown in Figure 4.18. The particle counters were sensitive to changes in water quality. Total particle counts from 2-100 µm were shown as the light blue line at the top, among which, particles in the 3-6 µm range dominated, followed by 2-3 µm, 6-10 µm and 10-20 µm. Few of particles between 20-100 µm were detected. Intermittent peaks in influent particle counts were caused by seeding events of 4.5 µm microspheres. No backwash was conducted until the end of experiment. Influent particle counts for coagulant B is shown in Figure 4.20. The similar trend was obtained by coagulant B compared with coagulant A. Influent particle counts for coagulant C is shown in Figure 4.22. Influent particle counts for coagulant C were different from coagulant A and B without significant decreasing. Influent particle counts for coagulant D is shown in Figure 4.24, for coagulant E is shown in Figure 4.26, and for coagulant F is shown in Figure 4.28. Different influent particle counter trends for coagulant D and E compared with other coagulants (i.e., coagulant A, B, C, and F) was caused by the precipitate in coagulant D and E solution increased particle count numbers (Figure 4.24 and 4.26). Coagulant D and coagulant E precipitated because they were Al based. Lots of small insoluble grains were observed in coagulant D solution during experiments.

Effluent particle counts for coagulant A, B, C, D, E, and F are shown in Figure 4.19, 4.21, 4.23, 4.25, 4.27, and 4.29, respectively. Similar trends of effluent particle counters were observed for coagulants A, B, D, and F, which showed that particles decreased over time in each microsphere seeding trial (as shown in Figures 4.19, 4.21, 4.25, and 4.29). The 3-6 μm particles in effluent decreased compared with influent particles for coagulants A, B, D, E, and F. It demonstrated that excellent filter effluents were achieved during experiments with coagulants A, B, D, and F. Effluent particle counts for coagulant C increased over time (as shown in Figure 4.21), which could be interpreted by the poor microsphere removals obtained by coagulant C in Figure 4.21. Results illustrated that particle count was a good tool for monitoring filter performance, which agreed with the previous research (Edzwald, et al., 2000; Gregory, 1994; Hunt, 1995; Lewis, et al., 1992). Figure 4.30 displays the influent particle counts in 2-100 μm for all the six coagulants. Figure 4.31 displays the effluent particle counts in 2-100 μm for all the six coagulants. Total particle counts between 2 μm and 100 μm were higher for coagulants D and E relative to coagulants A, B, C, and F. It appears the Al-based coagulants tend to have more small particles entering and leaving the filter even through microsphere removals were generally very high as shown in Figures 4.24, 4.25, 4.26, and 4.27.

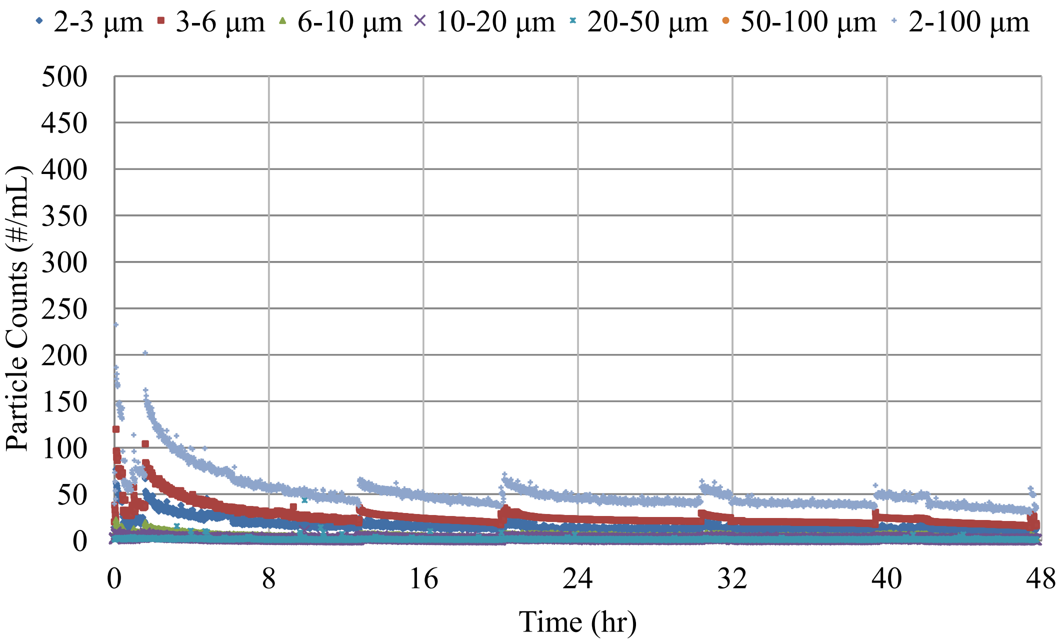


Figure 4.18 Influent Particle Counts Variation over Treatment Time *(1.56 mg/L Coagulant A, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

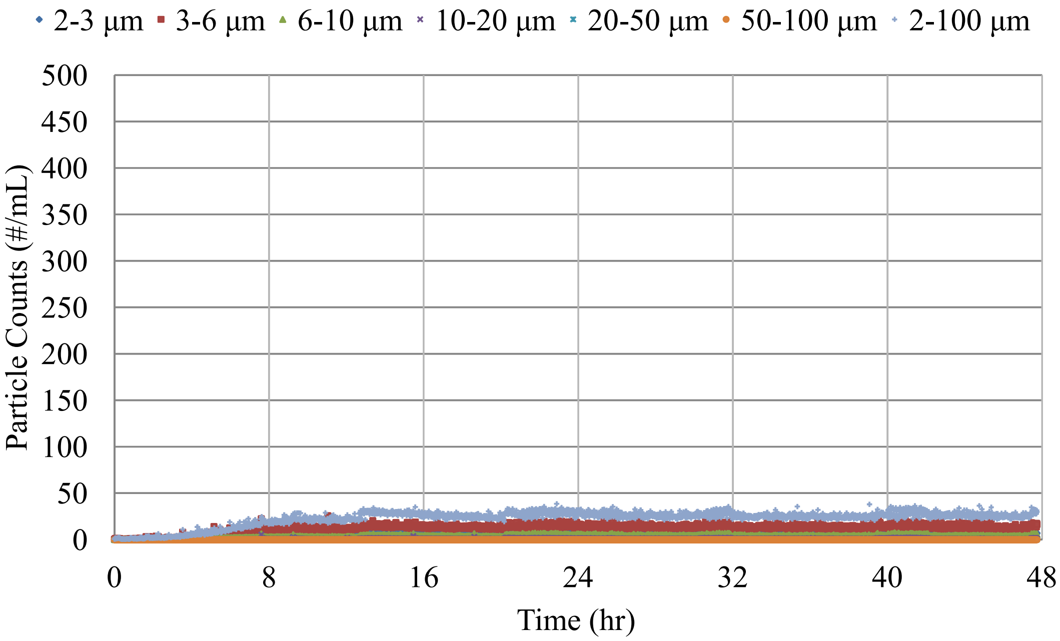


Figure 4.19 Effluent Particle Counts Variation over Treatment Time *(1.56 mg/L Coagulant A, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

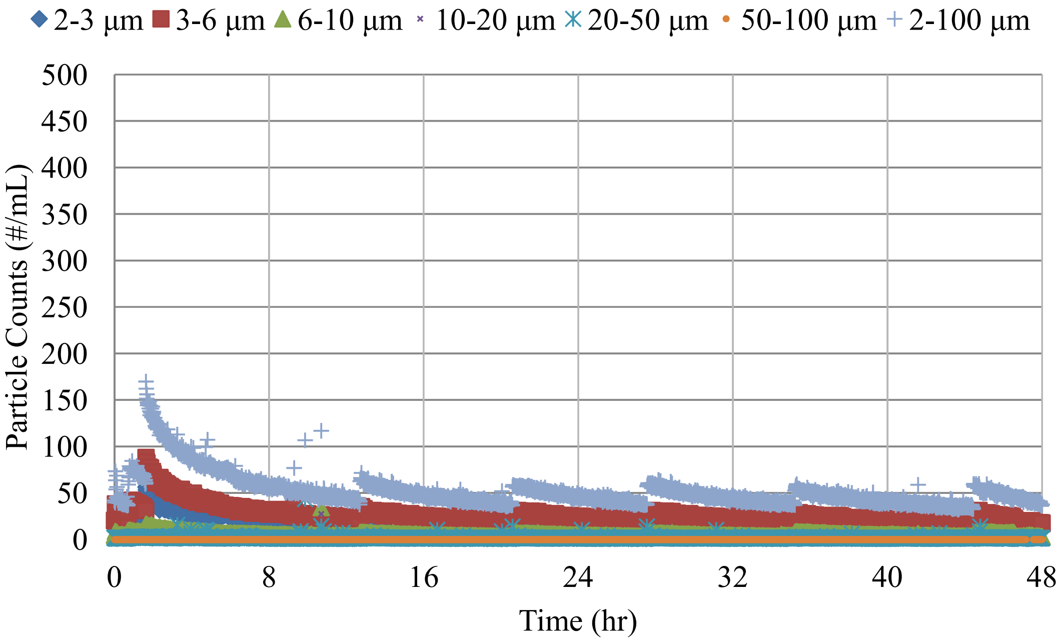


Figure 4.20 Influent Particle Counts Variation over Treatment Time *(1.56 mg/L Coagulant B, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

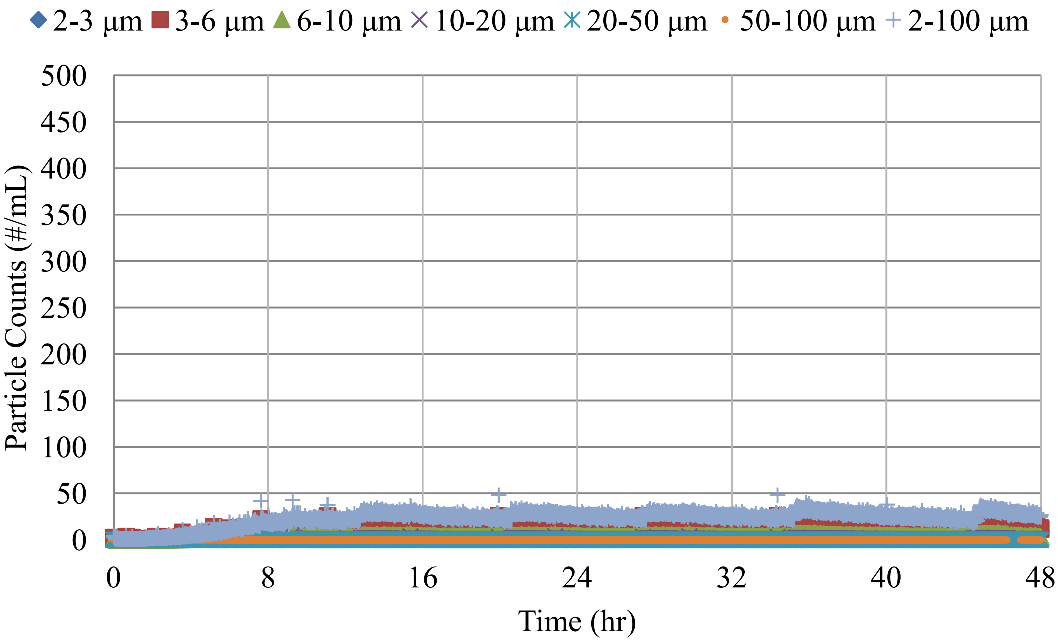


Figure 4.21 Effluent Particle Counts Variation over Treatment Time *(1.56 mg/L Coagulant B, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

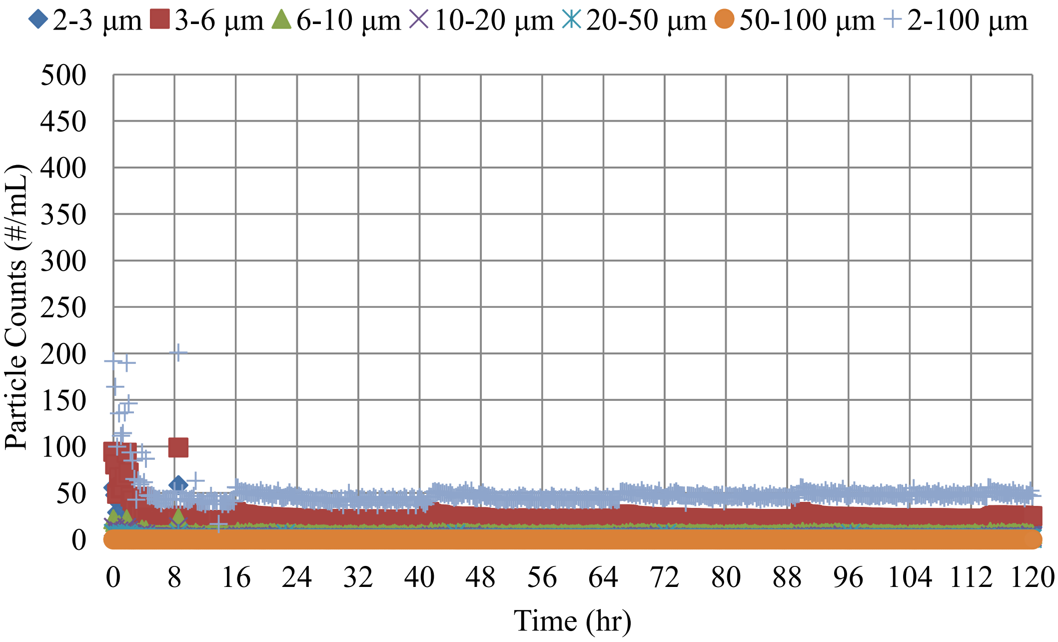


Figure 4.22 Influent Particle Counts Variation over Treatment Time *(1.56 mg/L Coagulant C, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

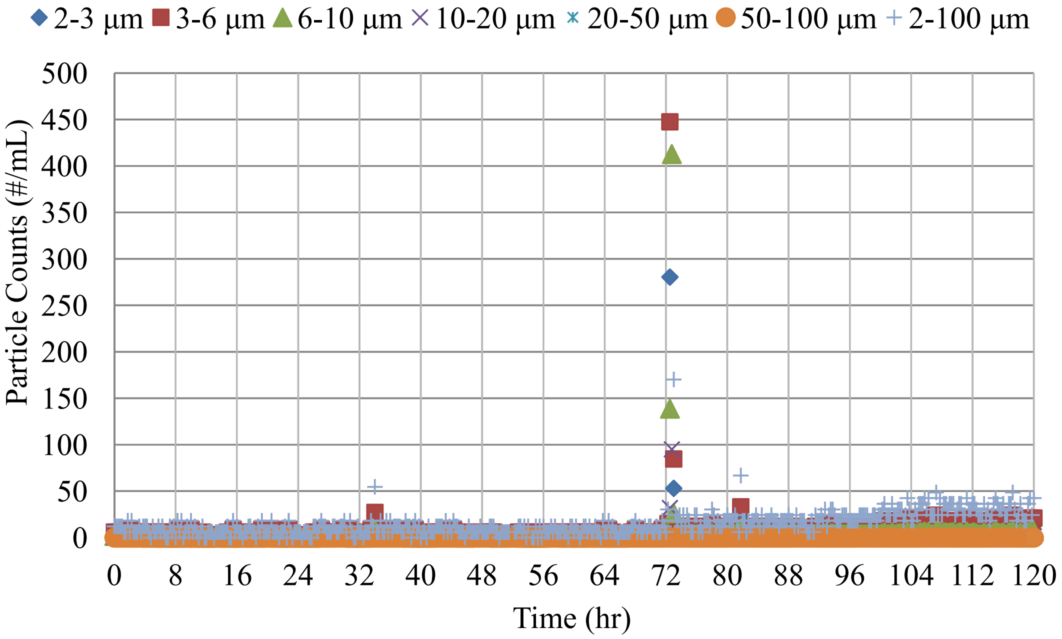


Figure 4.23 Effluent Particle Counts Variation over Treatment Time *(1.56 mg/L Coagulant C, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

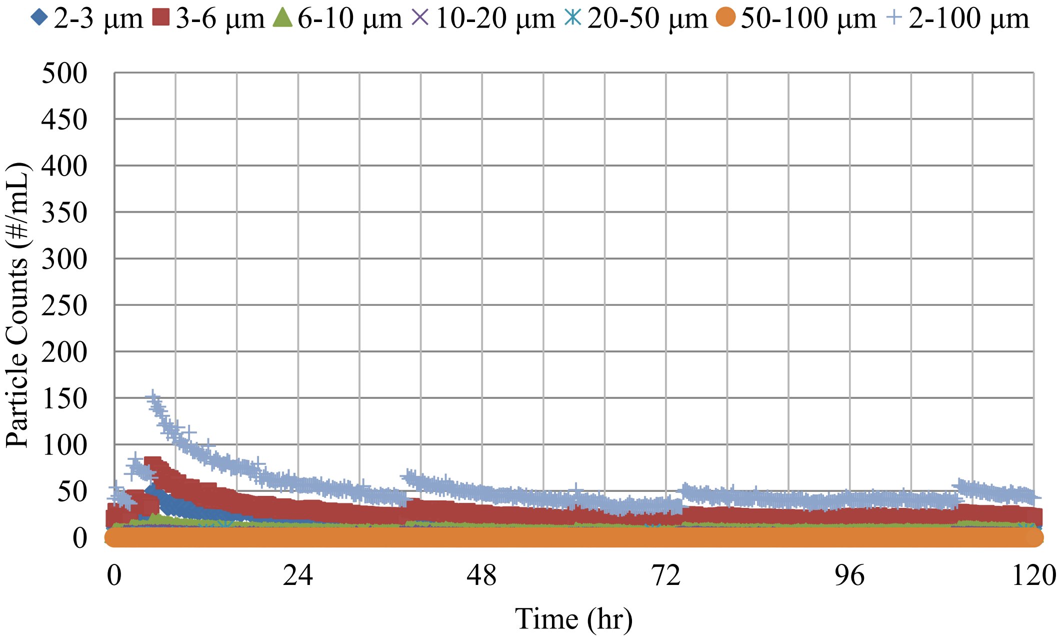


Figure 4.24 Influent Particle Counts Variation over Treatment Time *(305 g/m^2 Coagulant D, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

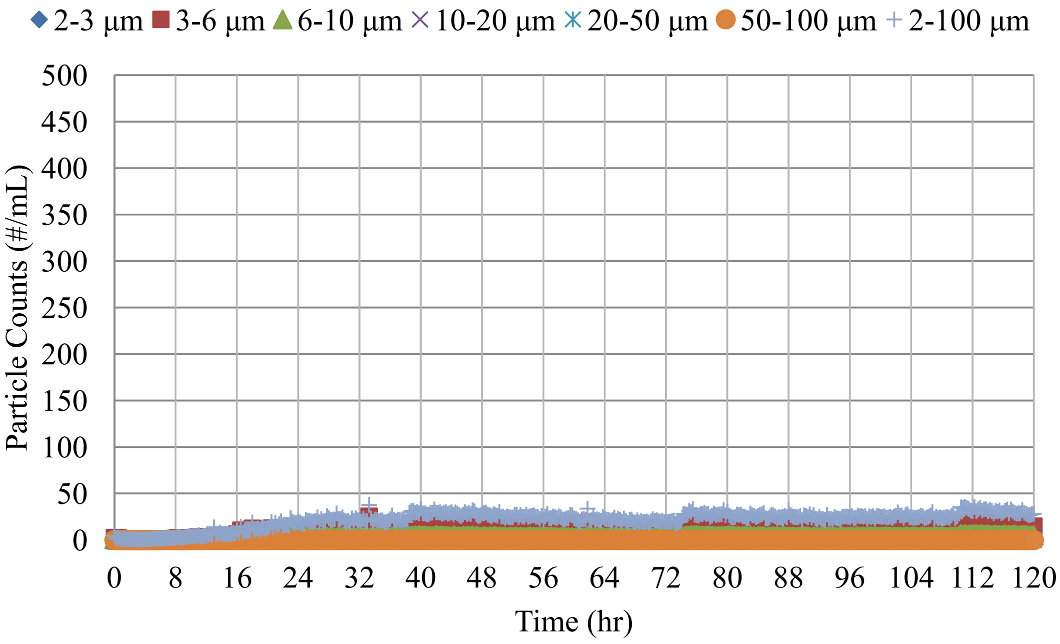


Figure 4.25 Effluent Particle Counts Variation over Treatment Time *(305 g/m^2 Coagulant D, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

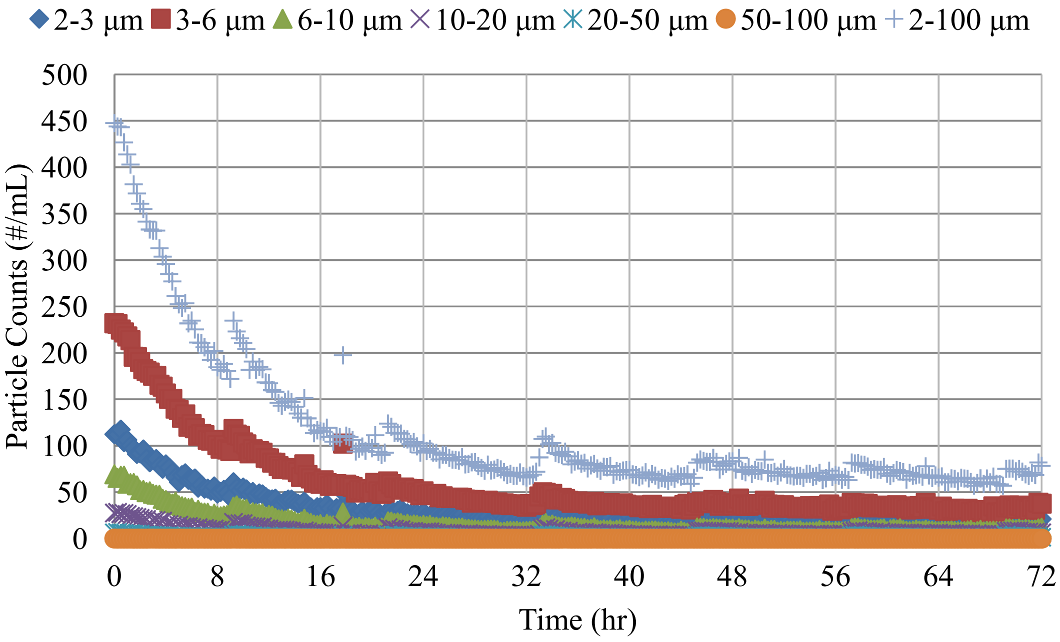


Figure 4.26 Influent Particle Counts Variation in One Filter Run Time *(0.1 mg·Al/L Coagulant E, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

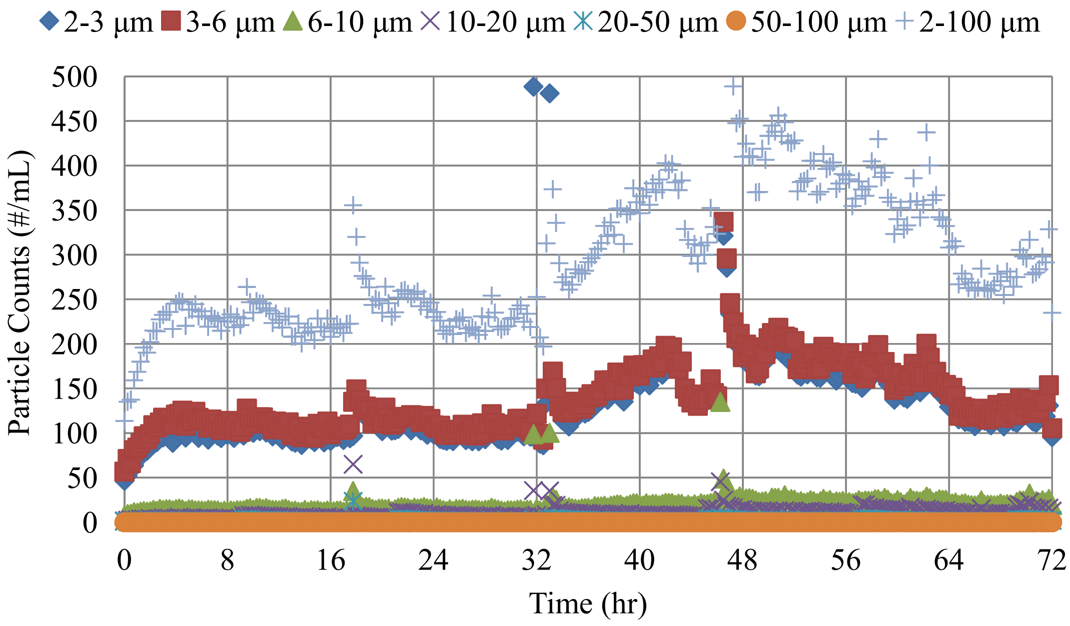


Figure 4.27 Effluent Particle Counts Variation in One Filter Run Time *(0.1 mg·Al/L Coagulant E, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

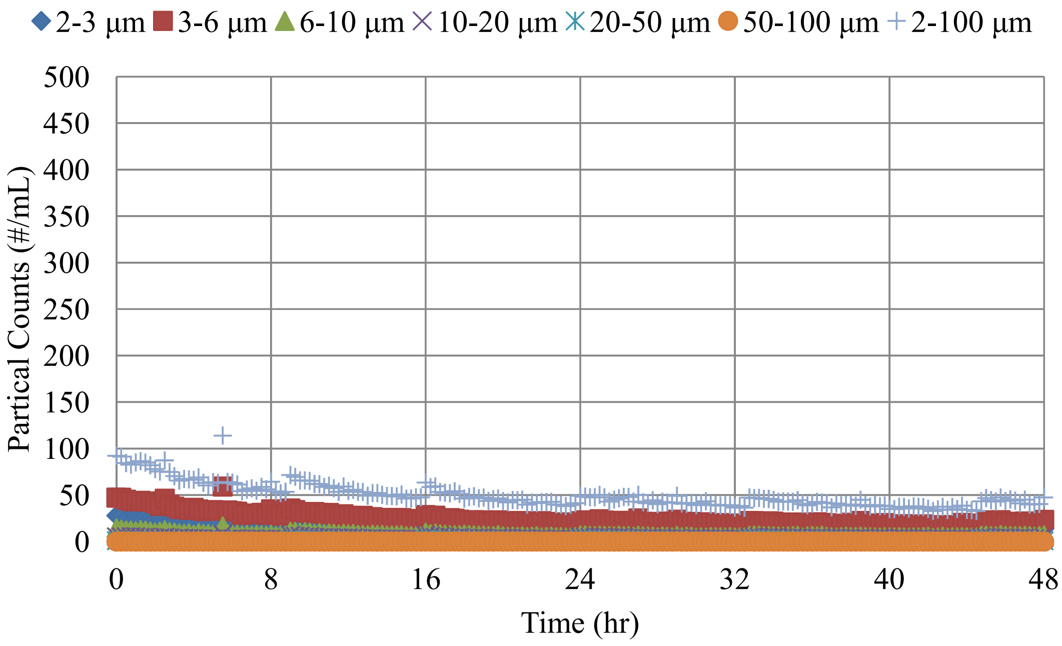


Figure 4.28 Influent Particle Counts Variation over Treatment Time *(1.56 mg/L Coagulant F, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

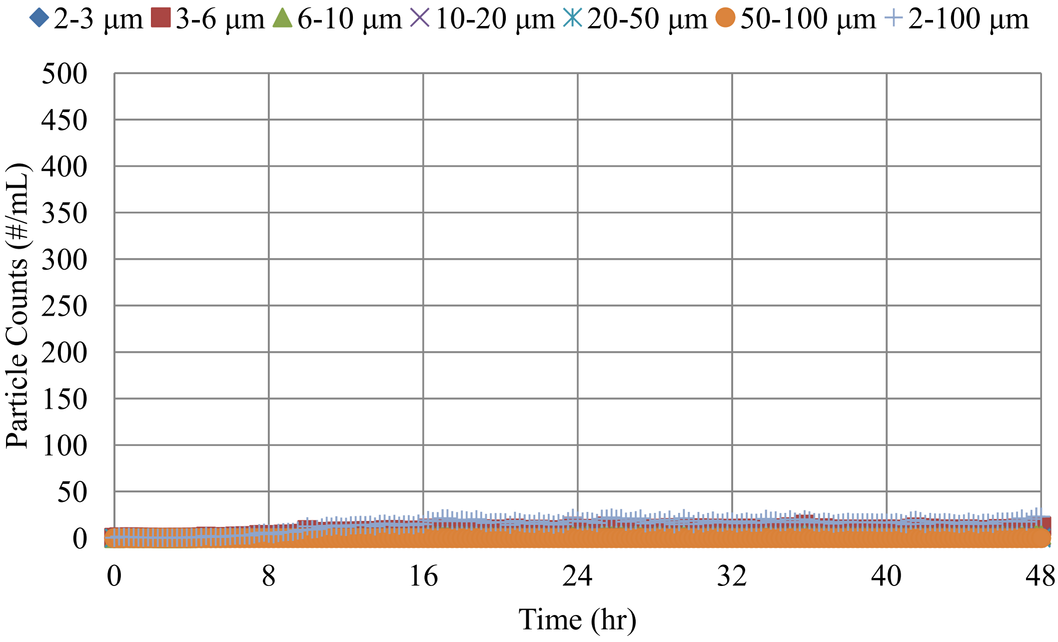


Figure 4.29 Effluent Particle Counts Variation over Treatment Time *(1.56 mg/L Coagulant F, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

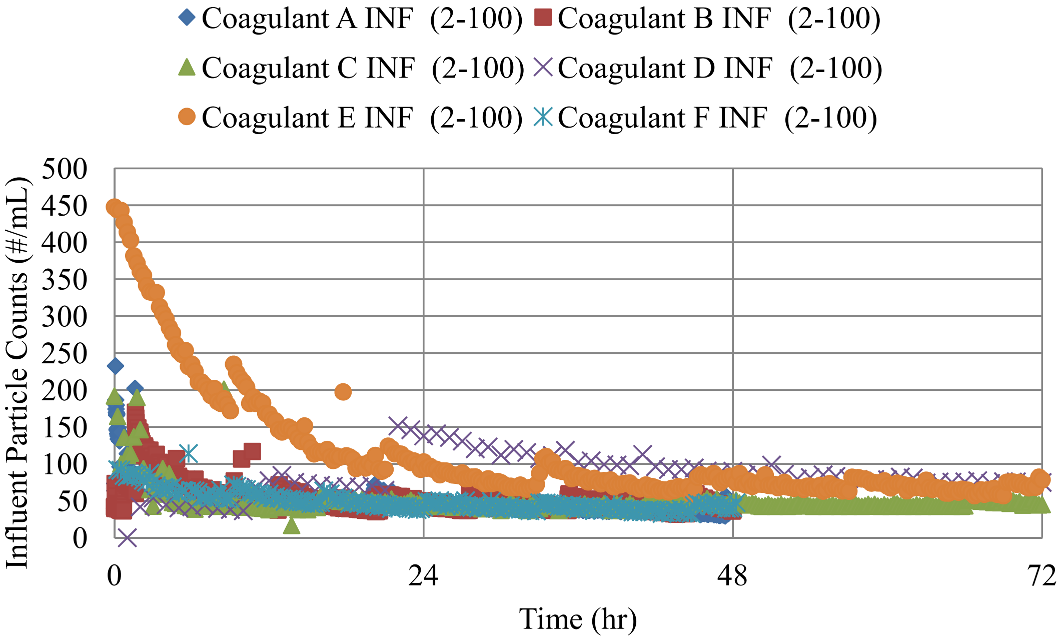


Figure 4.30 Influent Particle Counts Variation over Treatment Time for Six Coagulants

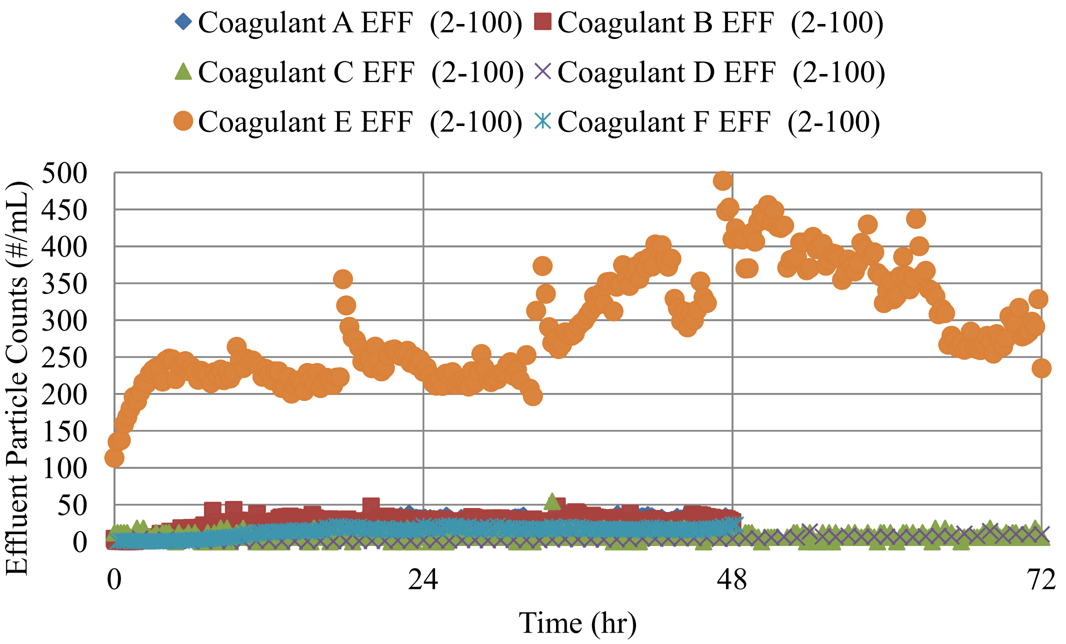


Figure 4.31 Effluent Particle Counts Variation over Treatment Time for Six Coagulants

(3) Turbidity

Turbidity was another parameter to evaluate the particle removal in this system. The reading of the turbidimeter was mostly influenced by the number of submicron particles (<1 µm) present in the sample (Gregory, 1994; Hunt, 1993). Turbidity variation for coagulant A is illustrated in Figure 4.32. Initial simulated pool water turbidity was approximately 0.2 NTU. Effluent turbidity for coagulant A was less than guideline, 0.5 NTU. Figure 4.33 shows turbidity for coagulant B. The similar turbidity variation for coagulant B was obtained compared with coagulant A. Figure 4.34 shows influent and effluent turbidity for coagulant C. The influent turbidity decreased and ultimately approached the effluent turbidity over time for coagulant C. Effluent turbidity for coagulant C was also less than guideline, 0.5 NTU. Figure 4.35 shows elevated turbidity near end for coagulant D, which indicates a backwash might have been necessary, also the poor microsphere removals were obtained near end. Influent turbidity for coagulant D was higher compared with coagulant A, B, and C, because of the aluminum precipitate in these coagulants increased the turbidity measurements. Figure 4.36 shows influent and effluent turbidity for coagulant E. Peaks in influent turbidity variations for E corresponded with microsphere seeding. Effluent turbidity for coagulant E was also less than 0.5 NTU. The reading of a turbidimeter is more strongly influenced by number of submicro particles (< 1 µm) present in the sample (Gregory, 1994; Hunt, 1993), which is a plausible size for Al precipitate. Influent and effluent turbidity variation for coagulant F is shown in Figure 4.37. Influent turbidity for coagulant F was different from other coagulants, and there was not a plausible explanation about this. Effluent turbidity for coagulant F was less than guideline, 0.5 NTU.

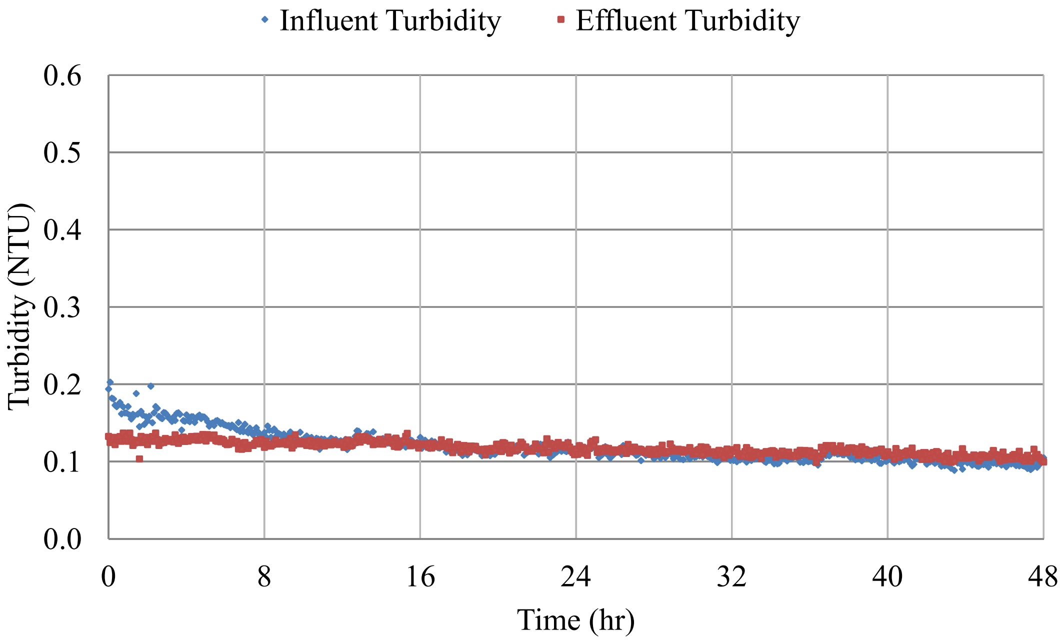


Figure 4.32 Turbidity of Influent and Effluent over Time *(1.56 mg/L Coagulant A, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

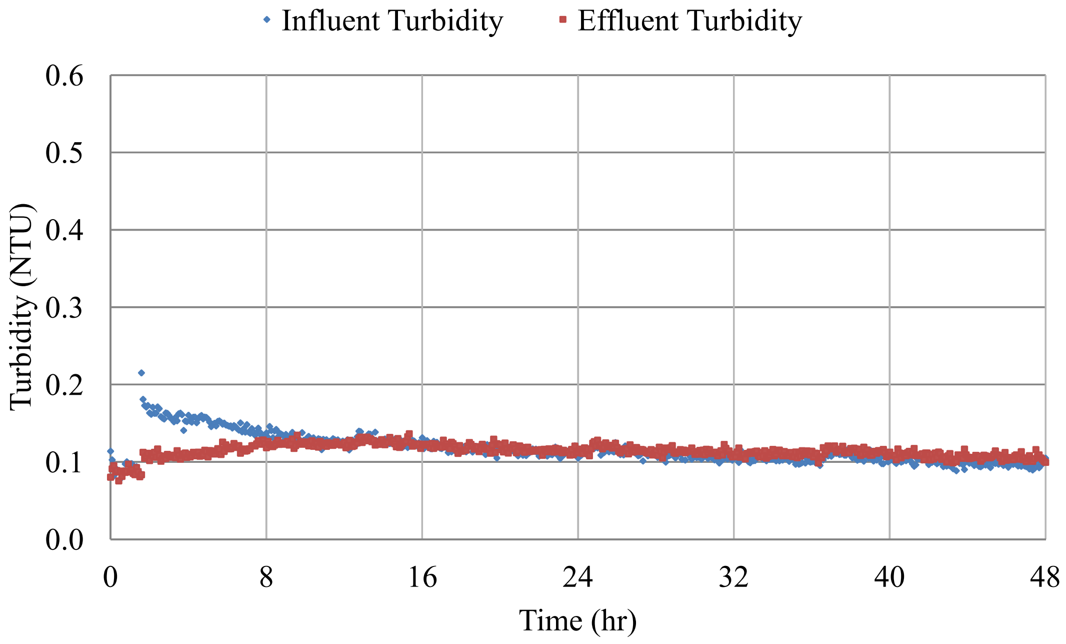


Figure 4.33 Turbidity of Influent and Effluent over Time *(1.56 mg/L Coagulant B, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

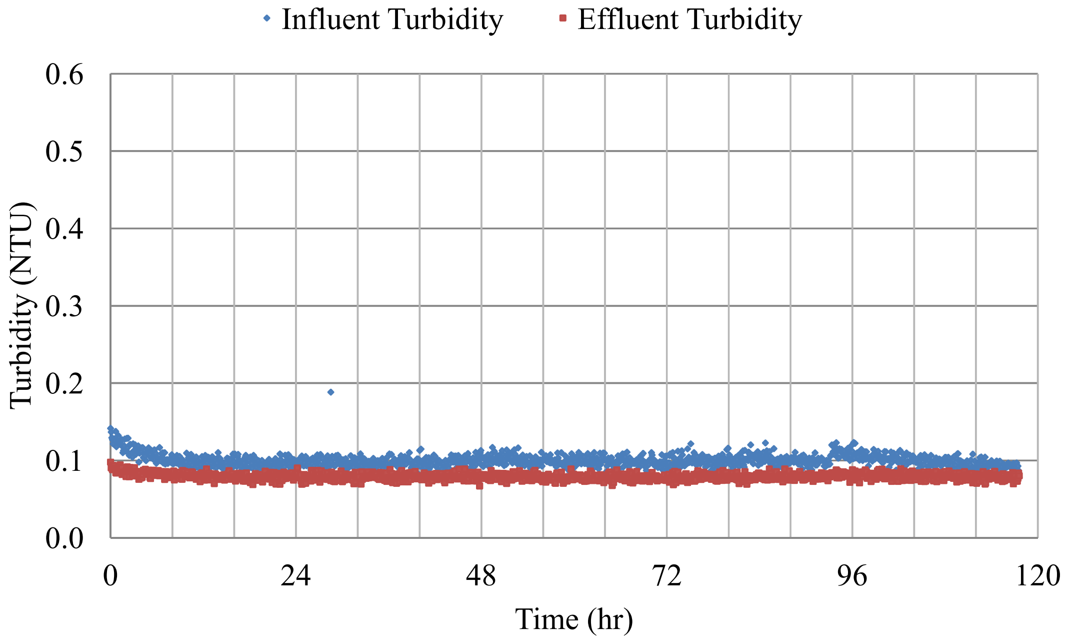


Figure 4.34 Turbidity of Influent and Effluent over Time *(1.56 mg/L Coagulant C, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

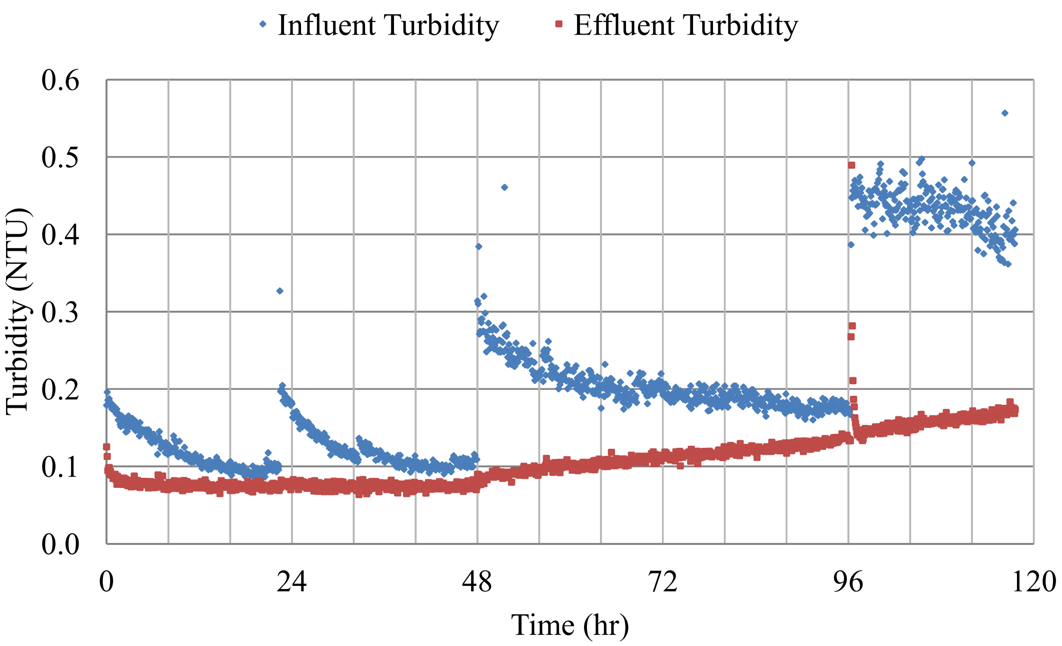


Figure 4.35 Turbidity of Influent and Effluent over Time *(305 g/m^2 Coagulant D, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

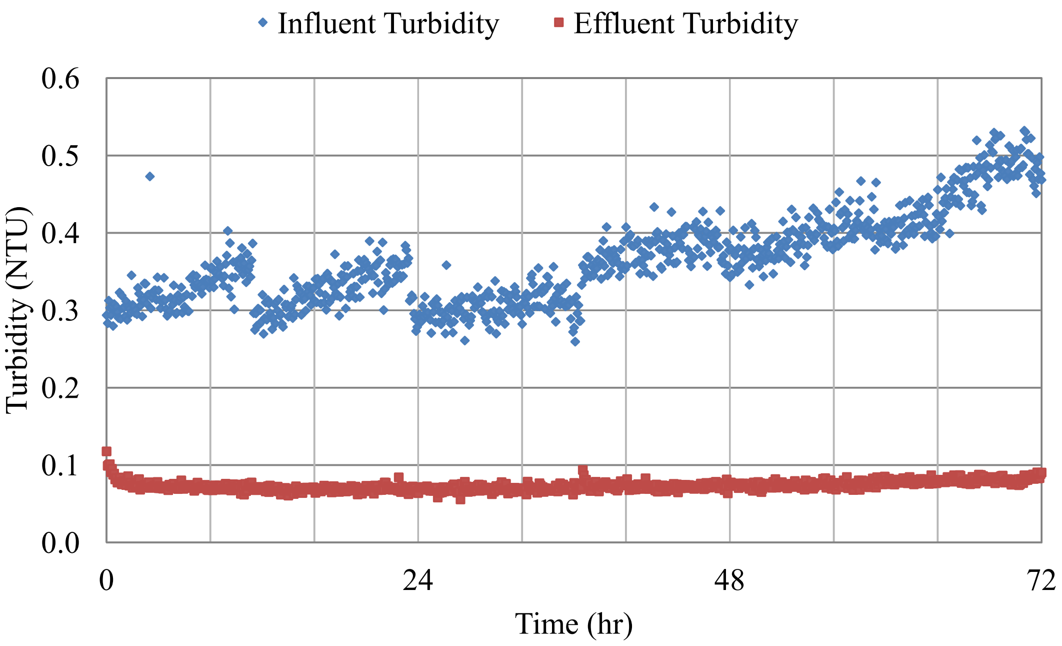


Figure 4.36 Turbidity of Influent and Effluent over Time *(0.1 mg·Al/L Coagulant E, 1.8 #/mL Microspheres, 30 cm Sand, 30 m/h Filtration Rate)*

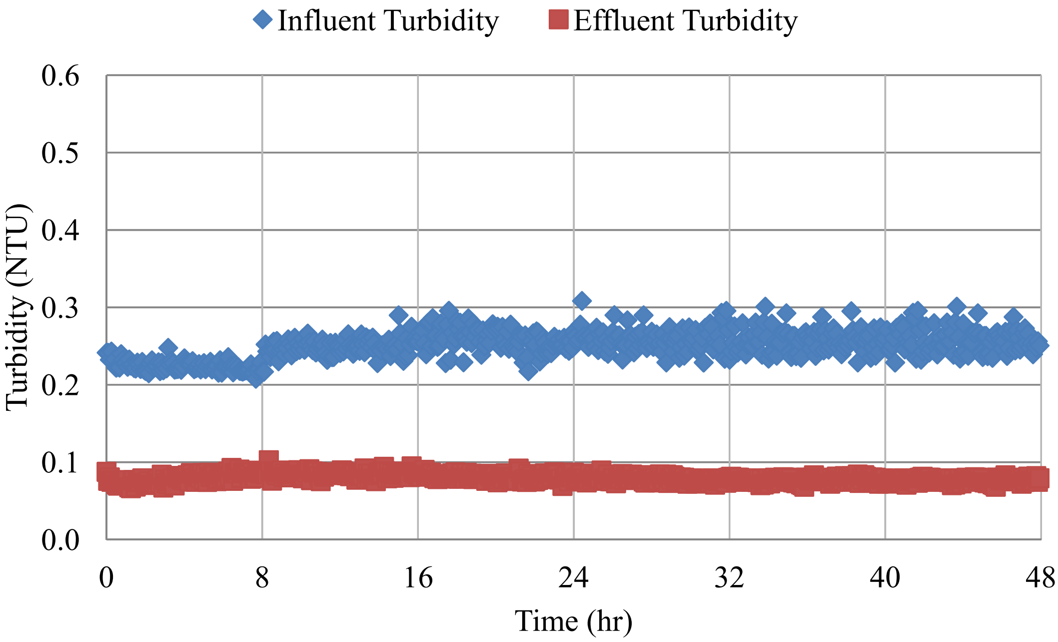


Figure 4.37 Turbidity of Influent and Effluent over Time *(1.56 mg/L Coagulant F, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

4.3.2.2 UV_{254} Transmittance Monitoring

The approximate removal of organic matter was monitored by continuously measuring the UV transmittance at 254 nm. The filter influent water UV_{254} transmittance was in the range of 96% to 97%. Influent and effluent UV_{254} transmittance for each coagulant are shown in Figures 4.38 (coagulant A), Figure 4.39 (coagulant B), Figure 4.40 (coagulant C), Figure 4.41 (coagulant D), Figure 4.42 (coagulant E), and Figure 4.43 (coagulant F). Influent UV_{254} was very close to effluent UV_{254} for all the six coagulants. There was no significant removal of UV_{254} in the filter system for coagulants A, B, C, D, and F. Coagulant A, B, C, D, and F were polymeric coagulants. Polymeric coagulants were not as effective in reducing UV_{254} absorption were reported by others

(Freese, et al., 2001). UV_{254} variations for coagulant E were different. Particles observed in turbidity readings were likely interfering with UV_{254} measurements for coagulant E.

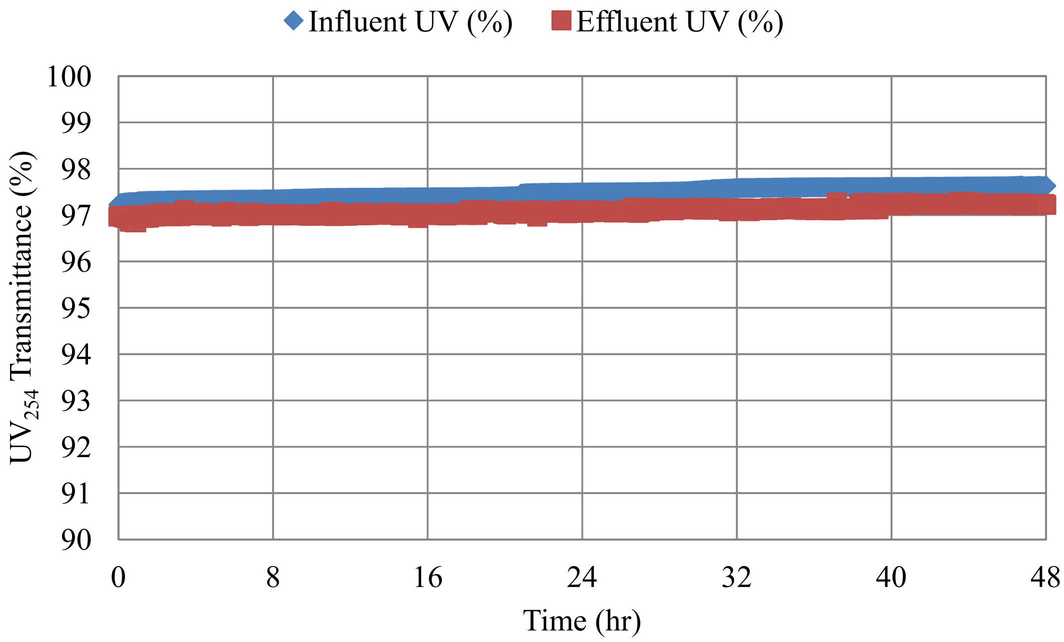


Figure 4.38 UV_{254} of Influent and Effluent over Time *(1.56 mg/L Coagulant A, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

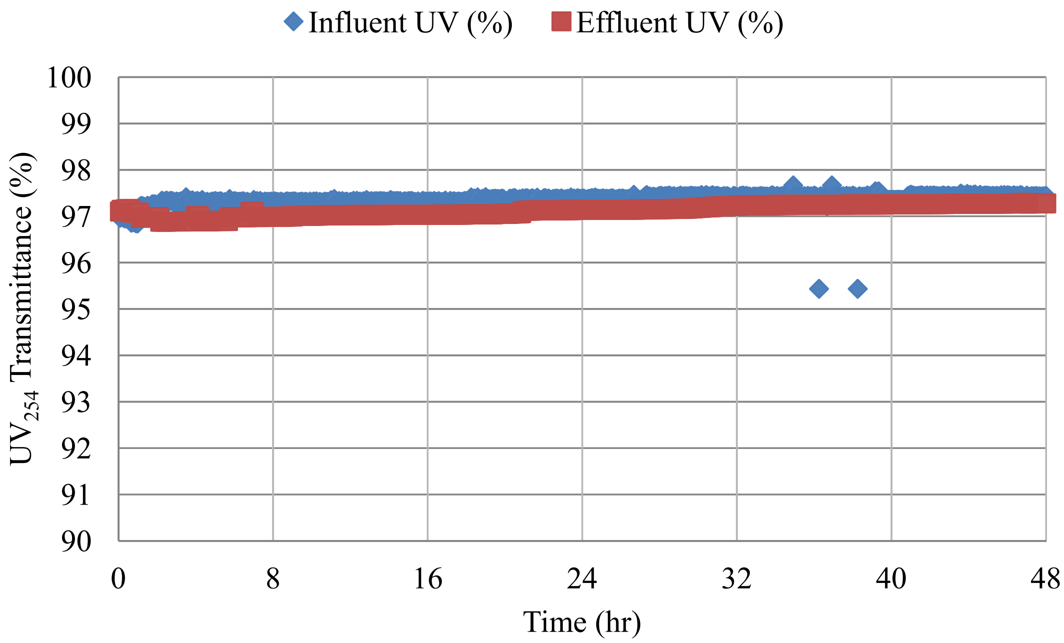


Figure 4.39 UV_{254} of Influent and Effluent over Time *(1.56 mg/L Coagulant B, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

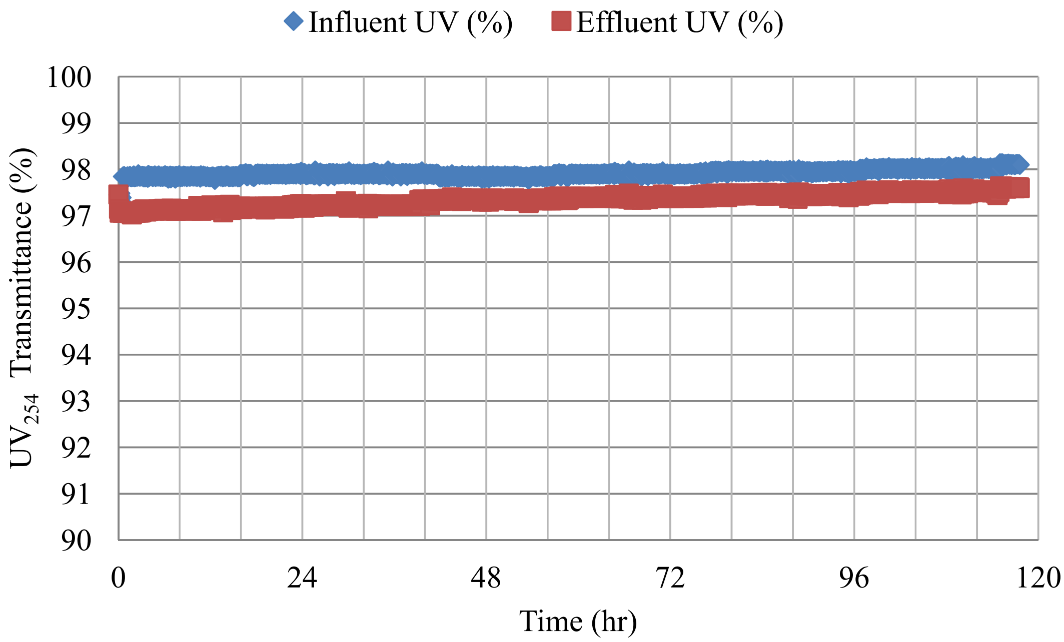


Figure 4.40 UV_{254} of Influent and Effluent over Time *(1.56 mg/L Coagulant C, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

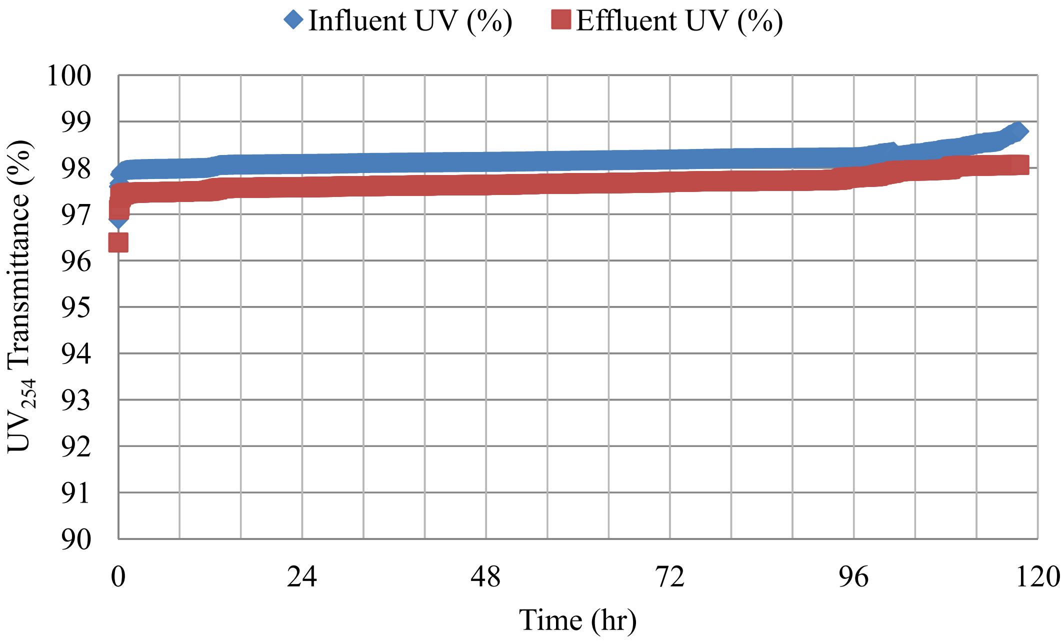


Figure 4.41 UV_{254} of Influent and Effluent over Time *(305 g/m^2 Coagulant D, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

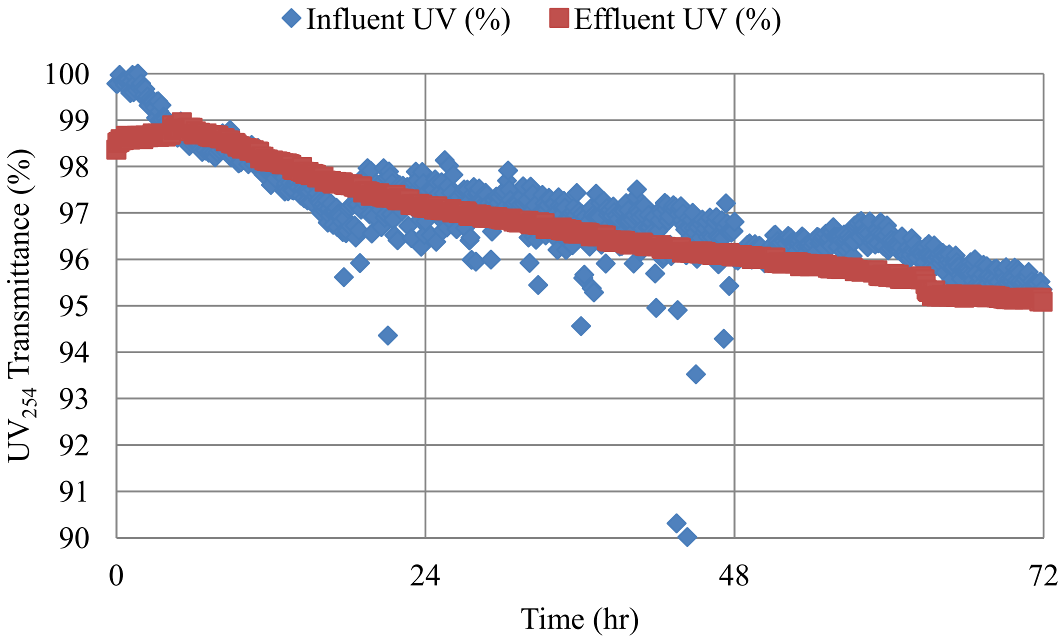


Figure 4.42 UV_{254} of Influent and Effluent over Time *(0.1 mg·Al/L Coagulant E, 1.8 #/mL Microspheres, 30 cm Sand, 30 m/h Filtration Rate)*

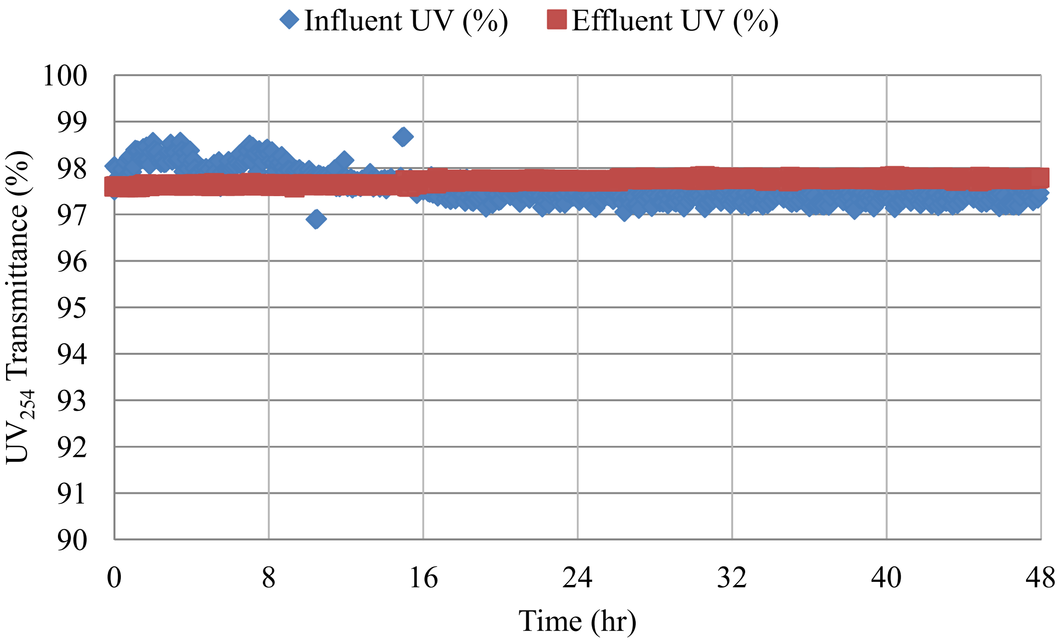


Figure 4.43 UV_{254} of Influent and Effluent over Time *(1.56 mg/L Coagulant F, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

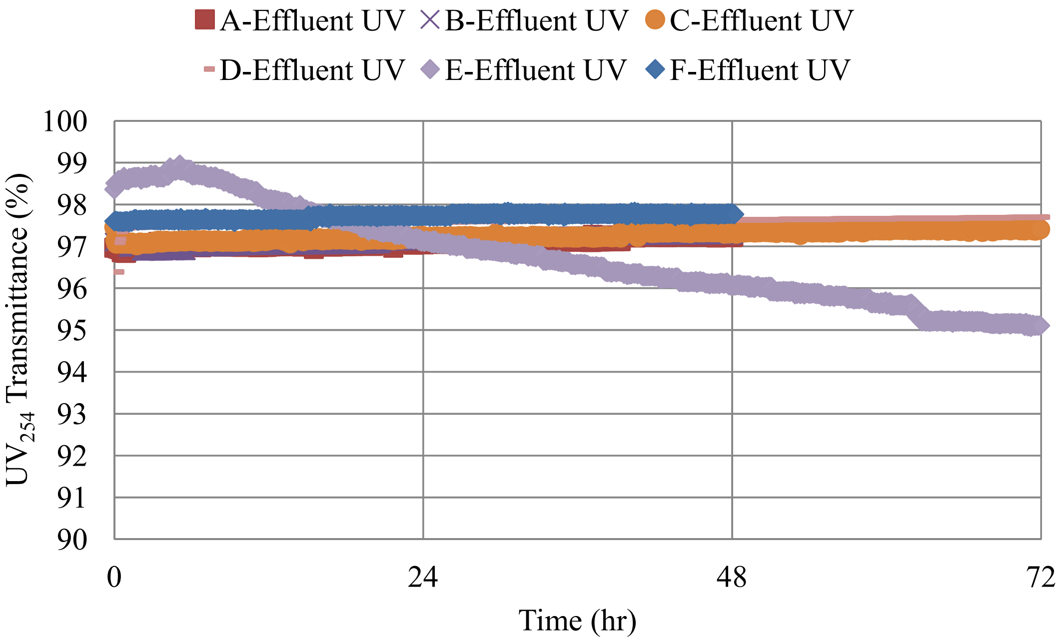


Figure 4.44 UV_{254} of Filter Effluent for Six Coagulants over Time

4.3.2.3 Coagulation Evaluation

A streaming current meter (SCM) was installed on the influent sample line. A SCM reported changes with the charge of the particles in the water (Edney, 2011). Raw water streaming current was negative. Streaming current increased with cationic coagulants added since negative particles can be charge neutralized by coagulants. Figure 4.45 displays the streaming current values for each coagulant over time. Streaming current typically increased to a certain value with the addition of coagulants A, B, and F from -200 streaming current unit (SCU) to 400 SCU or 500 SCU, and the SCM detector was saturated at high polymer concentration. Coagulant A, B, and F appeared to overdose, which was confirmed by microsphere removals, zeta potential, and polyDADMAC concentration variation for each turnover. Streaming current was not changing with addition of coagulant C, which corresponded with zeta titrations and helped explain the pool microsphere removals obtained by coagulant C. Coagulant D and E did not show a tendency to overdose or accumulation.

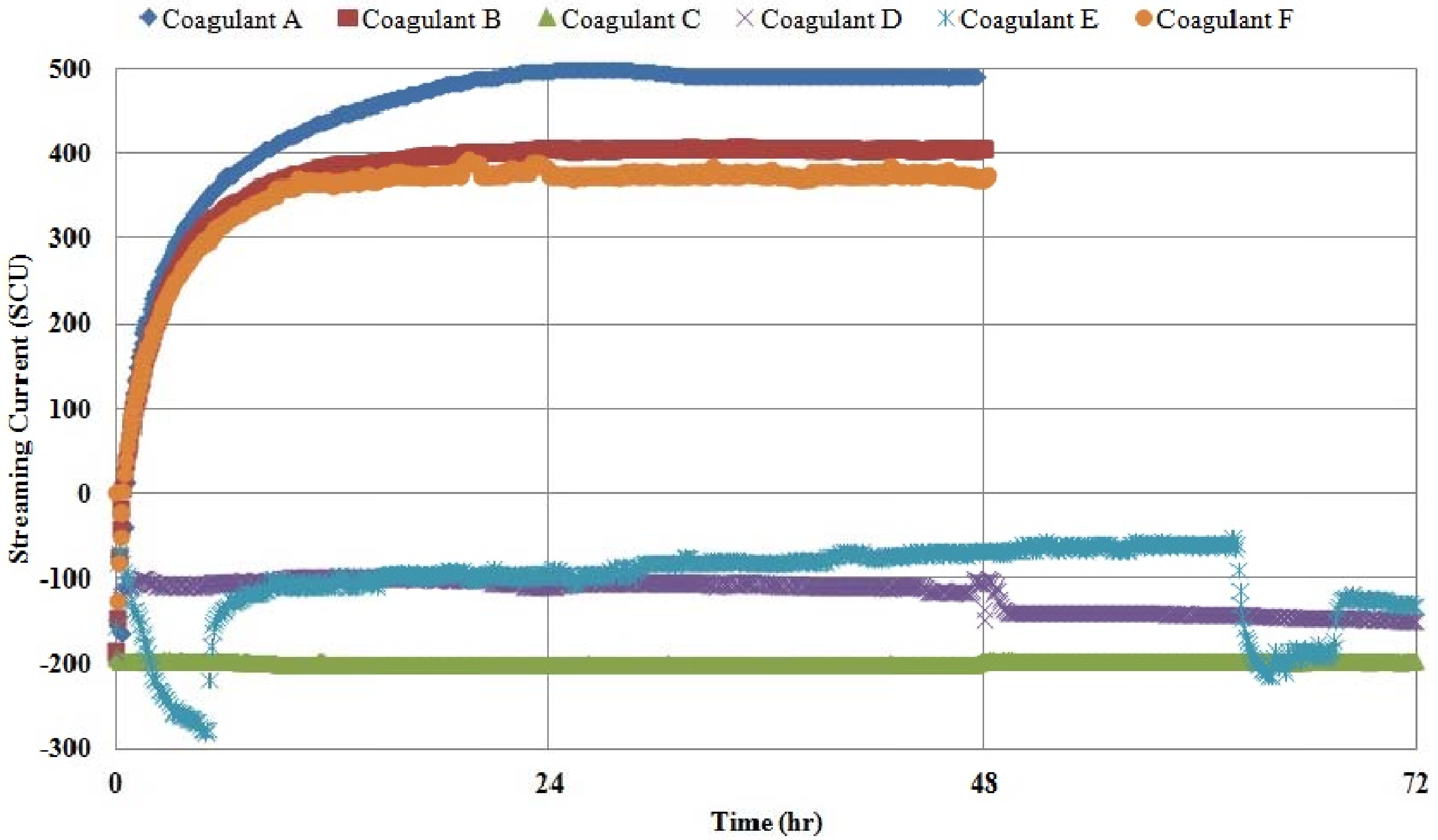
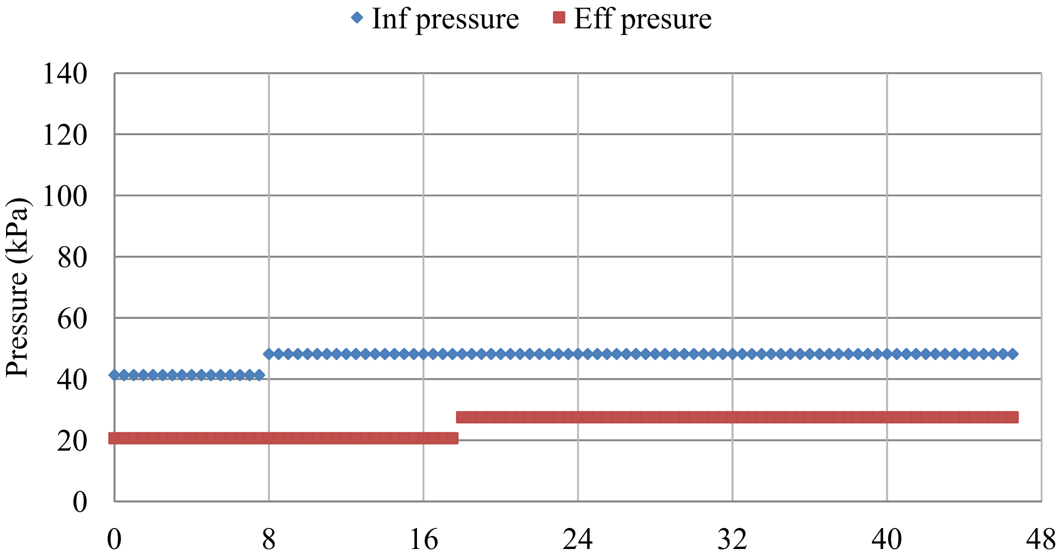


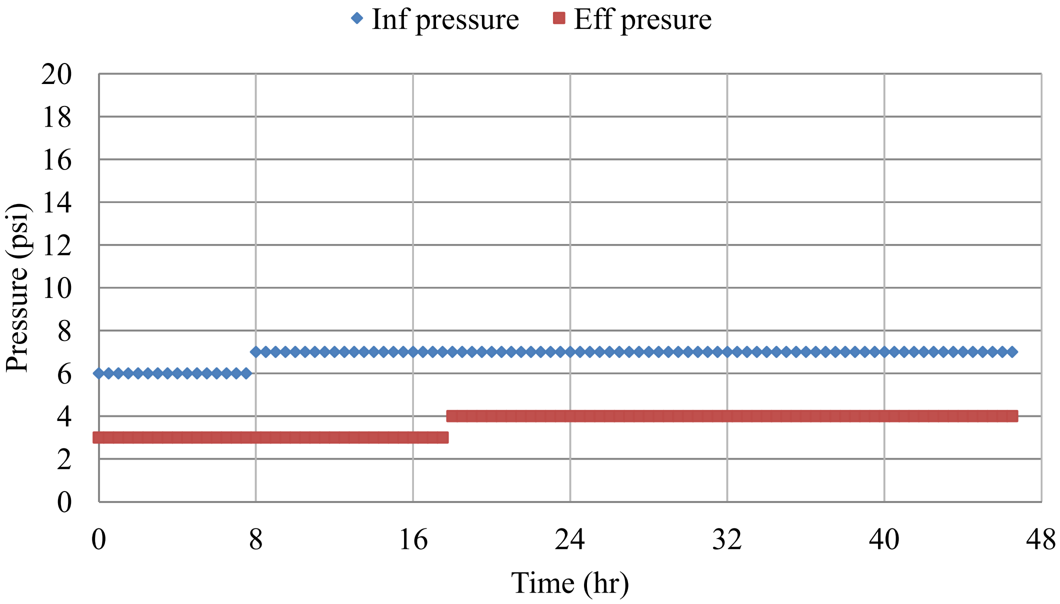
Figure 4.45 Streaming Current Variation over Treatment Time *(1.56 mg/L Coagulant A, 1.56 mg/L Coagulant B, 1.56 mg/L Coagulant C, 305 g/m^2 Coagulant D, 0.1 mg·Al/L Coagulant E, 1.56 mg/L Coagulant F, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

4.3.2.4 Pressure Losses

Figures 4.46, 4.47, 4.48, 4.49, 4.50 and 4.51 show pressure variation during each experiment for coagulant A, B, C, D, E, and F respectively. The initial filter influent pressure was 41 kPa (6 psi), and effluent pressure was 21 kPa (3 psi) for the six coagulants. Both influent pressure and effluent pressure for each coagulant increased during the experiments. There was not significant pressure buildup for coagulants A, B, C, and F. However, influent and effluent pressures were increased significantly for coagulant D and E. Influent pressure was 70 kPa (10 psi) higher than the original starting pressure, which was because the precipitate in coagulant D and E solution were retained by the filter media and created a fine cake layer. Pressures decreased after backwash for coagulant D and E. Pressure buildup (pore clogging) for coagulant D and E could help to explain the decreased microsphere removals with time. Figure 4.52 compares the influent and effluent pressure differences (pressure loses) for the six coagulants. Pressures losses for coagulant D and E were significantly more than coagulant A, B, C, and F.

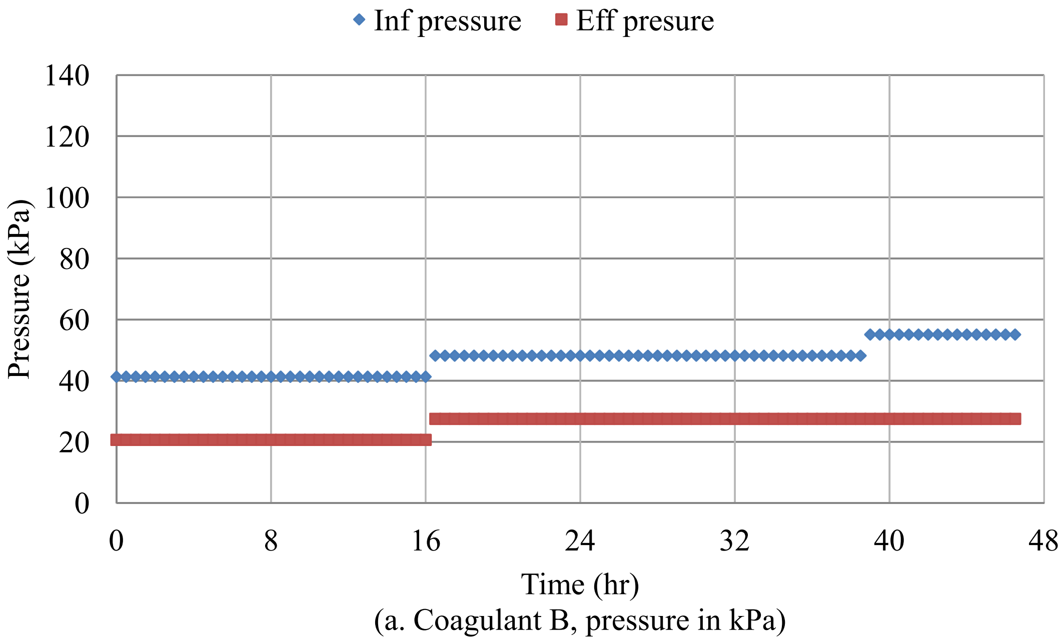


(a. Coagulant A, pressure in kPa)

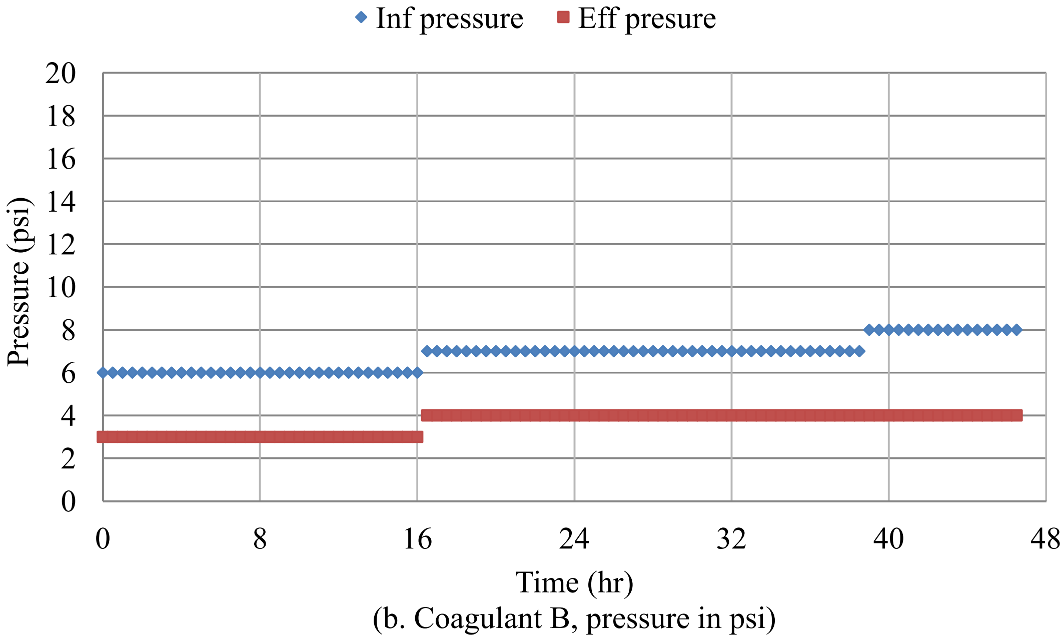


(b. Coagulant A, pressure in psi)

Figure 4.46 Pressure Variations over Treatment Time *(1.56 mg/L Coagulant A, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

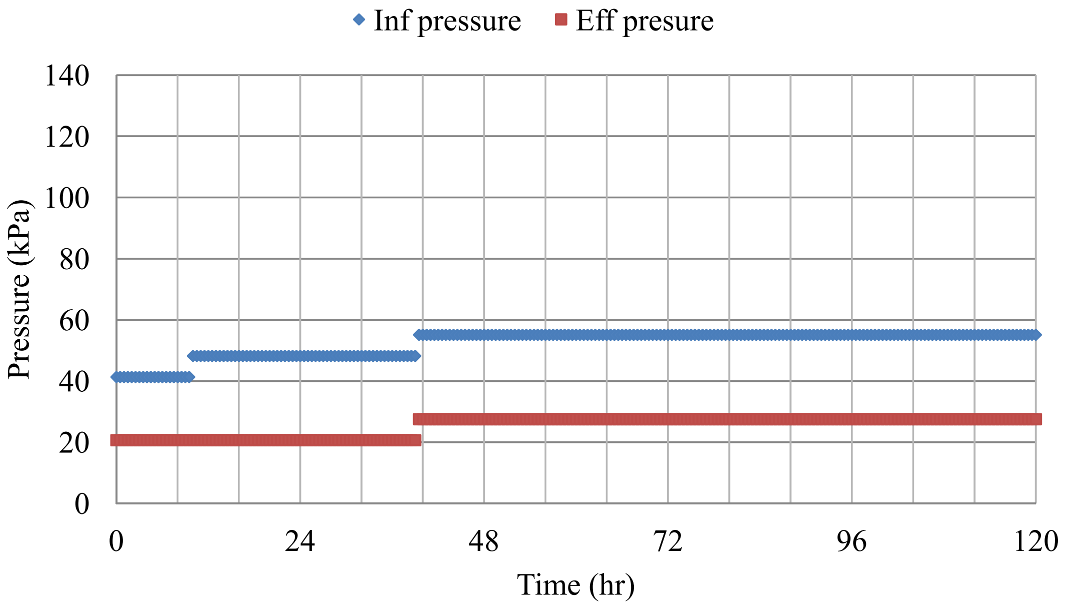


(a. Coagulant B, pressure in kPa)

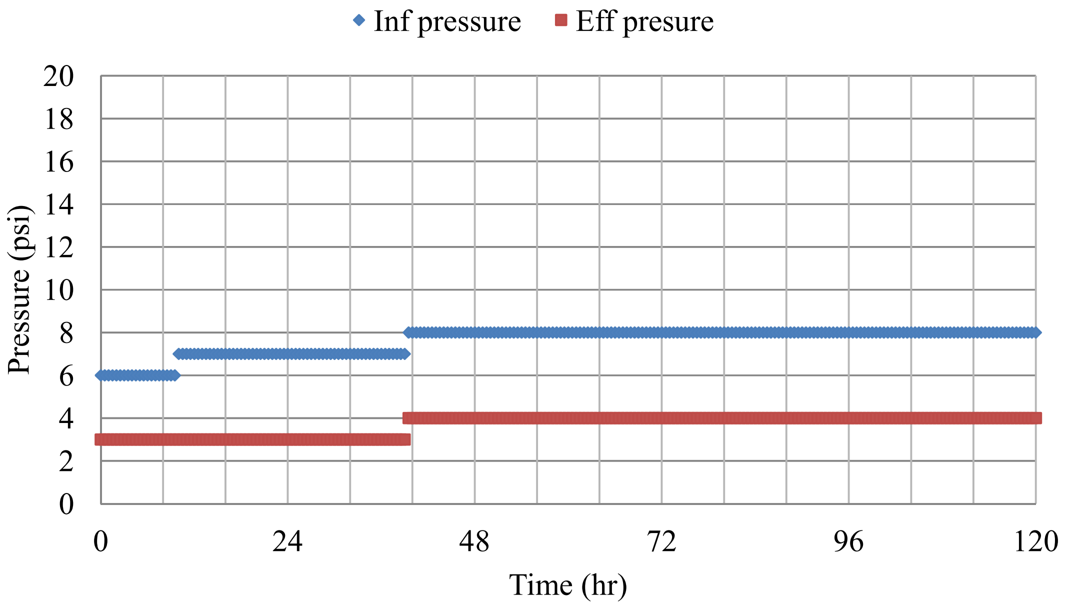


(b. Coagulant B, pressure in psi)

Figure 4.47 Pressure Variations over Treatment Time *(1.56 mg/L Coagulant B, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

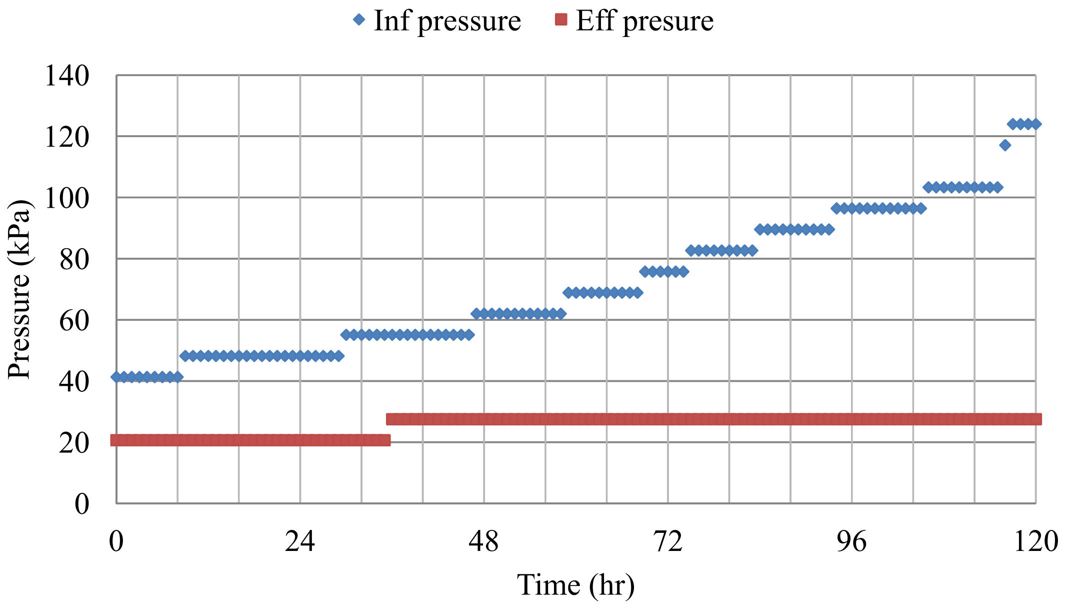


(a. Coagulant C, presssure in kPa)

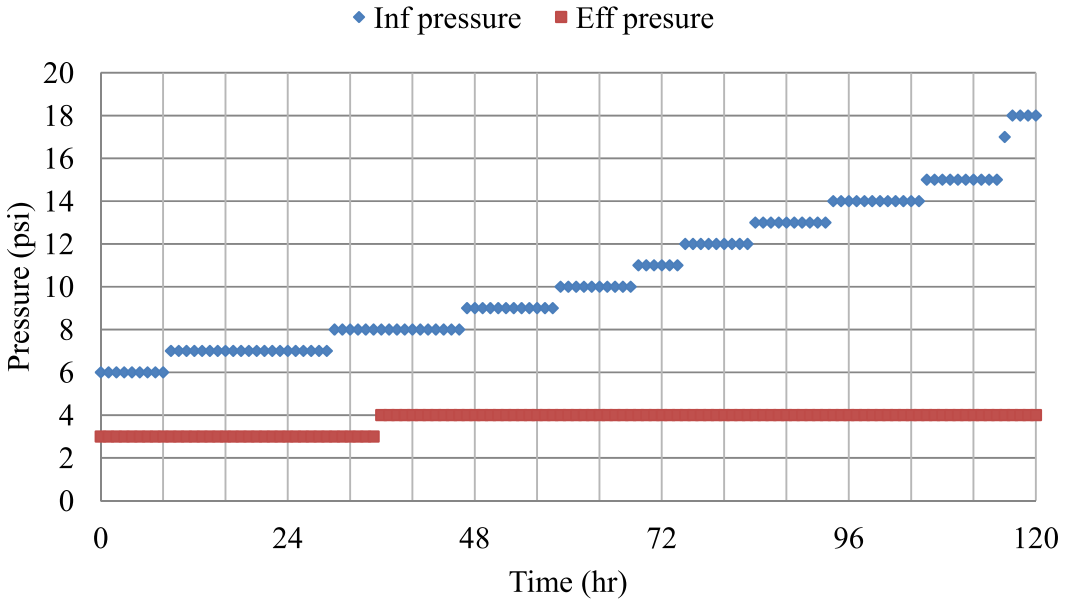


(b. Coagulant C, pressure in psi)

Figure 4.48 Pressure Variations over Treatment Time *(1.56 mg/L Coagulant C, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

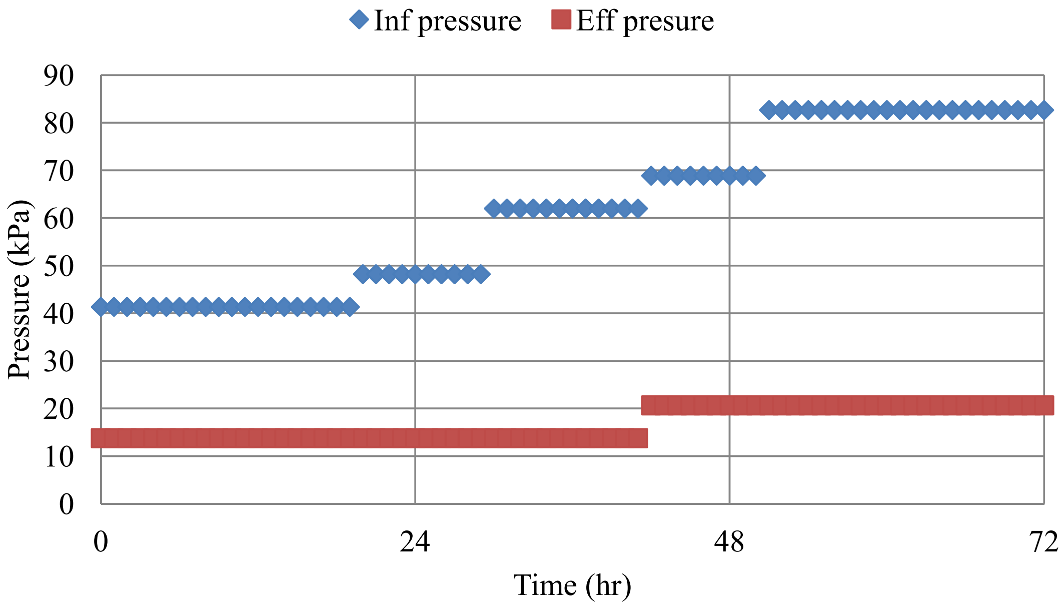


(a. Coagulant D, pressure in kPa)

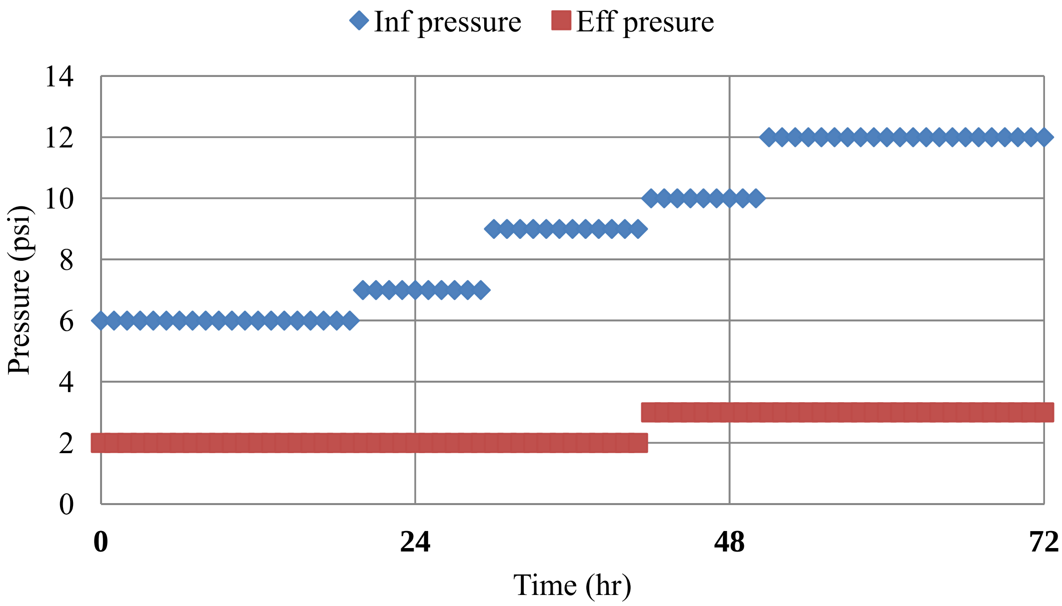


(b. Coagulant D, pressure in psi)

Figure 4.49 Pressure Variations over Treatment Time *(305 g/m^2 Coagulant D, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

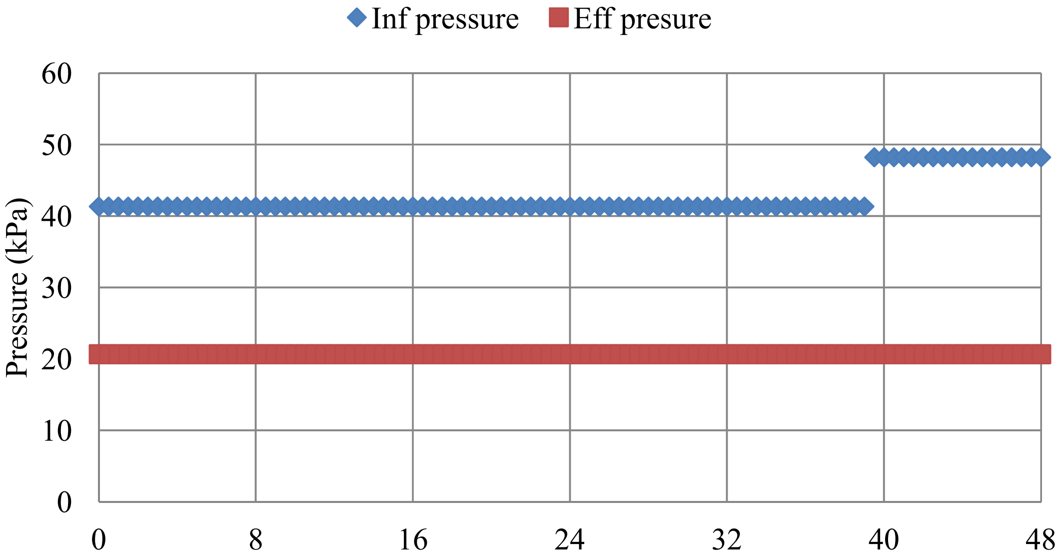


(a. Coagulant E, pressure in kPa)

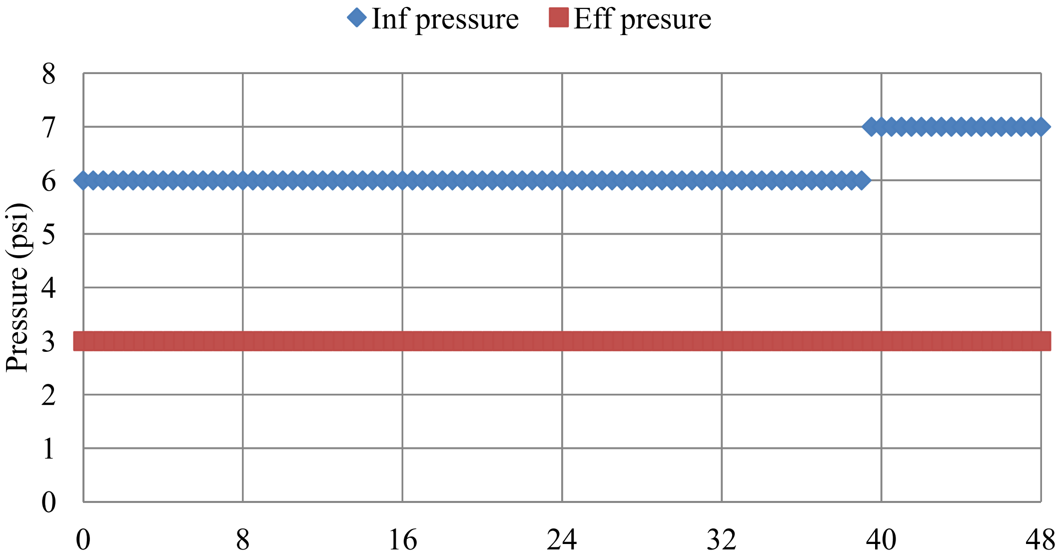


(b. Coagulant E, pressure in psi)

Figure 4.50 Pressure Variations over Treatment Time *(0.1 mg·Al/L Coagulant E, 1.8 #/mL Microspheres, 30 cm Sand, 30 m/h Filtration Rate)*

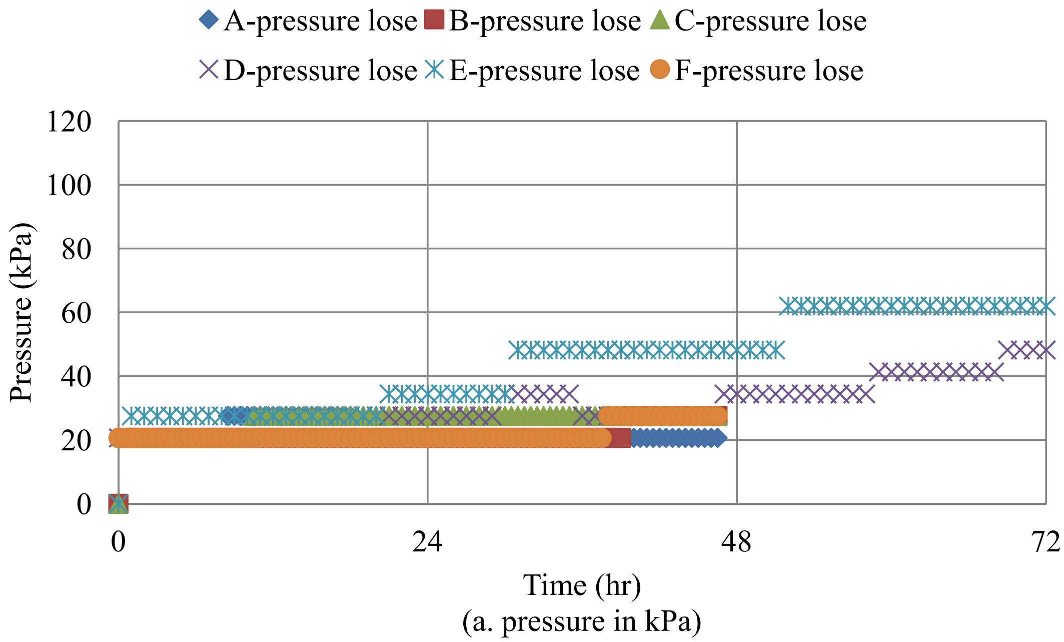


(a. Coagulant F, pressure in kPa)

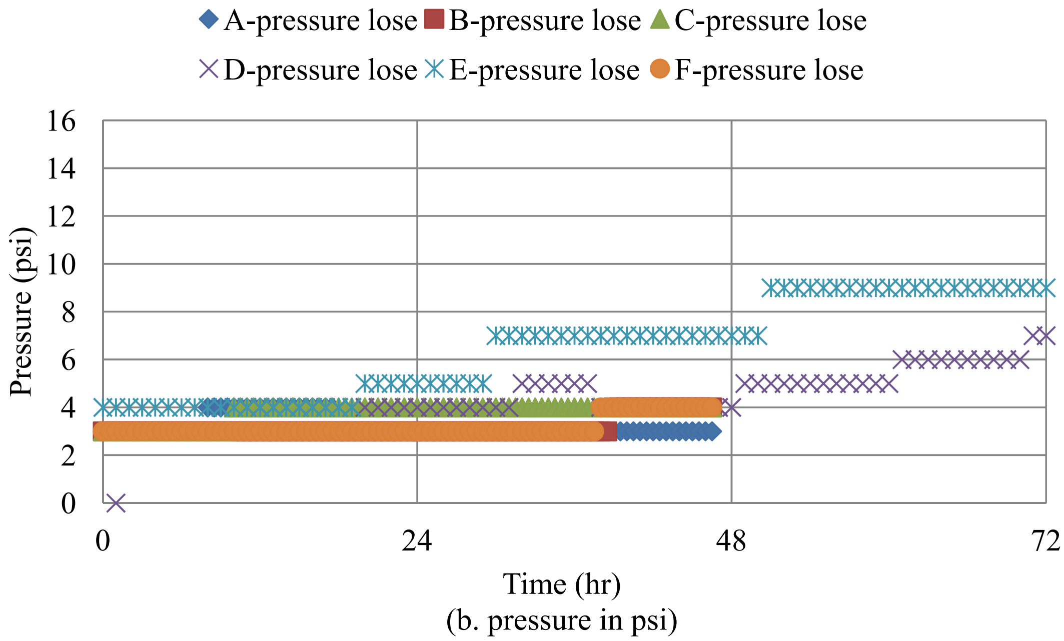


(b. Coagulant F, pressure in psi)

Figure 4.51 Pressure Variations over Treatment Time *(1.56 mg/L Coagulant F, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*



(a. pressure in kPa)



(b. pressure in psi)

Figure 4.52 Pressure Losses over Treatment Time for Six Coagulant *(1 recommended dosage of coagulant, 1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

4.3.3 Perlite/Sand Filtration

Perlite with 0.24 kg/m^2 (0.05 lbs/ft^2), 0.37 kg/m^2 (0.075 lbs/ft^2), 0.49 kg/m^2 (0.1 lbs/ft^2), and 0.61 kg/m^2 (0.125 lbs/ft^2), were added onto the surface of the sand media, respectively. The depths for perlite were approximately 0.30 cm, 0.35 cm, 0.60 cm, and 0.70 cm for 0.24 kg/m^2, 0.37 kg/m^2, 0.49 kg/m^2, and 0.61 kg/m^2, respectively, based on the photos shown in Figure 4.53 (the top white color media was the added perlite). Figure 4.54 shows microsphere removals by perlite/sand filter. Microsphere removals were equal to or greater than 99% (2 log) when amount of precoat was 0.37 kg·perlite /m^2 or above. The perlite filtration provided roughly 2 log improvement for removal of microspheres compared a high-rate sand filtration control. The increased removal was attributed to the fine perlite grain size. The effective diameter of the sand was more than 28 times larger than that of the perlite. Straining appears to be the predominant removal mechanism. Figure 4.55 shows pressure variation for the perlite/sand filter. The initial pressure loss was 21 kPa (3 psi) for sand only without perlite addition, while increased significantly as the amount of perlite increased. The influent pressure increased because the perlite was captured at the surface of sand media. A finer grain size media at the top of the bed led to less penetration of solids into the bed. Figure 4.56 shows UV$_{254}$ values for the perlite/sand filtration. There were no significant reductions in UV$_{254}$.

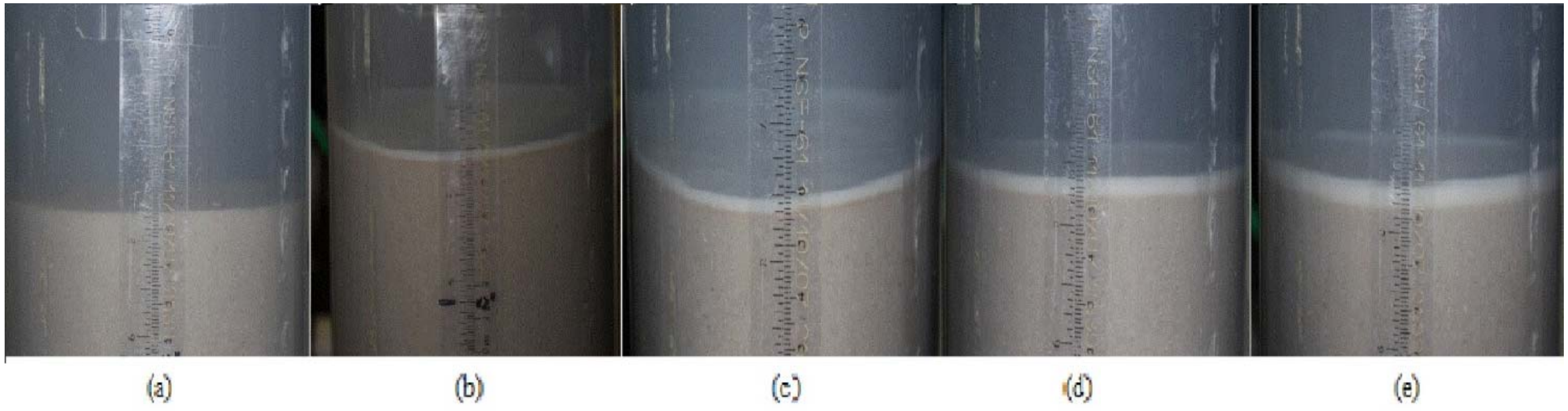


Figure 4.53 Perlite Depths for Four Different Amount of Perlite per Unit Area ((a) control; (b) 0.24 kg·perlite/m^2, 0.3 cm perlite; (c) 0.37 kg·perlite/m^2, 0.35 cm perlite; (d) 0.49 kg·perlite/m^2, 0.4 cm perlite; (e) 0.61 kg·perlite/m^2, 0.5 cm perlite)

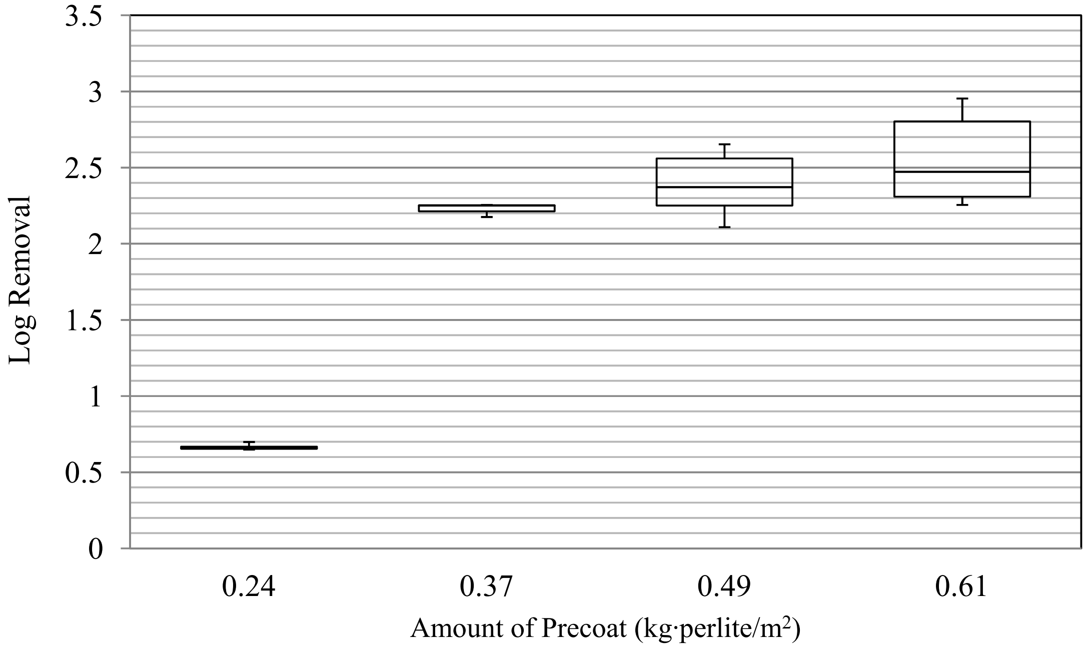
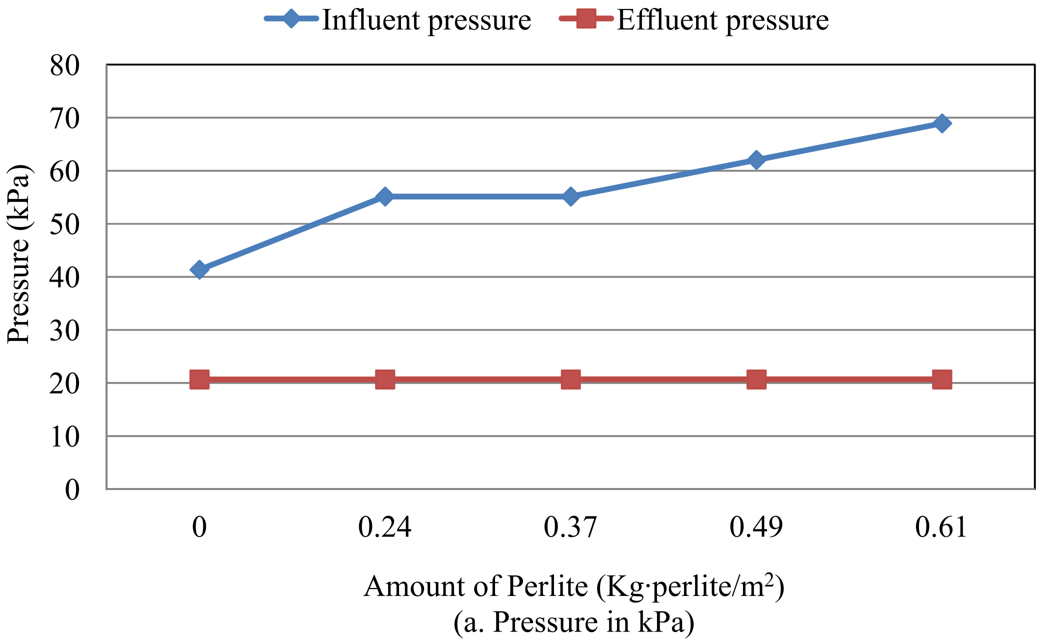
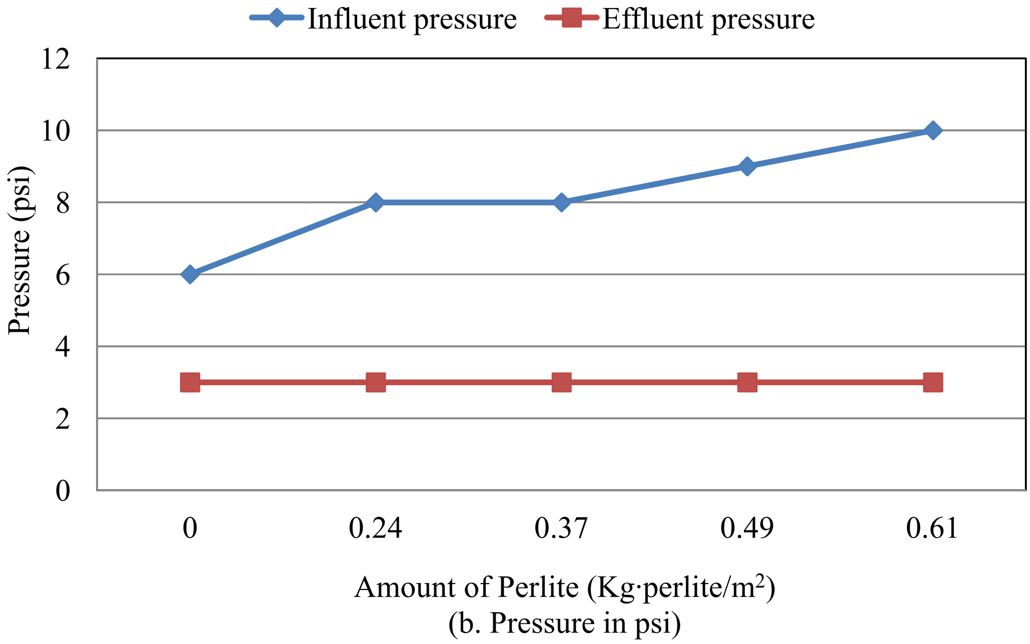


Figure 4.54 Microsphere Removals by Perlite/Sand Filter *(1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate) (number of experiments = 2, number of samples = 3)*



(a. Pressure in kPa)



(b. Pressure in psi)

Figure 4.55 Filter Influent and Effluent Pressure versus Amount of Perlite *(1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

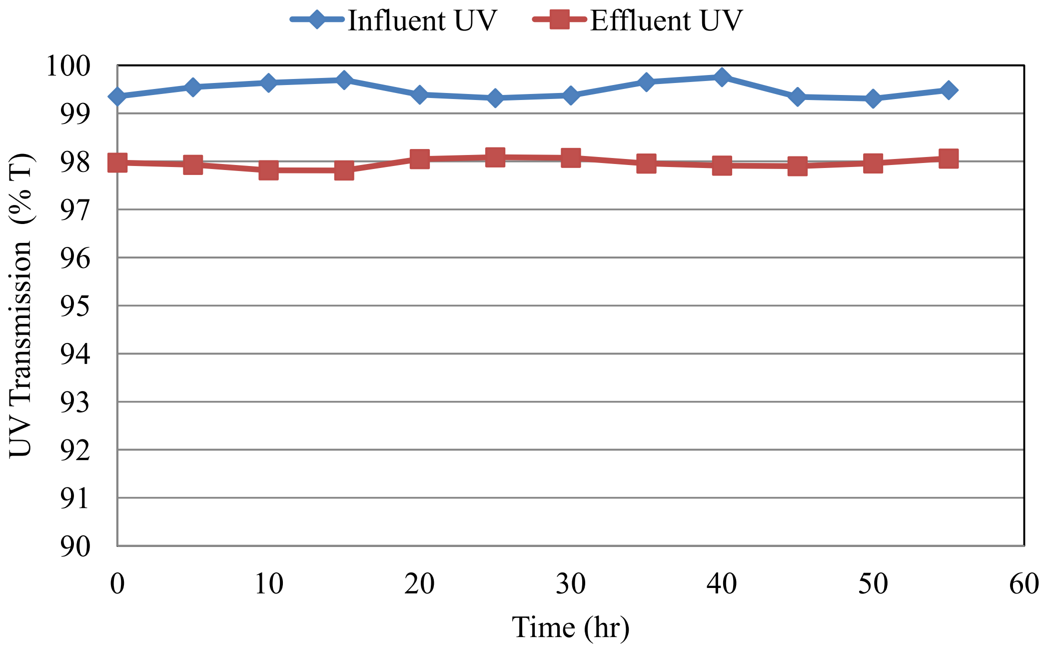


Figure 4.56 Filter Influent and Effluent UV_{254} Transmittance Changing over Time for Perlite/Sand Filter *(1.8 #/mL Microspheres, 30 cm Sand, 37 m/h Filtration Rate)*

4.3.4 Diatomaceous Earth (DE) Filtration

An independent series of seeded runs were made through DE filtration. Microspheres were seeded 30 minutes after each bumping for 5 minutes. Figure 4.57 shows microsphere removals under 5 m/h filtration rate for DE filter with different amount of precoat. Removals of *Cryptosporidium*-sized microspheres were observed from operation of test filters at 5 m/h (2 gpm/ft^2), ranging as follows: 95%-98% (1.3-1.8 log) for 0.5 kg·DE/m^2 (0.1 lbs·DE /ft^2), 97%-99.6% (1.5-2.4 log) for 0.7 kg·DE /m^2 (0.15 lbs·DE /ft^2), and 97%-99.8% (1.6-2.7 log) for 1.0 kg·DE /m^2 (0.2 lbs·DE /ft^2). Analysis of variance (ANOVA) result showed the removal under operation of 0.5 kg·DE /m^2 was different from others, and lower removals were obtained at 0.5 kg·DE/m^2 (0.1 lbs/ft^2).

Figure 4.57 shows microspheres removals after bumping with a 5-minute stop at 5 m/h. Removals of *Cryptosporidium*-sized microspheres after bumping with a 5-minute stop were: 97%-98% (1.5-1.8 log) for 0.5 kg·DE /m^2 (0.1 lbs·DE /ft^2), 98%-99.6% (1.7-2.4 log) for 0.7 kg·DE /m^2 (0.15 lbs·DE /ft^2), and 97%-99.8% (1.6-2.8 log) for 1.0 kg·DE /m^2 (0.2 lbs·DE /ft^2). No significant differences were observed between the removals before and after bumping at filtration rate of 5 m/h (2 gpm/ft^2) with a 5-minute stop of filter at different amounts of precoat.

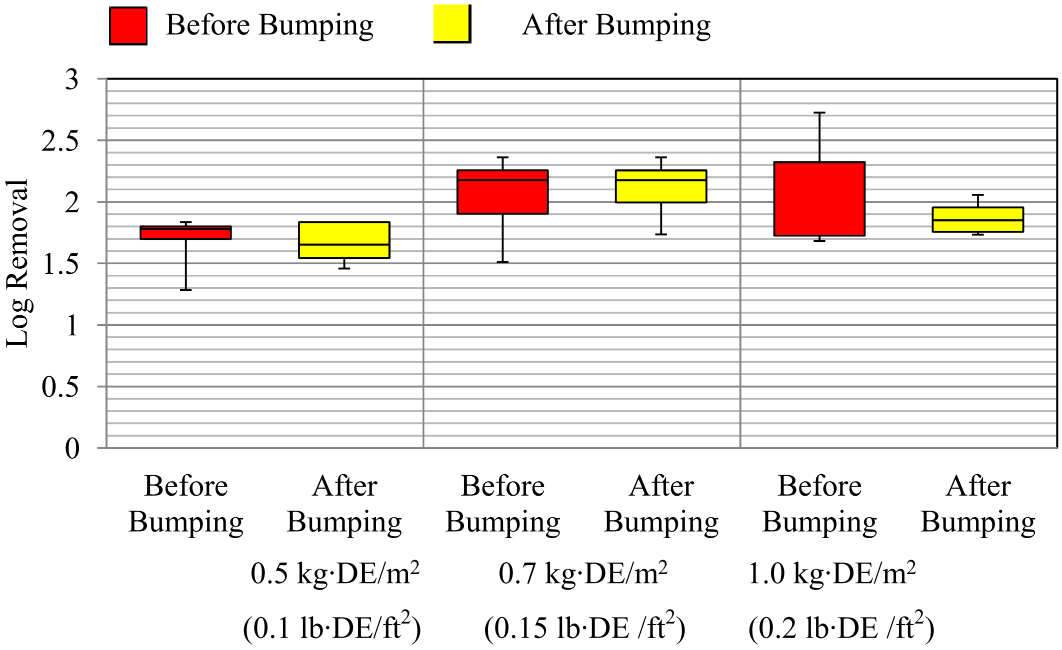


Figure 4.57 *Cryptosporidium*-sized Microsphere Removals by DE Filtration Before and After Filter Bumping under Different Amounts of Precoat, a 5-minute Filter Stop, 5 m/h *(Red color box — removal before bumping; Yellow color box — removal after bumping) (number of experiments = 2, number of samples = 3)*

Figure 4.58 shows removals before and after bumping with a 15-minute stop at different amounts of precoat and filtration rates. Significant differences in removals were obtained before and after bumping with a 15-minute stop of filter at filtration rates of 3.6 m/h, 5 m/h, and 6 m/h. The removals were decreased at least 0.5 log after bumping under the three different filtration rates and amounts of precoat.

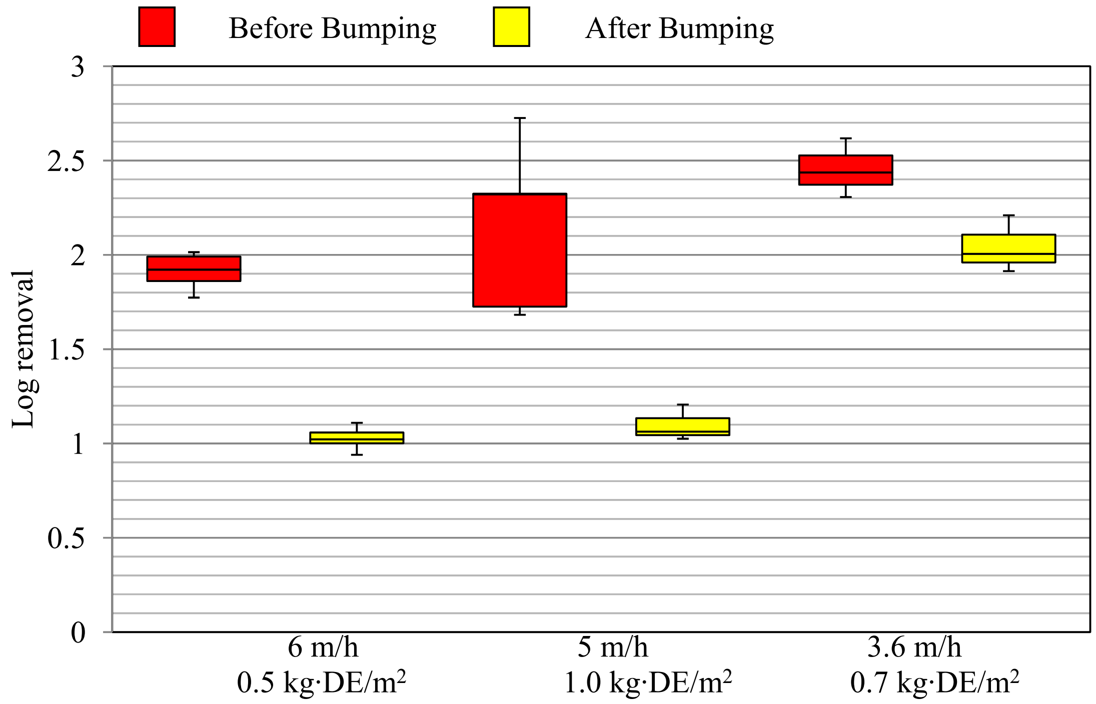


Figure 4.58 *Cryptosporidium*-sized Microsphere Removals by DE Filtration Before and After Filter Bumping under Different Amount of Precoat and Different Filtration Rate of 6 m/h, 5 m/h, and 3.6 m/h, a 15-minute Filter Stop *(Red color box — removal before bumping; Yellow color box — removal after bumping) (number of experiments = 2, number of samples = 3)*

Figure 4.59 shows removals before bumping and after bumping under different filter stopping time by 0.7 kg·DE /m^2 DE at 3.6 m/h. Microspheres were seeded in four cycles in this experiment. The number of microsphere seeding cycles might impact DE filter performance and will be discussed later (section 4.4.5). Removals were above

2.3 log for both before and after filter bumping with a 5-minute stop. Results indicated removal was decreased after bumping with a 15-minute stop or above. Results indicated the longer filter stopping time led to lower removals for the same filtration rate and amount of precoat.

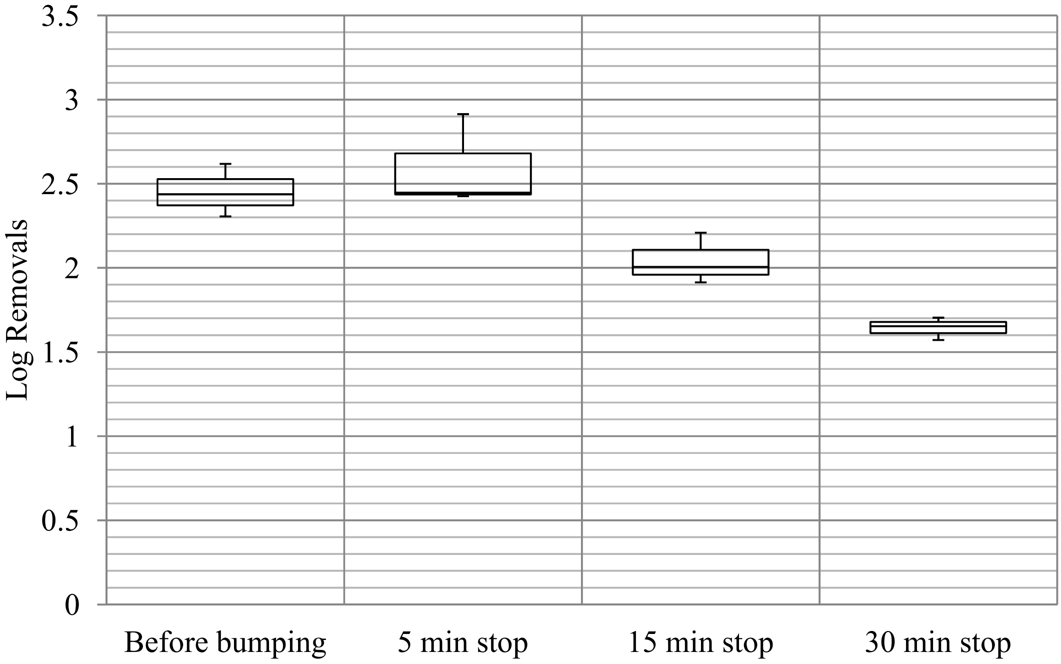


Figure 4.59 *Cryptosporidium*-sized Microsphere Removals by DE Filtration Before and After Filter Bumping with a 5-minute, 15-minute, and 30-minute Filter Stops (number of microsphere seeding cycles = 3), 0.7 kg·DE/m^2, Filtration Rate of 3.6 m/h *(number of experiments = 2, number of samples = 3)*

Figure 4.60 shows removals by DE filtration with and without coagulation A at 5 m/h. Figure 4.61shows microsphere removals by DE filtration with and without coagulant D at 5 m/h. Removals were, 95%-98% (1.3-1.8 log) for 0.5 kg·DE /m^2 (0.1 lbs·DE /ft^2) DE without coagulation, and 97%-99% (1.5-2 log) for 0.5 kg·DE /m^2 (0.1 lbs·DE /ft^2) DE with coagulant A and D. T-test results illustrated no significant differences between with and without coagulation ($P<0.05$), which indicated the coagulation did not improve the DE filtration. Previous study reported coagulants were rarely required for DE filtration (Fulton, 2000). Pressure loss of the DE filter was observed, and was between 2.1-5.6 kPa (0.3-0.8 psi) during the experiments.

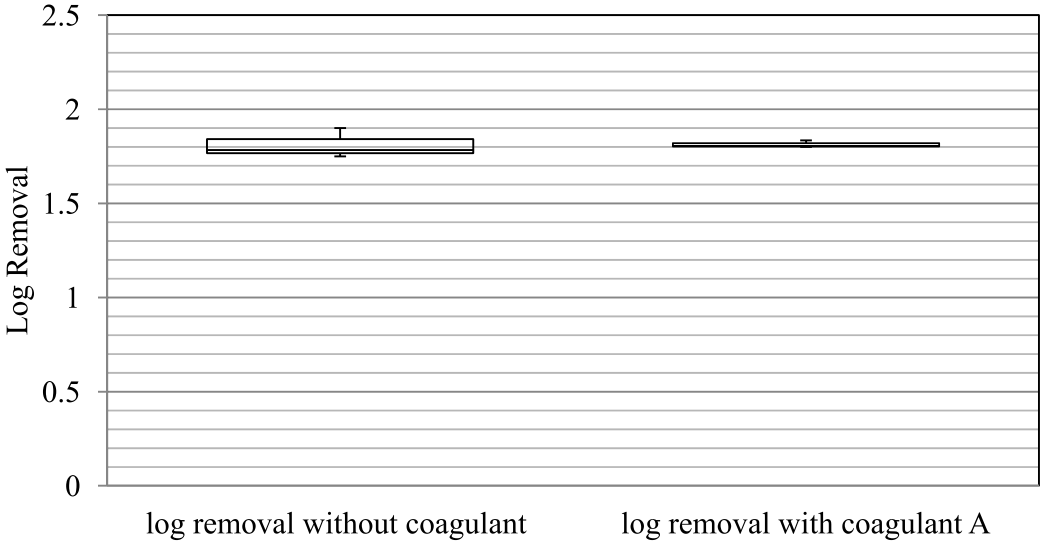


Figure 4.60 Removals of *Cryptosporidium*-sized Microsphere by DE Filtration With or Without 1.56 mg/L Coagulant A at 5 m/h *(number of experiments = 2, number of samples = 3)*

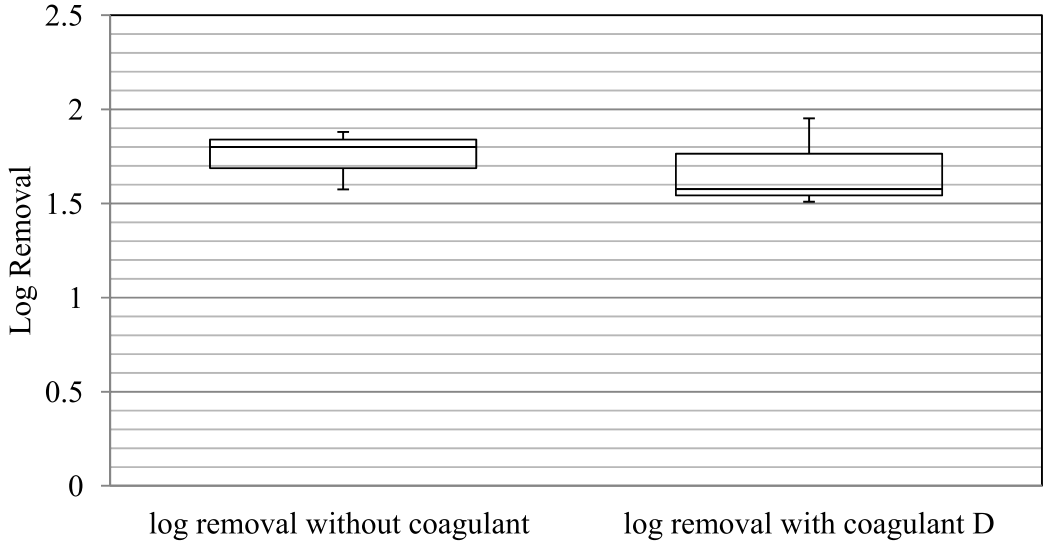


Figure 4.61 Removals of *Cryptosporidium*-sized Microsphere by DE Filtration With or Without Coagulant D at 5 m/h *(number of experiments = 2, number of samples = 3)*

4.4 Discussions

4.4.1 PolyDADMAC Based Coagulant

Excellent removal, more than 99% (> 2 log) was achieved by polyDADMAC products, indicating the polyDADMAC was a promising coagulant in *Cryptosporidium* removal from swimming pool. Similar performance of polyDADMAC coagulation was reported previously for drinking water treatment (Bolto and Gregory, 2007; Wei, et al., 2009; Wei, et al., 2010). However, the polyDADMAC product accumulated in the recirculating pool system after multiple turnovers, which led to the decreased microsphere removals, that was likely due to the charge reversal observed in surface titration results. The reversal of the zeta potential of the microspheres indicated that the coagulant adsorbed onto their surface at higher concentration. A similar conclusion was made in the research on the interaction between *Cryptosporidium* and coagulants (Bustamante, et al., 2001).

4.4.2 Chitosan Coagulant

Coagulant C (chitosan) could only remove <80% of *Cryptosporidium*-sized microspheres. This can be related back to surface titration results that chitosan could not achieve the minimum zeta potential, -10 mV, at recommended dosage of 1.56 mg/L as product under the experimental condition. The microsphere removals by coagulant C (chitosan) were contradictory to the research conducted by in-line filtration with chitosan in pH between 7.3 and 7.4, which showed the approximate 99% of *Cryptosporidium* and microspheres removal with 1.5 mg/L chitosan (Brown and Emelko, 2009). The possible reasons were the differences between chitosan concentrations, filtration rates, filter media, and raw water turbidity. Filtration rate was 10 m/h compared with 37 m/h in this study. High filtration rates resulted in somewhat deceased filtrate quality (Letterman and Yiacoumi, 2010). In addition, dual media, anthracite and sand were used, while single sand media was used in this study. Moreover, the turbidity was 2.5-5.0 NTU compared with the approximately turbidity of 0.2 NTU in this study. The long chains coagulant was demonstrated more effective for raw waters of higher turbidity (Lee, et al., 2001).

Chitosan is a polymer with low charge density (Parsons, et al., 2007). In acidic solutions, chitosan becomes extended chain and charged, while in neutral solutions, chitosan is more coiled structure and only slightly charged (Huang, et al., 2000; Pan, et al., 1999). The pH was 7.5 in this study, and pH was proved to impact chitosan performance. When pH values shift from 4 to 7, the positively charge on the chitosan surface significantly decreases, and the contribution of the charge neutralization of chitosan to destabilize particles is less significant in neutral pH condition (Huang and Yin, 1996; Parsons, et al., 2007). It was reported optimum dose for chitosan coagulation is smaller in acidic solutions ($pH < 7$), since the increased number of protonated amine groups on chitosan at lower pH, and hence destabilization of particles was enhanced by the increased charged groups (Huang, et al., 2000; Pan, et al., 1999). A non-charge coagulation mechanism has been proposed for chitosan. The basic chitosan appear to function by a non-charge mechanism involving hydrogen bonding of the $–OH\cdots\cdots NH_2–$ type (Parsons, et al., 2007).

4.4.3 Aluminum Based Coagulant

Aluminum based coagulant performed better than other coagulants according to the removals. Alum was reported to perform better than the polyDADMAC and chitosan on NOM removal (Bolto, 2001) also, but filter pressure loss increased significantly compared with other coagulants.

4.4.4 Perlite/Sand Filtration

The removal of *Cryptosporidium*-sized microsphere in a precoat media filter occurs by straining through the pores in the filter bed, or by sedimentation of particles in the media pores (Letterman and Yiacoumi, 2010). The predominant removal mechanisms of single sand media filter was deposit within the pore spaces of a filter. According to DLVO theory, the electrostatic repulsion force dominants between the two *Cryptosporidium*-sized microspheres, also between microspheres and sand grains (Haaland, 2008; Hunter, 2001). Thus, microspheres removals by sand filter were only 20% - 63%. Perlite added on the top-layer of sand filter achieved significantly higher removals, because perlite was finer and had larger surface area than sand, which enhanced the filtration processes. The similar results were reported previously that 98% to 99.9% of 5 μm microspheres were removed by precoat/sand filter with 1.2 kg·perlite/m^2 were from 757 L (200 gal) swimming pool (Amburgey, et al., 2009; Amburgey, 2011).

4.4.5 DE Filtration

Previous study indicated precoat filter with 4-5 μm^2 diatomaceous earth (DE) media (DE filtration) could remove 2.3 log to 4.4 log (99.5%-99.996%) *Cryptosporidium* from swimming pool water at filtration rate of 6.1 m/h (swimming pool volume was less than 1,000 L) (Amburgey, et al., 2009; Amburgey, et al., 2012). On the basis of the work reported here and previously (Amburgey, et al., 2009), the increase in amount of precoat led to greater removals as well as indicating the finer DE grains resulted in greater removal. Although DE has reportedly been effective to remove *Cryptosporidium*, the practice does not appear to be widespread.

DE filtration used in drinking water treatment can remove up to 6 log *Cryptosporidium* with approximate 1-1.2 μm^2 DE grades (Ongerth and Hutton, 1997; Ongerth and Hutton, 2001; Schuler, et al., 1988; Schuler and Ghosh, 1990). The lower removal obtained from swimming pool water treatment is due to the typical DE used in drinking water industry is approximate 1 μm^2, which is finer grade than that used in swimming pool water treatment, around 4-5 μm^2 (Amburgey, et al., 2009; Hendricks, 2006). Surface blockage is one of the mechanism for precoat filtration, and when an appropriate grade of DE is selected, the pore structure of the filter cake physically blocks the passage of particles into filtered water (Letterman and Yiacoumi, 2010).

Potential distributions of precoat media and microspheres before and after bumping are shown in Figure 4.62. The precoat is shown as evenly distributed on filter septum before bumping and was recoated after bumping. Potential mechanisms impacting DE filter performance were potentially caused by all these distributions. (1) Microspheres are removed by surface blockage as shown in Figure 4.62 (a). Thus the removals are related to the distribution of precoat, pore size of precoat, and amount of precoat, etc. (2) Precoat and microsphere mixtures led to microspheres passing through the filter septum easily as shown in Figure 4.62 (b). (3) Uneven coating of precoat can occur after bumping as shown in Figure 4.62 (c), which allows microsphere pass through DE filters from the location with less or no precoat on filter septum. (4) Precoat and microsphere mixture as well as uneven coating combined to reduce filter performance as shown in Figure 4.62 (d). (5) Number of microsphere seeded (prior to a bumping) impacted DE filter performance by higher microsphere concentrations in the filter relative to the amount of precoat (as shown in Figure 4.62 (e)).

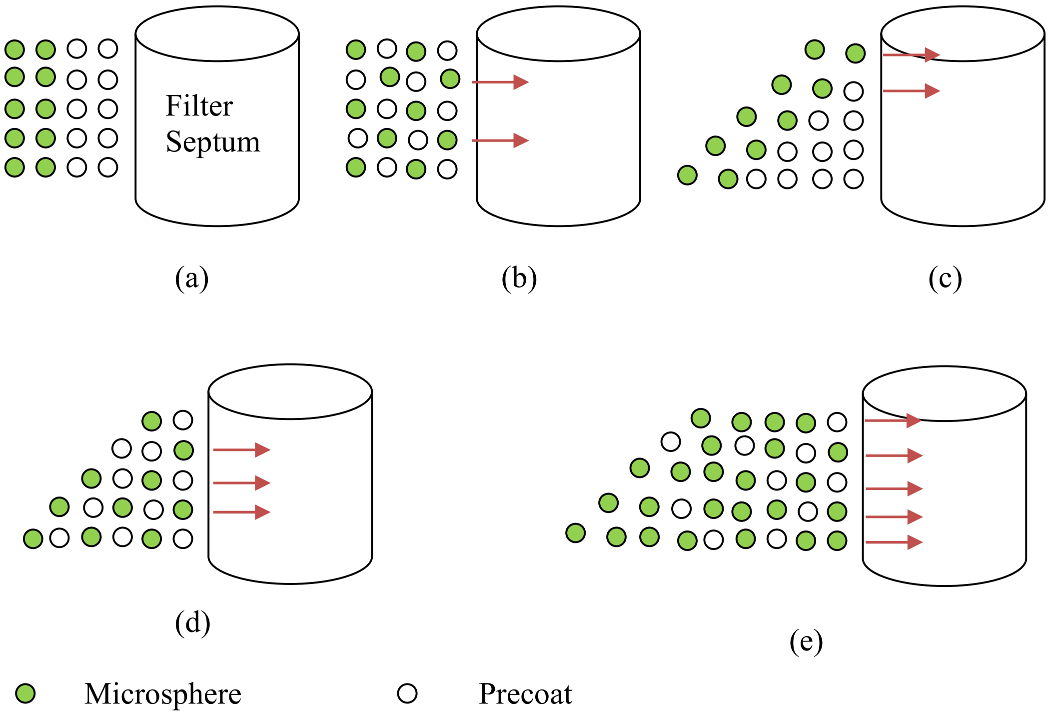


Figure 4.62 Conceptual Model of Distribution of Precoat and Microsphere Before and After DE filter Bumping ((a) before bumping, (b) after bumping — mixture of precoat and microsphere, (c) after bumping — uneven coating, (d) after bumping — combination of (b) and (c), (e) after bumping — three microsphere seeding cycles)

4.5 Conclusions

Cryptosporidium-sized microsphere removals from a pilot-scale swimming pool via high-rate sand filtration with coagulants, sand/perlite filtration, and DE filtration were studied separately. Microspheres removals, streaming current of influent, filter influent and effluent particle counts, turbidity, and UV_{254} transmittance were recorded during each experiment. The following conclusions were drawn:

(1) High-rate sand filtration with coagulants

C*ryptosporidium*-sized microsphere removals were between 20% - 63% (0.1 - 0.4 log) by high-rate sand filtration without coagulation (control). Up to 99%

(2 log) of *Cryptosporidium*-sized microsphere was removed through high-rate sand filtration with coagulants A, B, D, and F at 37 m/h. Decreasing filtration rate to 30 m/h, microsphere removals were increased to above 90% by coagulant E. Continuously feeding coagulant (coagulants A, B, and F) led to coagulant accumulation in the system and further resulted in the average removal decreasing to 83% to 87% range for coagulants A, B, and F.

(2) Perlite/sand filtration

Adding a layer of perlite on the top of a sand filter increased the *Cryptosporidium* oocysts-sized microsphere removals compared with sand filter control. The average removals were 79% (0.66 log), 99.4% (2.3 log), 99.7% (2.4 log), and 99.8% (2.5 log) for 0.24 kg·perlite/m^2 (0.05 lbs·perlite /ft^2), 0.37 kg·perlite /m^2 (0.075 lbs·perlite /ft^2), 0.49 kg·perlite /m^2 (0.1 lbs·perlite /ft^2), and 0.61 kg·perlite /m^2 (0.125 lbs·perlite /ft^2), respectively. The filter influent pressure increased since perlite and most particles were captured at the surface of sand media.

(3) DE filtration

The amount of precoat appeared to make some differences in the *Cryptosporidium*-sized microsphere removals. Bumping did not impair the microsphere removals when the filter was stopped for 5 minutes before restart, but bumping with a 15-minute stop of the filter decreased approximate 1 log microsphere removals at 5 m/h and 6 m/h. Bumping with a 30-minute stop decreased approximate 1 log microsphere removals at 3.6 m/h. Coagulation did not improve the microsphere removals for DE filtration under the studied condition.

CHAPTER 5: FULL-SCALE STUDY ON INCREASING *CRYPTOSPORIDIUM PARVUM* OOCYST AND *CRYPTOSPORIDIUM*-SIZED MICROSPHERE REMOVALS FROM RECREATIONAL WATER THROUGH FILTRATION

5.1 Introduction

5.1.1 Swimming Pool Water Treatment of *Cryptosporidium* Oocysts

Control of *Cryptosporidium* requires an integrated multiple barrier approach (Edzwald and Kelley, 1998). The drinking water industry has made significant progress in the removal of *Cryptosporidium* (Edzwald and Kelley, 1998; Edzwald, et al., 2000). The United State Environmental Protection Agency (EPA) (1998) promulgated the "Interim Enhanced Surface Water Treatment Rule" (IESWTR) in 1998 and established 2 log (99%) *Cryptosporidium* removal requirement for filtration (EPA, 1998).

EPA published the long-term 1 Interim Enhanced Surface Water Treatment Rule (LT 1) in 2000 to strengthen filter performance requirements to ensure 2 log *Cryptosporidium* removal specifically the protozoan *Cryptosporidium* (EPA, 2002). Long-term 2 Interim Enhanced Surface Water Treatment Rule (LT 2) was finalized in 2005. Systems classified in higher treatment bins must provide 90% to 99.7% (1.0 to 2.5 log) additional treatment for *Cryptosporidium*. Systems will select from a wide range of treatment and management strategies in the "microbial toolbox" to meet their additional treatment requirements. All unfiltered water systems must provide at least 99% or 99.9% (2 log or 3 log) inactivation of *Cryptosporidium*, depending on the results of their monitoring (EPA, 2005).

However, swimming pool water treatment is different from drinking water treatment. Coagulation and flocculation are conducted prior to filtration in drinking water treatment, thus the surface charge of particles is neutralized and the size of particles is increased. Coagulation is not typically conducted in U.S. swimming pools (Perkins, 2000). In addition, drinking water treatment plants typically operate filters at four to five times lower surface loading rates than swimming pool facilities, 4.9 to 10 m/h (2 to 4 gpm/ft^2) rather than 37 to 49 m/h (15 to 20 gpm/ft^2) for swimming pools (Howe, et al., 2012; NSPF, 2009; Perkins, 2000). This reduction in filtration rate lowers the velocity of particles in the filter and provides a higher probability of particles colliding and adhering to the filter media.

The increasing demands for recreational water activities combined with *Cryptosporidium* outbreaks have pushed the research on *Cryptosporidium* removal from swimming pools to the fore front. Little full-scale information is available on swimming pool water treatment for the removal of *Cryptosporidium*.

5.1.1.1 Pressure Sand Filters

The removal of particles by a filter can occur by straining through the pores in the filter bed for large particles, or by interception, sedimentation, or diffusion of particles in the media pores as shown in Figure 5.1 (Letterman and Yiacoumi, 2010). Approximately 20% to 60% of *Cryptosporidium*–sized microspheres were removed by sand filter without coagulation (Amburgey, et al., 2007; Amburgey, et al., 2008; Amburgey, et al., 2009; Amburgey, et al., 2009; Croll, et al., 2007).

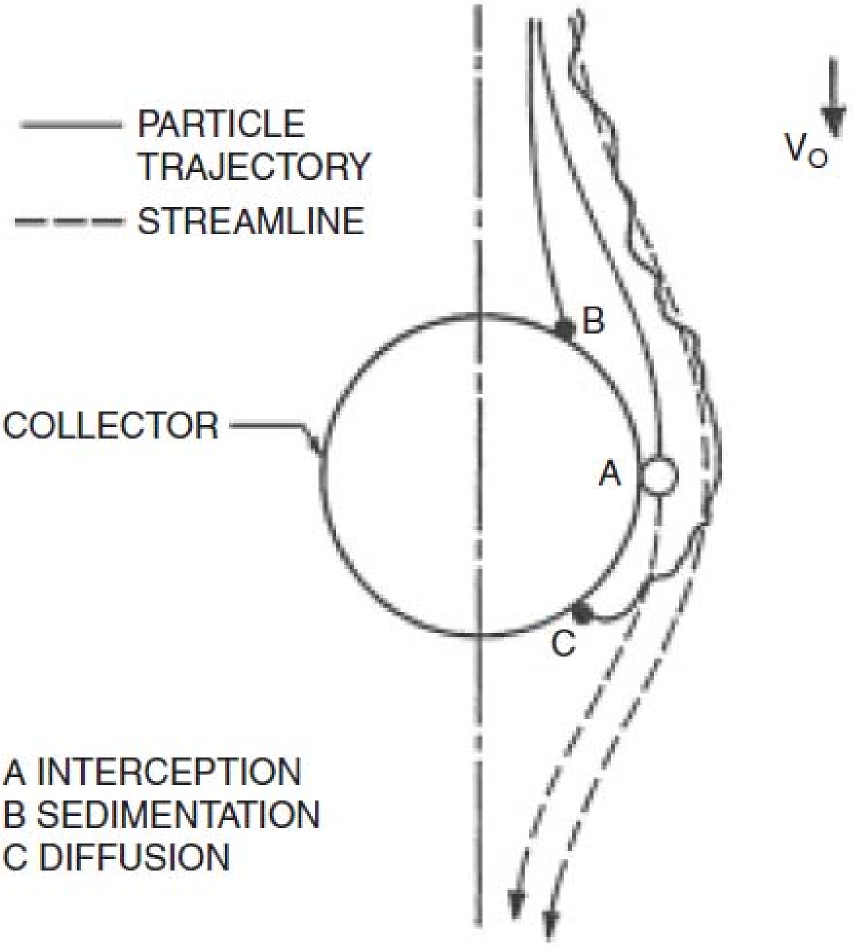


Figure 5.1 Basic Transport Mechanisms in Water Filtration (Tobiason, et al., 2010)

Pressure sand filters use graded sand as the filter medium in circular tanks for swimming pools. Vertical downward flow and horizontal are the two types of pressure filter used for swimming pools. There should be at least two filters for all the public pools for redundancy (Perkins, 2000). Filters are normally rated on the basis of flow rate per unit surface area (e.g., m^3/m^2/hour), and the rate is classified as low, medium and high. For club, hotel and private pools, high-rate filters are usually installed, for public pools and school pools medium-rate filters are usually selected (Perkins, 2000).

High-rate filters operate in the range 30 – 50 m^3/m^2/hour and medium-rate filters in the range 20 – 30 m^3/m^2/hour (Perkins, 2000). Pressure sand filters have to be back-washed when the filter influent pressure increases 1.5 kPa (10 psi) or higher (or as required depending on the efficiency of the filter in removing suspended and colloidal matter). As the deposits in the filter increase, there is a loss of pressure (or head) through the filter, which is typically measured by two pressure gauges on the two main connections to the filter (one near the top of the filter and the other near the bottom).

5.1.1.2 Filtration with Coagulation

A swimming pool water treatment plant should consist of strainer, coagulant dosing equipment, and pressure filter in order to maintain the desired small particles and organisms removals. The process of swimming pool water treatment is shown in Figure 5.2 (Perkins, 2000). The swimming pool filters must ensure a high degree of clarity water by reducing the matter in suspension and assisting the disinfection of the water by reducing the microorganisms.

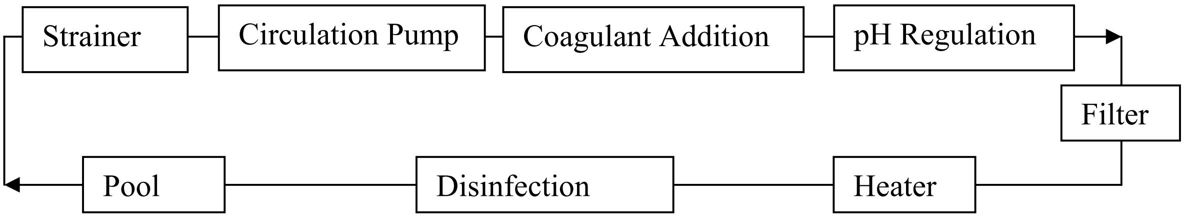


Figure 5.2 Diagram of Recommended Layout of Water Treatment Plan for Swimming Pools

Coagulants need to be added for efficient filtration. Aluminium sulphate (alum) and polyaluminum chloride (PACl) are generally used in European pools for this purpose.

The addition of alum has been shown to significantly improve removals of *Cryptosporidium*-sized microspheres to greater than 1 log in a single pass with continuous doses of 0.1 mg/L as Al and filter loading rates of 25 m/h and 30 cm of sand media (Goodman, 2011). The addition PACl at a continuous dosage of 0.1 mg/L as Al was able to remove greater than 2 log (99%) *Cryptosporidium*-sized microspheres in a single pass with a 25 m/h filter loading rate and 30 cm of sand media (Goodman, 2011). Another study found that removals of 1.6 log (97%) could be achieved using alum at dosages of 0.1 mg/L as Al, at 25 m/h filtration rate with sand bed depth of 60 cm (Croll, et al., 2007). However, the Pool Water Treatment Advisory Group (PWTAG) minimum recommended dosage is 0.005 mg/L as Al, and the Pool Air and Water Standard (PAWS) recommended dosage is in the range of 0.02 mg/L to 0.05 mg/L as Al.

An acidic solution is formed when alum dissolved in water. Alum used as a coagulant before the water enters the filters, the pH might be lowered slightly, which could contribute to erosion of the pools' circulation system. To raise the pH to the required level, alkali is added (usually in the form of sodium carbonate). This pH control can be manual or automatic. The pH should be maintained in the range of 7.2 to 7.8 (Perkins, 2000).

5.1.2 Swimming Pool Disinfection

The most common disinfecting agent used in swimming pools is chlorine. Chlorine residual is not elemental chlorine but consists of compounds containing available chlorine, expressed as 'free residual' chlorine (EPA, 2012; Perkins, 2000; Shields, et al., 2008). Sodium hypochlorite is normally supplied as a solution, while calcium hypochlorite is supplied as a dry chemical. Both compounds are strongly alkaline, and acidic solutions may have to be added to correct the pH and maintain it in the range of 7.2 to 7.8. A concentrated solution of sodium hypochlorite will attack cement-based concrete, so the concrete floor of the storage area should be protected (NSPF, 2009). Table 5.1 presents the oxidizing potential for each oxidizing reagent (WEP, 2012). C*ryptosporidium* is highly chlorine-resistant with 3 log inactivation requiring Ct values of 15,300 mg/L·min (CDC, 2011; Shields, et al., 2008).

Table 5.1 Oxidizing Potentials of Various Oxidizers

Oxidizer	Oxidizing Potential (V)
Fluorine	3.06
Hydroxyl free radicals	2.80
Atomic oxygen	2.42
Ozone	2.07
Permanganate	1.67
Hypobromous acid	1.59
Chlorine dioxide	1.50
Hypochlorous acid	1.49
Chlorine	1.36
Oxygen	1.23
Bromine	1.09
Hypochlorite	0.94

5.2 Materials and Methods

5.2.1 Research Objectives

The objective of this study was to examine the removal of *Cryptosporidium parvum* oocysts and *Cryptosporidium* sized-microspheres by various treatments (i.e., high-rate sand filtration with four different coagulants, perlite/sand filtration, and DE filtration) in full-scale swimming pools to verify field-relevant performance. Four types of coagulants were independently added to separate full-scale swimming pools, and particle removals were determined after one and multiple passes through the filter system. Precoat and perlite/sand filters were also similarly evaluated in full-scale experiments.

5.2.2 Experimental Materials

Experiments were conducted in simulated swimming pool water type-1 (as described in Appendix E). Coagulant B, D, E, and F were applied (characteristics of coagulants are shown in Appendix C). All these coagulants were proven to be effective in pilot-scale swimming pool study. *Cryptosporidium parvum* and *Cryptosporidium*-sized polystyrene microspheres were mixed and fed into the swimming pool.

5.2.3 Experimental Approach

Five full-scale swimming pools with volume of 37.9 m^3 (10,000 gal) in Conley, GA, USA, were studied. Figure 5.3 shows the swimming pool set-up. Figure 5.4 shows the plan view of the five swimming pools and pool parameters. Four coagulants were independently added into the pools. Four coagulant dosages were tested, which included a control (zero) dosage, a remediation dosage, a maintenance dosage, and an excessive dosage. Control experiments were conducted without coagulant for all pools. Remediation dosage is defined as the amount of coagulant required on the first use to achieve excellent particle removal; the maintenance dosage is defined as the coagulant dose required to seed continuously into the pool and to keep excellent particle removals. Approximate 2.54 #/mL (10^8 for total) *Cryptosporidium parvum* oocysts and 2.54 #/mL (10^8 for total) *Cryptosporidium*-sized microspheres were seeded into the four separate swimming pools, and four coagulants at remediation dosage were fed. Coagulants were also fed as one maintenance dosage per turnover time to the pool for one month, in order to evaluate the *Cryptosporidium parvum* and *Cryptosporidium*-sized microspheres removal under maintenance condition. Approximate 2.54 #/mL (10^7 for total) *Cryptosporidium parvum* oocysts and 2.54 #/mL (10^7 for total) *Cryptosporidium*-sized microspheres were seeded under maintenance coagulant dose.

A thin layer of fine perlite (0.5 kg·perlite/m^2 or 0.1 lb·perlite/ft^2) was added on an uncoagulated sand filter to test the performance of perlite on removals of *Cryptosporidium parvum* and *Cryptosporidium*-sized microsphere. DE was added to the precoat filter surface with 0.7 kg·DE/m^2 (0.15 lb·DE/ft^2). DE filtration was conducted for 2 weeks to test the removals of *Cryptosporidium parvum* oocyst and *Cryptosporidium*-sized microsphere under swimming pool condition.

Duplicate experiments were conducted. Triplicate samples were taken for each. Five separate swimming pools were used (as shown in Table 5.2). A coagulant charge analyzer (CCA) was used to measure the streaming current of the samples (Chemtrac, Norcross, Georgia). CCA measured streaming current from -10 to 10, rather than -1,000 to 1,000 as measured by a streaming current meter.

Table 5.2 Swimming Pools versus Tested Coagulants

Pool Number	Coagulant
#1	Coagulant B
#2	Coagulant D
#3	Coagulant F
#4	Coagulant E
#5	Perlite/Sand & DE

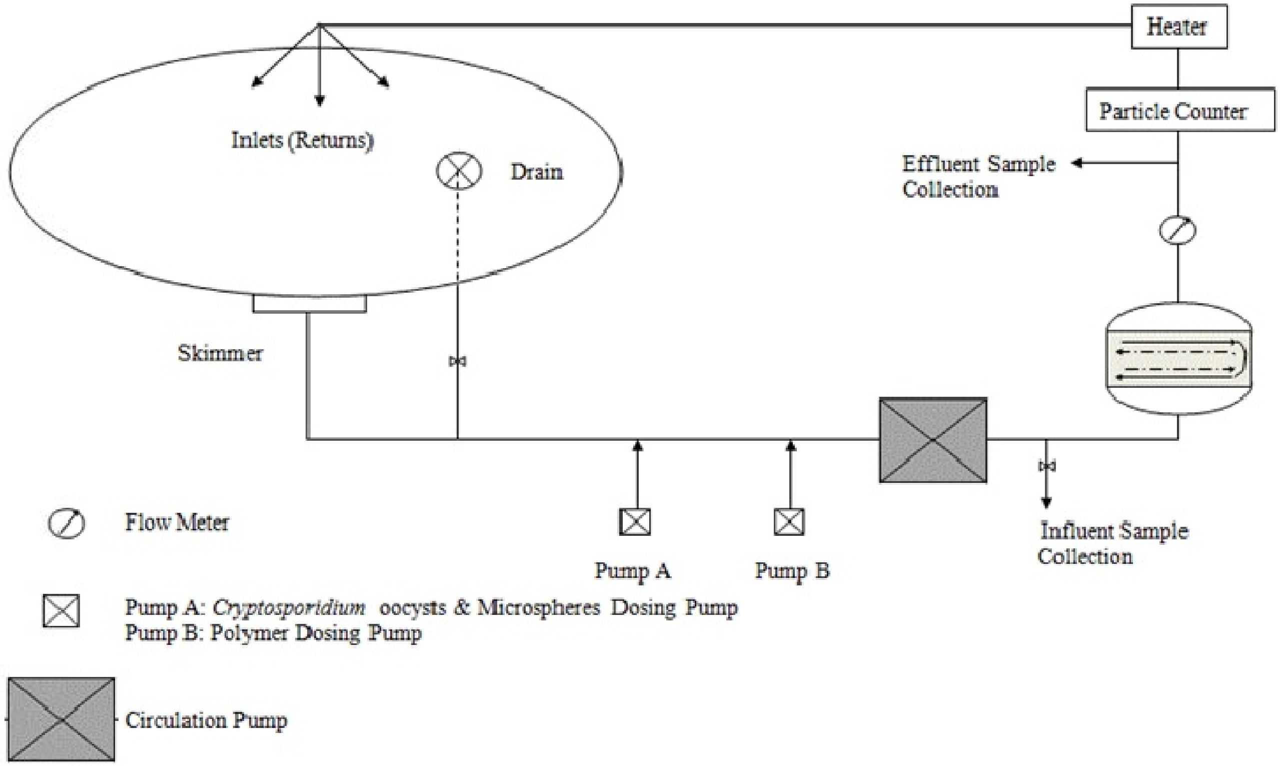
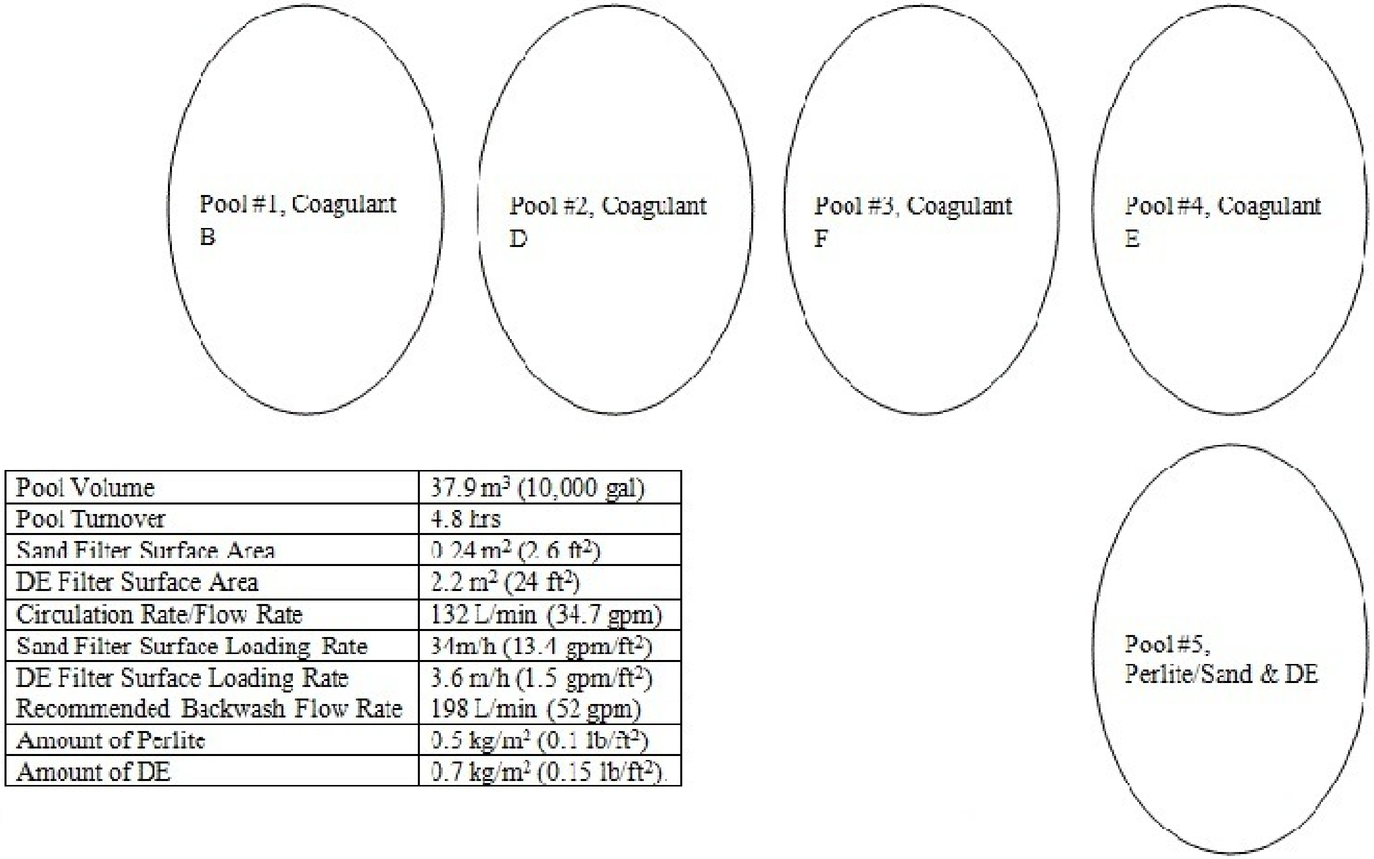


Figure 5.3 Full-Scale Swimming Pool Set-Up



Pool Volume	37.9 m^3 (10,000 gal)
Pool Turnover	4.8 hrs
Sand Filter Surface Area	0.24 m^2 (2.6 ft^2)
DE Filter Surface Area	2.2 m^2 (24 ft^2)
Circulation Rate/Flow Rate	132 L/min (34.7 gpm)
Sand Filter Surface Loading Rate	34m/h (13.4 gpm/ft^2)
DE Filter Surface Loading Rate	3.6 m/h (1.5 gpm/ft^2)
Recommended Backwash Flow Rate	198 L/min (52 gpm)
Amount of Perlite	0.5 kg/m^2 (0.1 lb/ft^2)
Amount of DE	0.7 kg/m^2 (0.15 lb/ft^2).

Figure 5.4 Full-Scale Swimming Pools Plan View

5.3 Results and Discussions

5.3.1 Performance of High-Rate Sand Filtration

5.3.1.1 Filtration with Coagulants of Control Dosage

Cryptosporidium parvum and *Cryptosporidium*-sized microsphere removals without coagulant with control dosage (zero dosage), were evaluated. Figure 5.5 shows the *Cryptosporidium parvum* and *Cryptosporidium*-sized microsphere removals with control dosage (zero) in pool #1to pool # 4. The missed data point in Figure 5.5 was because of sample was lost. Control trials illustrated 38% to 70% of *Cryptosporidium parvum* and *Cryptosporidium*-sized microsphere were removed, which were slightly higher than that in pilot-scale experiments (20% to 63%). Pool #4 was initially cloudy, which corresponded with the removal of 70% of *Cryptosporidium* and microspheres, which was the highest obtained by a control experiment without coagulation. Turbidity of pool #4 was 4.1 NTU (stardard deviation = 3 NTU), compared with 2.2 NTU (stardard deviation = 2.4 NTU) for pool #1, 2.4 NTU(standard deviation = 2 NTU) for pool #2, and 1.8 NTU (stardard deviation = 1.8 NTU) for pool #3. Appendix N shows turbidity, pH, conductivity, temperature, and pressure for full-scale experiments. Full-scale experiments raw data are shown in Appendix O.

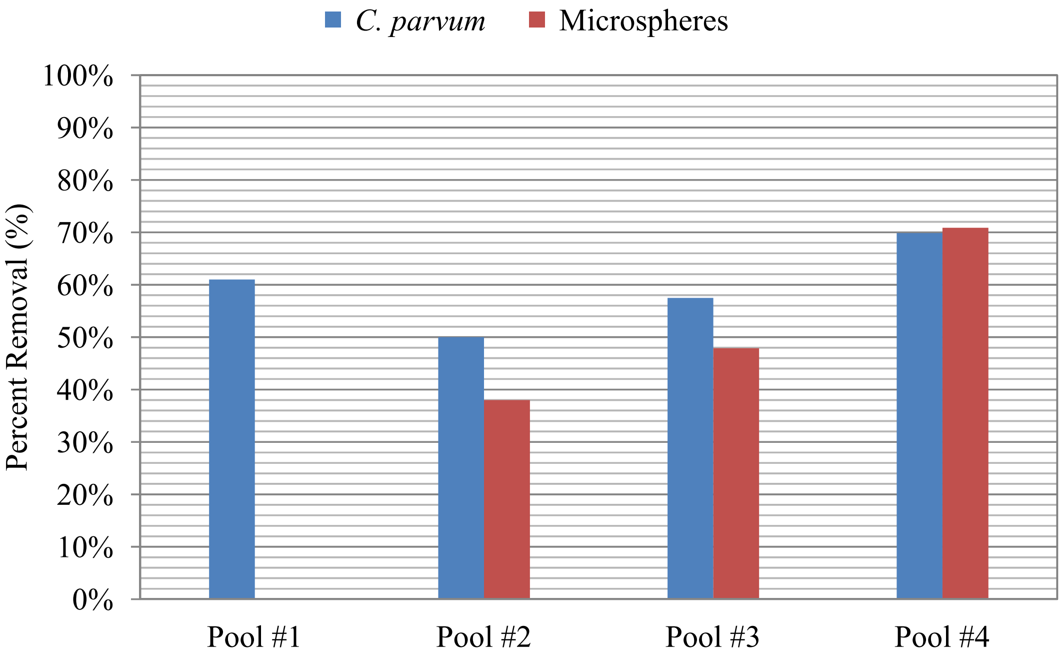


Figure 5.5 Removals without Coagulant, SLR 34m/h (13.4 gpm/ft^2), Pool #1 to Pool #4, *Cryptosporidium parvum* and *Cryptosporidium*-sized Microspheres concentration both were 2.54 #/mL (n=1)

5.3.1.2 Filtration with Coagulants of Remediation Dosage

Approximate 2.54 #/mL *Cryptosporidium parvum* oocysts and 2.54 #/mL *Cryptosporidium*-sized microspheres were seeded into the four separate swimming pools to simulate the *Cryptosporidium parvum* contamination in swimming pool. Removals of *Cryptosporidium parvum* and *Cryptosporidium*-sized microsphere are shown in Figure 5.6. High-rate sand filtration with the remediation dosage of coagulant B or F (1.56 mg/L as product), and coagulant D (305 g/m^2 or 1 oz/ft^2) achieved approximately 90% removals (1 log) for both *Cryptosporidium parvum* and microsphere. Filtration with coagulant E (0.1 mg/L as Al) removed 97% (1.5 log) of microsphere and 82% (0.7 log) of *Cryptosporidium parvum*.

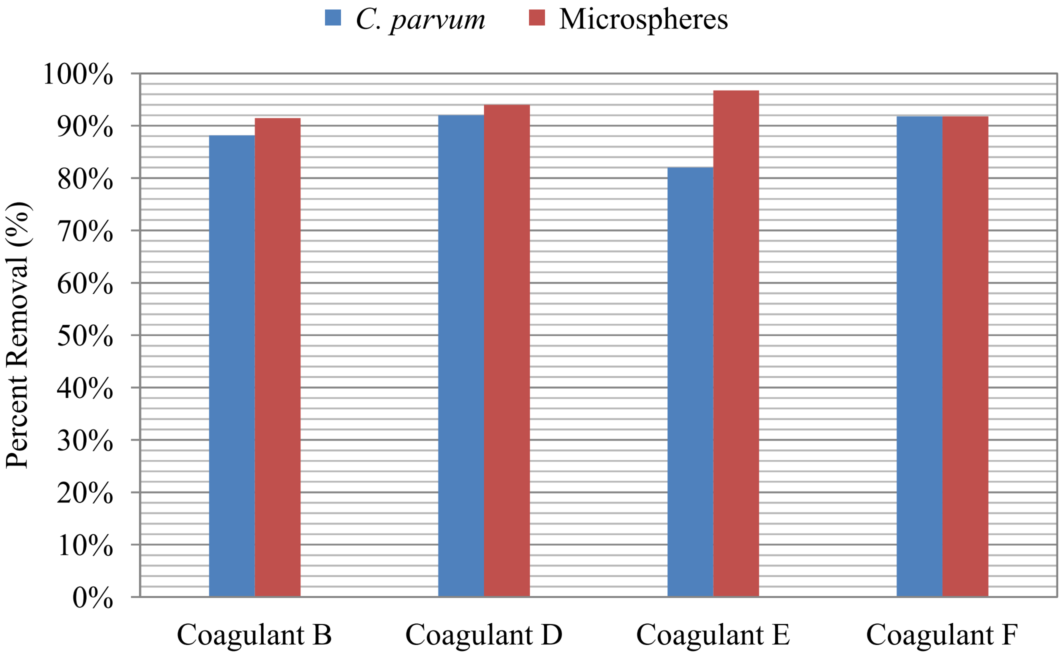


Figure 5.6 *Cryptosporidium parvum* and *Cryptosporidium*-sized Microsphere Removals with 1.56 mg/L coagulant B, 305 g/m^2 coagulant D, 1 mg/L coagulant E (0.1 mg/L as Al), 1.56 mg/L coagulant F (dosed before sample collection), SLR 34m/h (13.4 gpm/ft^2), under Remediation Condition, *Cryptosporidium parvum* and *Cryptosporidium*-sized Microspheres Concentration were 2.54 #/mL (n=1)

Figure 5.7 shows the filter effluent particle counts for coagulant B with the remediation dosage. Microspheres were fed at 0-hour, and control samples without coagulant feeding were taken at 0-hour. Samples with remediation dosage of coagulant were collected followed by backwash at 5-hour. Particle counts were high at first. Particles in 2-4 µm dominated followed by 4-6 µm for coagulant B. Figure 5.8 shows effluent particle count for coagulant D. Particle counts decreased over time. Larger particles (8-10 µm and 10-20 µm) were observed in filter effluent for coagulant D compared with coagulant B. Effluent particle counts for coagulant E is shown in Figure 5.9. Lower particle counts were observed for coagulant E compared with coagulant B and D, and microsphere removals were higher than coagulant B and D, but *Cryptosporidium* removals were not higher. Effluent particle counts for coagulant F were similar with coagulant B as shown in Figure 5.10. The peaks between 1 hr to 3 hr for coagulant B, E, and F were caused by filter backwash.

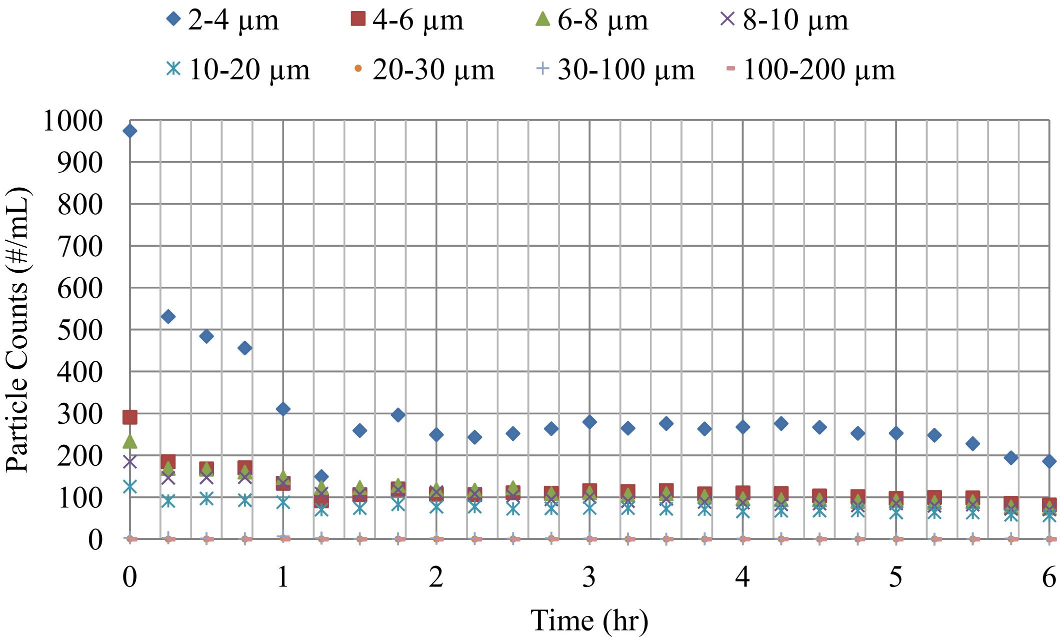


Figure 5.7 Filter Effluent Particle Count with 1.56 mg/L coagulant B, SLR 34 m/h (13.4 gpm/ft^2), under Control (0-1 hr) and Remediation (5-6 hr) Condition

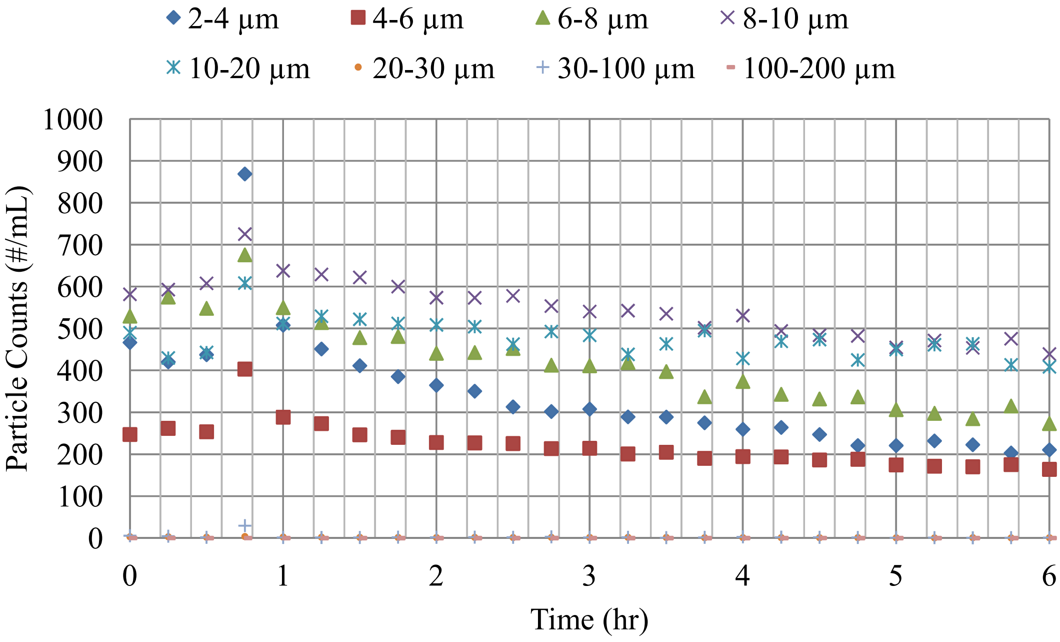


Figure 5.8 Filter Effluent Particle Count with 305 g/m^2 coagulant D, SLR 34 m/h (13.4 gpm/ft^2), under Control (0-1 hr) and Remediation (5-6 hr) Condition

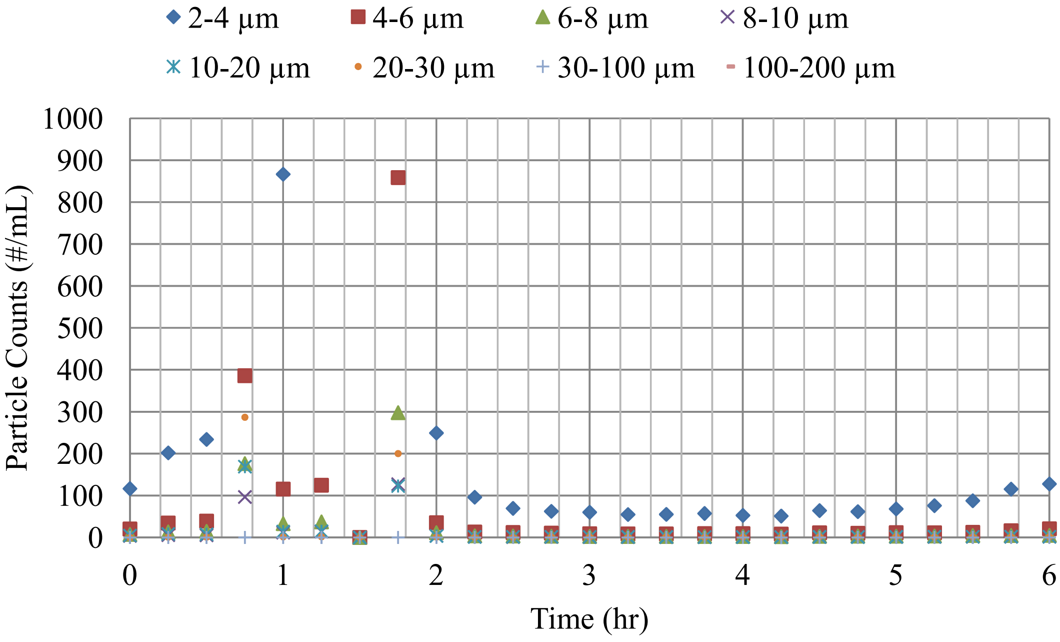


Figure 5.9 Filter Effluent Particle Count with 0.1 mg/L (as Al) coagulant E, SLR 34 m/h (13.4 gpm/ft^2), under Control (0-1 hr) and Remediation (5-6 hr) Condition

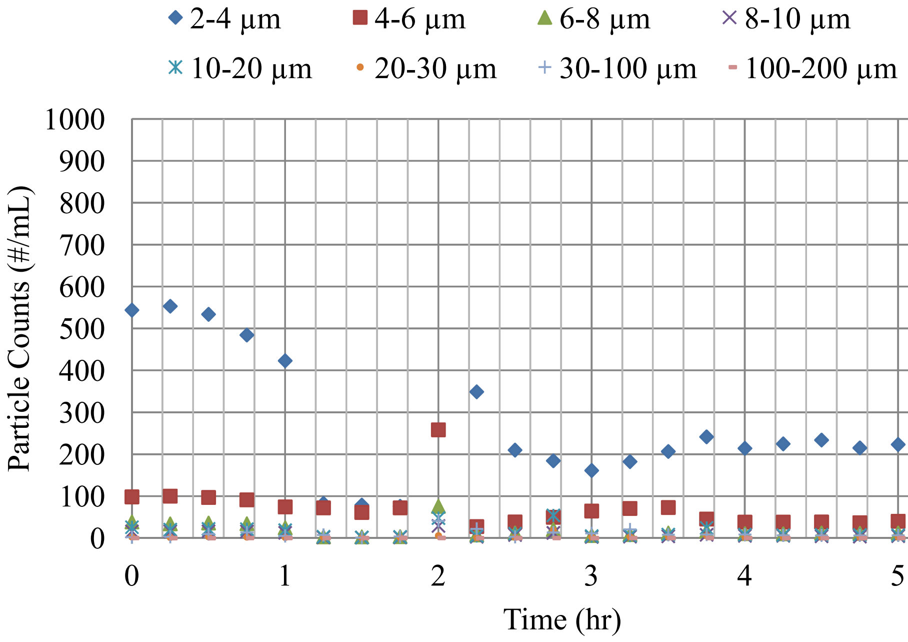


Figure 5.10 Filter Effluent Particle Count with 1.56 mg/L coagulant F, SLR 34 m/h (13.4 gpm/ft^2), under Control (0-1 hr) and Remediation (5-6 hr) Condition

5.3.1.3 Filtration with Coagulants of Maintenance Dosage and Overdose

Cryptosporidium and *Cryptosporidium*-sized microsphere were fed over 1 hr at a concentration of 2.54 #/mL prior to sample collections. Coagulation is a primary processing step used to hasten the agglomeration of fine particles in turbidity (Edzwald and Tobiason, 1999). Four coagulants that had been proven effective for *Cryptosporidium*–sized microsphere removals in pilot-scale trials were added into separate pools as the sole coagulant and followed by high-rate sand filtration. Up to 93% (1.2 log) of *Cryptosporidium* and 77% (0.6 log) of microspheres were removed by coagulant B as shown in Figure 5.11. As high as 99% (2 log) of *Cryptosporidium* and 98% (1.7 log) of microsphere were removed with coagulant D as shown in Figure 5.12. Up to 98% (1.8 log) of *Cryptosporidium* and 93% (1.2 log) of microspheres removals were obtained with coagulant E as shown in Figure 5.13. Up to 86% (0.85 log) of *Cryptosporidium* and 82% (0.73 log) of microspheres were removed with coagulant F as shown in Figure 5.14. Coagulant D and E removed up to 99% of microspheres, which were similar to pilot-scale results (i.e., up to 99% for coagulant D and E). *Cryptosporidium* and microsphere removals were higher after filter backwash for coagulant D. Based on pilot-scale study results, removals of microspheres decreased to less than 90% when coagulant B and F was dosed at 4.68 mg/L as product, and streaming current was saturated indicated the overdose of coagulant B and F. Data were obtained under condition of overdosing coagulant B or F in this full-scale study. *Cryptosporidium* and microsphere removals in full-scale experiments were similar to pilot-scale removals for coagulant B or F, which showed *Cryptosporidium* and microspheres removals with continuous feeding coagulant decreased because of overdosing of coagulant B or F. Approximate 74% of (26 out of 35) *Cryptosporidium* removals were higher than microsphere removals (as shown in Figure 5.5 to Figure 5.14). Twenty six percent of (9 out of 35) *Cryptosporidium* removals were lower than microsphere removals. Microspheres are a conservative surrogate in most cases (74%).

Streaming current increased with coagulant accumulation in the pools. CCA values for coagulant B are shown in Figure 5.11. CCA values increased at the end because the coagulant was dosed at 5 times faster than the normal rate (0.78 mg/L per turnover versus 0.156 mg/L per turnover). A significant increase of CCA values for coagulants D, E, and F was also obtained at the end of each experiment as shown in Figure 5.12, 5.13, and 5.14. However, CCA values did not appear to be a good indicator of the coagulants performance under these experimental conditions.

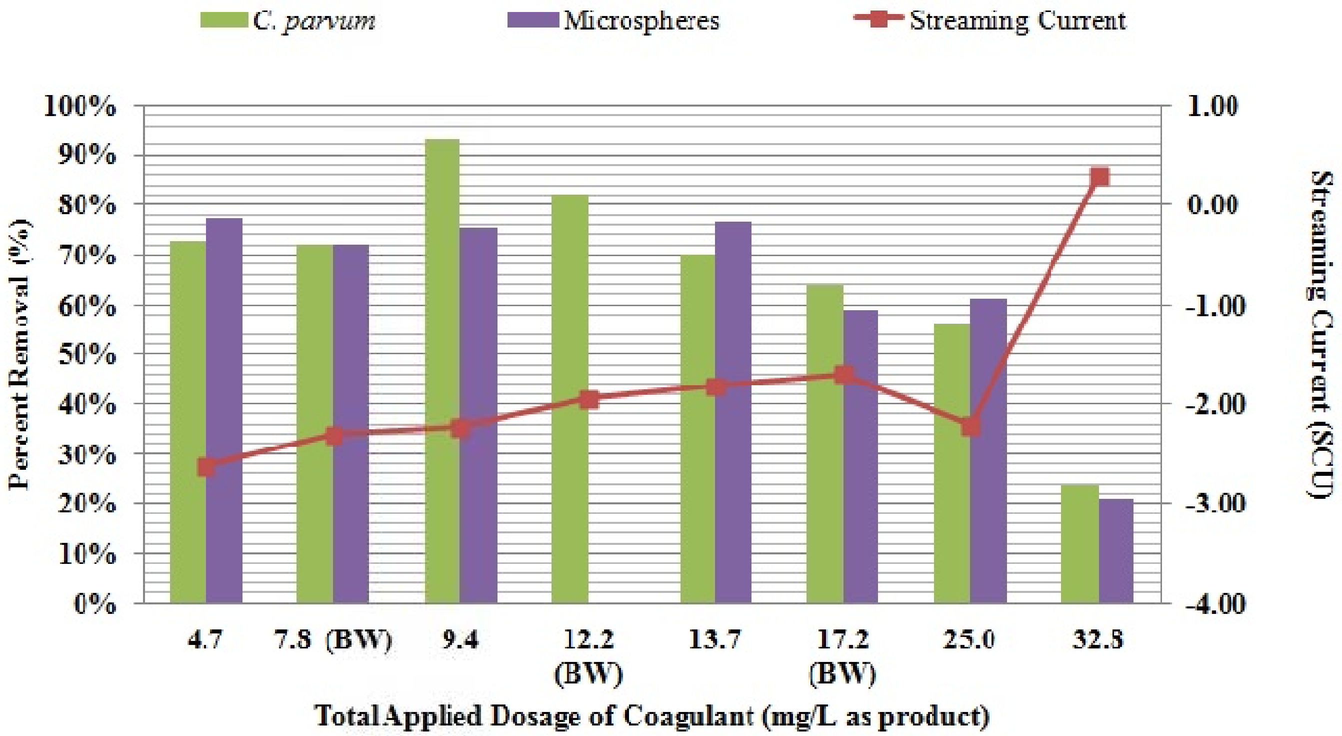


Figure 5.11 *Cryptosporidium Parvum* and Microsphere Removals (2.54 #/mL) with 0.16 mg/L coagulant B per turnover, SLR 29-34 m/h (11.3-13.4 gpm/ft^2), under Maintenance and Overdose Condition over 22 Days (n=1)

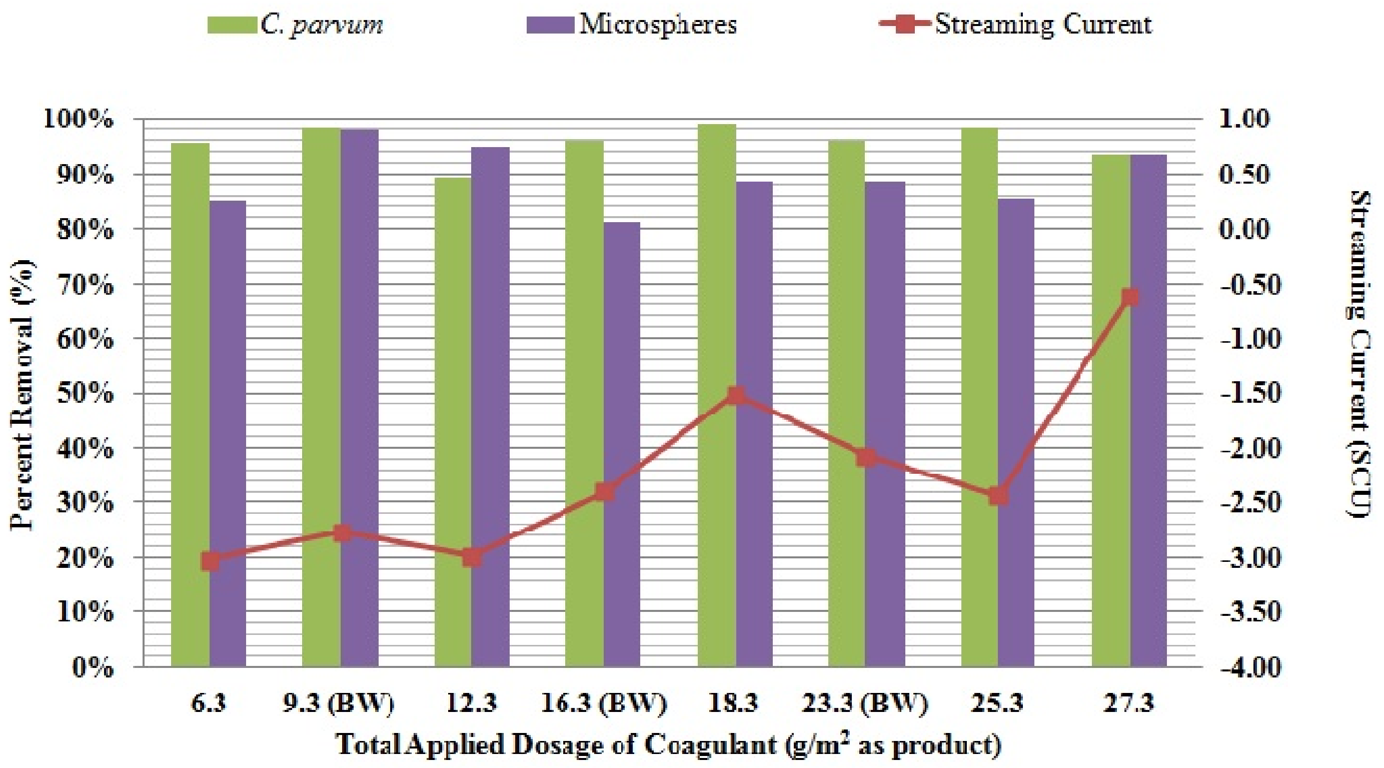


Figure 5.12 *Cryptosporidium Parvum* and Microsphere Removals (2.54 #/mL) with 305 g/m^2 coagulant D (dosed very week), SLR 26-34 m/h (10-13.4 gpm/ft^2), under Maintenance and Overdose Condition over 22 Days (n=1)

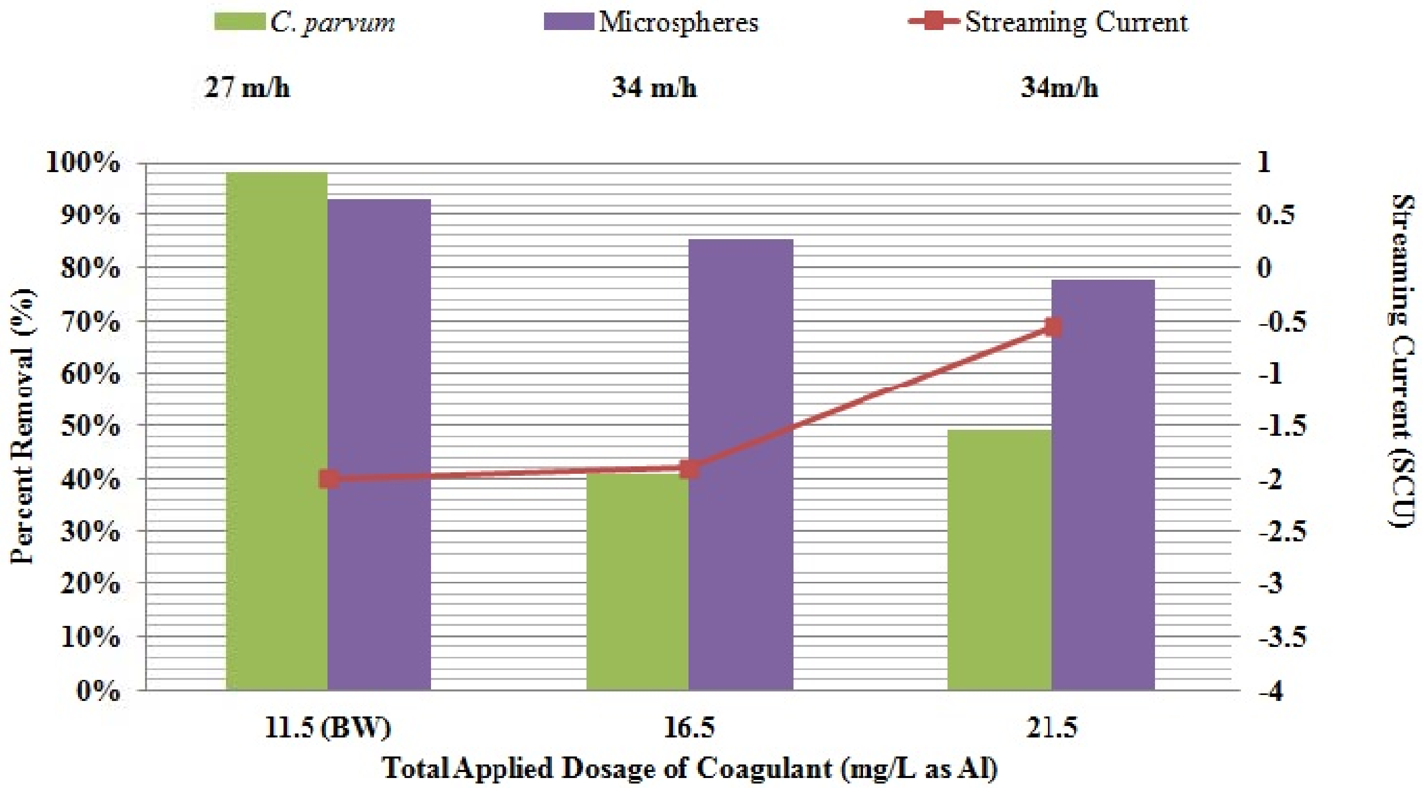


Figure 5.13 *Cryptosporidium Parvum* and Microsphere Removals (2.54 #/mL) with 1 mg/L coagulant E (0.1 mg/L as Al) per turnover, SLR 27- 34 m/h (11-13 gpm/ft^2), under Maintenance and Overdose Condition over 22 Days (n=1)

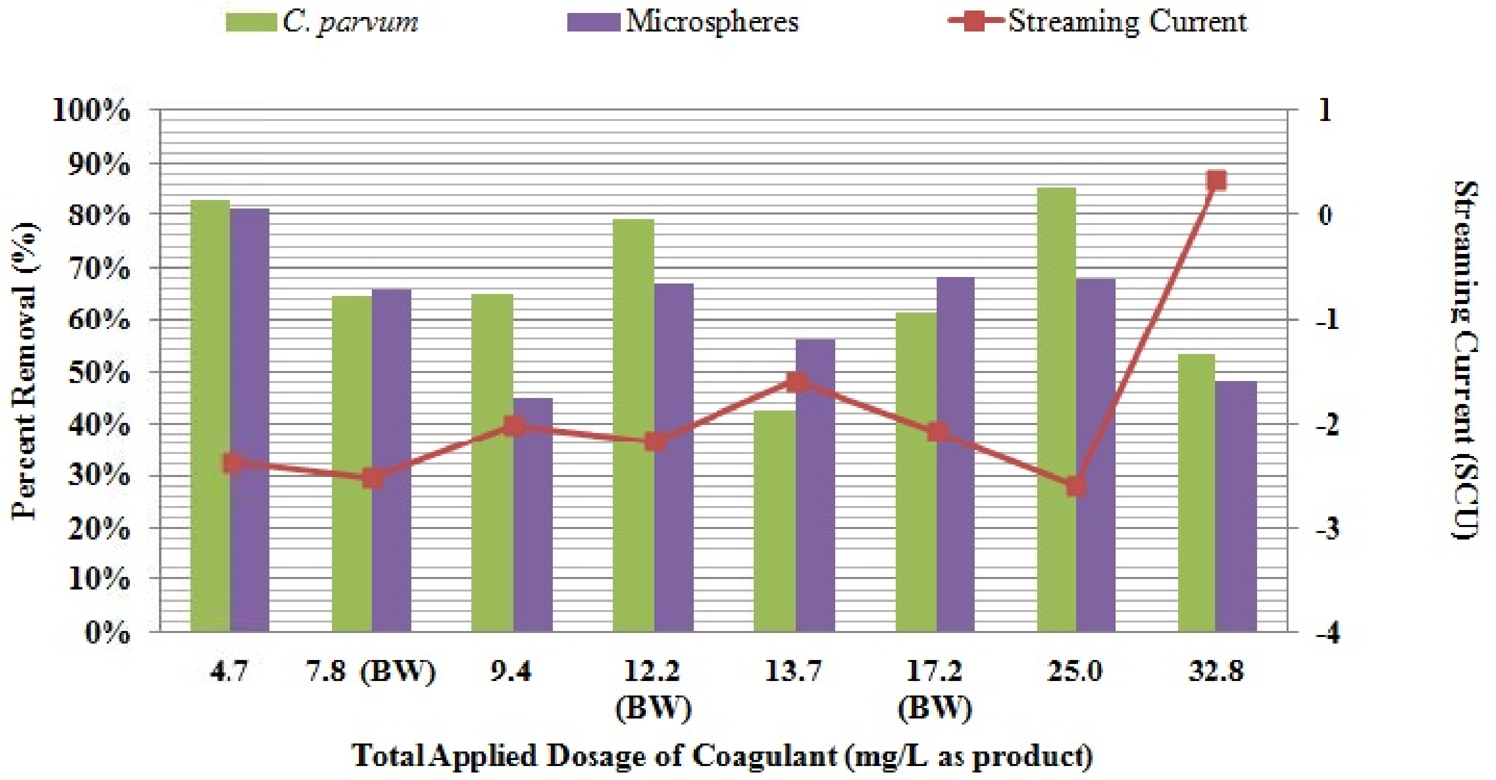


Figure 5.14 *Cryptosporidium Parvum* and Microsphere Removals (2.54 #/mL) with 0.16 mg/L coagulant F per turnover, SLR 31-34 m/h (12-13.4 gpm/ft^2), under Maintenance and Overdose Condition over 22 Days (n=1)

Figure 5.15 shows the filter effluent particle counts and removals for coagulant B with maintenance dosage and overdose. Absolute particle numbers could not represent real removals, but the trend of particle counts in one experiment could interpret the filter performance in terms of microspheres removal. Low microsphere removals correlated with high particle counts. High particle counts at the end (432 hr and 528 hr) were caused by over dosing of coagulant and corresponded decreased removals. Effluent particle counts for coagulant D is shown in Figure 5.16. Differences in particle counts were observed between pilot-scale and full-scale experiments, with higher particle concentration in full-scale experiments, since full-scale pools were outdoor pools while pilot-scale pools were indoor pools. Effluent particle counts and removals for coagulant E are shown in Figure 5.17. Overdoing coagulant led to particle counts increased significantly at the end. While removal increased after filter backwash for coagulant E (the first removal data points for microsphere and *Cryptosporidium* in Figure 5.17). Figure 5.18 shows particle counts and removals for coagulant F. Overdosing of coagulant at the end was indicated by particle counts breakup (i.e., at 432-hour for coagulant B and F). Particle counts in 2-4 μm dominated for all the four coagulants, followed by 4-6 μm.

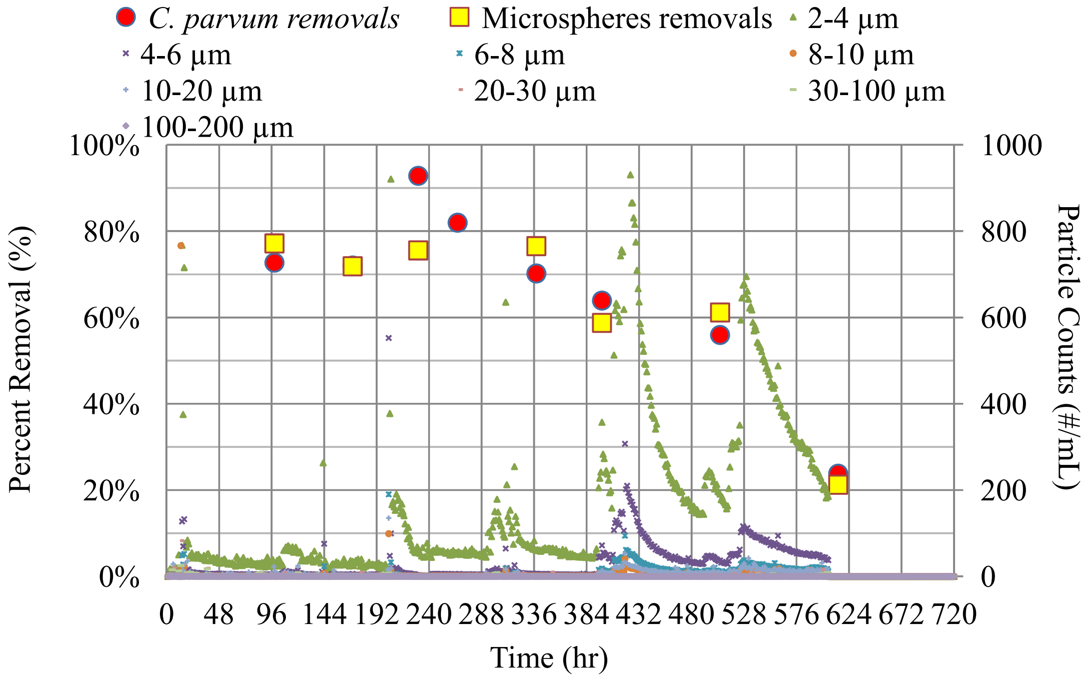


Figure 5.15 Effluent Particle Count with 0.16 mg/L coagulant B per turnover, SLR 34 m/h (13.4 gpm/ft^2), under Maintenance and Overdose Condition over 22 Days

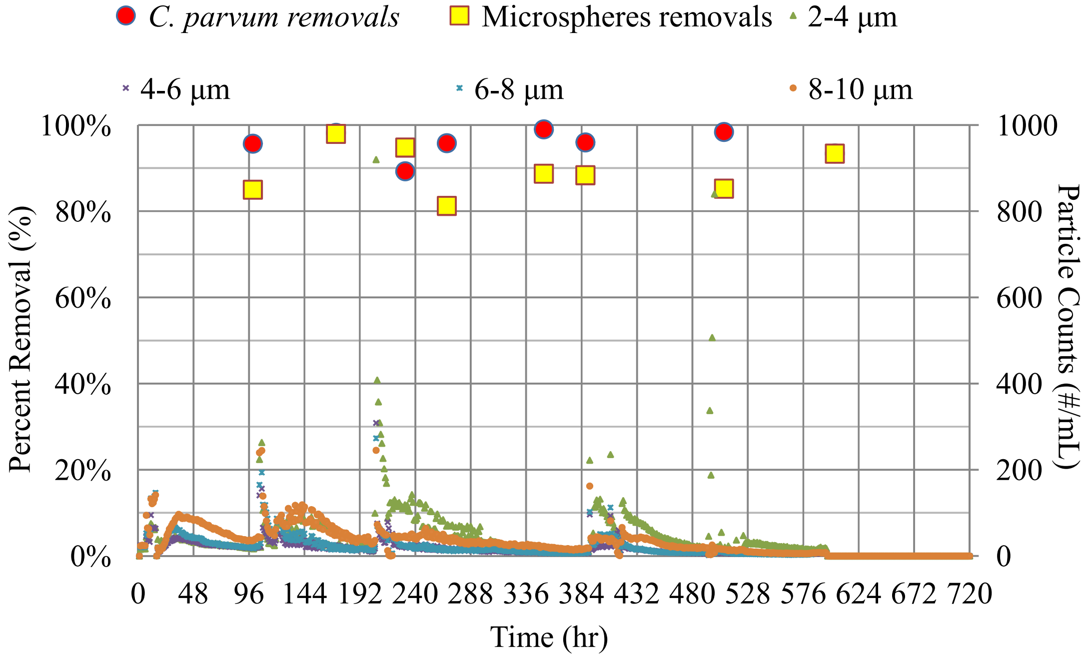


Figure 5.16 Effluent Particle Count with 305 g/m^2 coagulant D for turnover (dosed very week), SLR 34 m/h (13.4 gpm/ft^2), under Maintenance and Overdose Condition over 22 Days

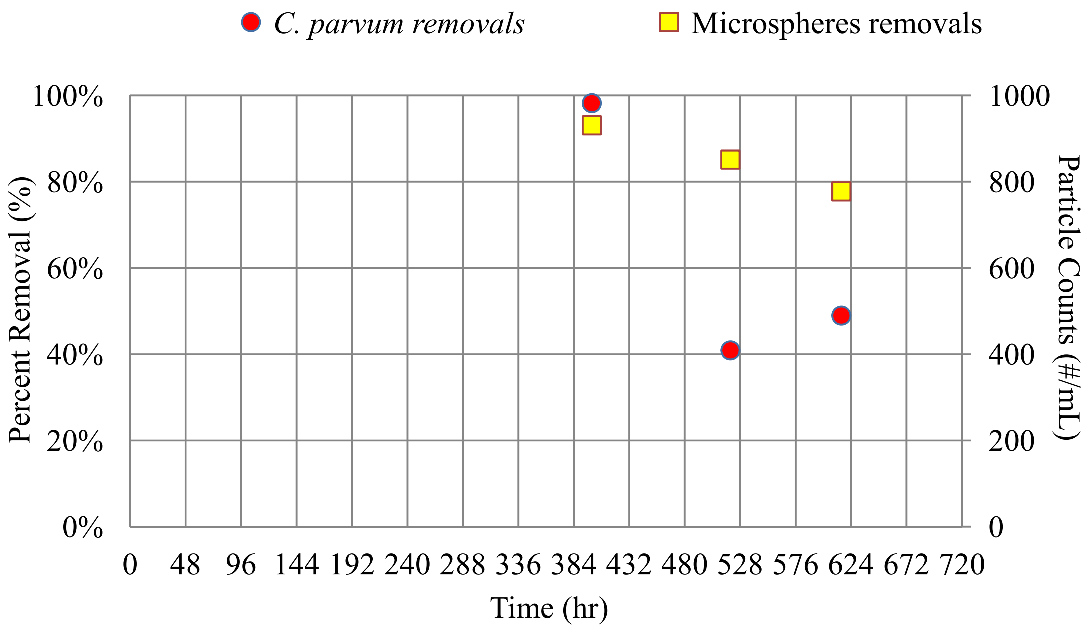


Figure 5.17 Effluent Particle Count with 1 mg/L coagulant E (0.1 mg/L as Al) per turnover, SLR 34 m/h (13.4 gpm/ft^2), under Maintenance and Overdose Condition over 22 Days

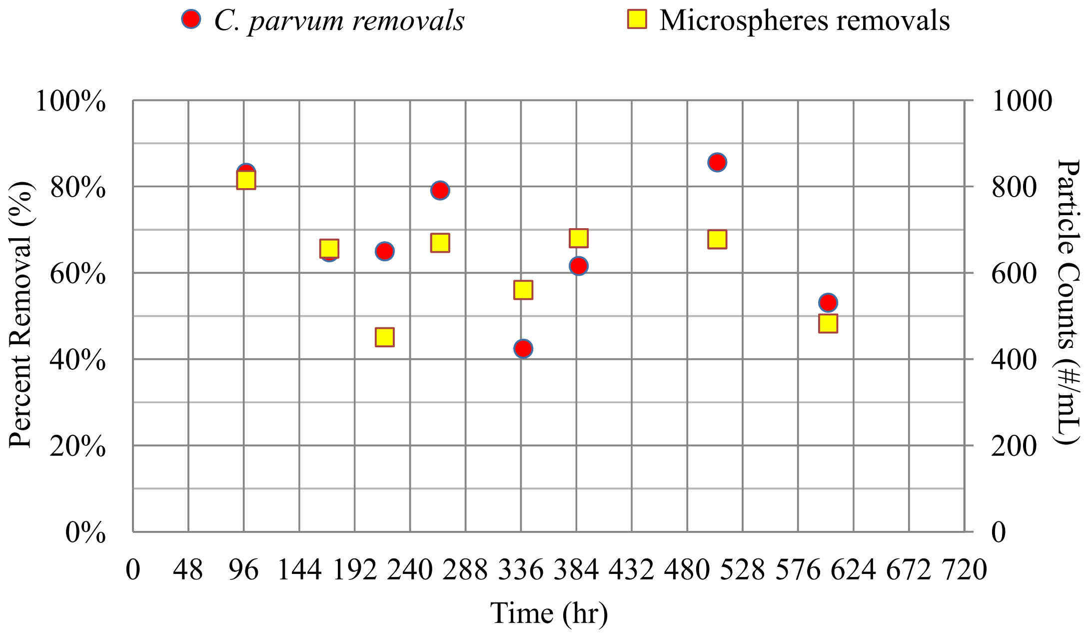


Figure 5.18 Effluent Particle Count with 0.16 mg/L coagulant F per turnover, SLR 34 m/h (13.4 gpm/ft^2), under Maintenance Condition and Overdose over 22 Days

5.3.2 Perlite/Sand Filtration

Removals of particle in suspension occurs by straining through the pores in the granular filter bed, and by sedimentation of particles while in the media pores (Betancourt and Rose, 2004). *Cryptosporidium* and *Cryptosporidium*-sized microsphere removals by a combination of fine perlite overlying sand in a filter are shown in Figure 5.19. Two samples were lost due to an unplanned backwash. Eighty eight percent (0.9 log) of *Cryptosporidium* was removed, which was lower than microsphere removals and might have resulted from influent sample variability. The measured *Cryptosporidium* concentration (of 0.08 #/mL) was more than an order of magnitude less than the average influent concentration (of 2.54 #/mL) for all of the full-scale experiments (raw data is shown in Appendix O). Effluent *Cryptosporidium* and microspheres concentrations were both < 0.001 #/mL. Microspheres removal was 99.8% (2.7 log), compared with 99.7% (2.4 log) in pilot-scale trials at 0.5 kg·perlite/m^2 (0.1 lbs·perlite/ft^2).

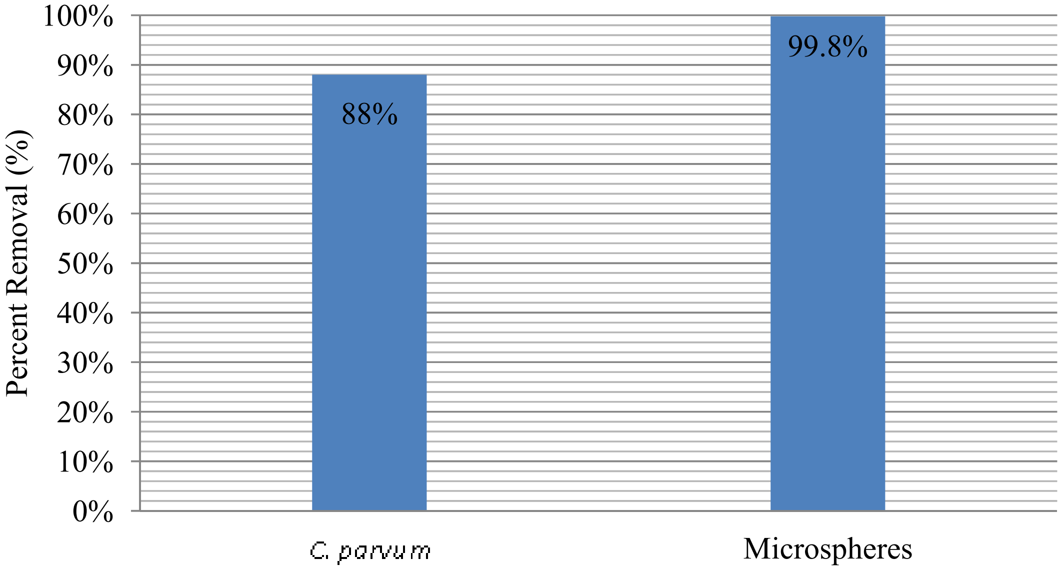


Figure 5.19 *Cryptosporidium Parvum* and Microsphere (2.54 #/mL) Removals through (0.5 kg·perlite/m^2, 0.1 lb/ft^2) Perlite/Sand Filtration at 34 m/h (13.4 gpm/ft^2) (n=1)

5.3.3 Diatomaceous Earth (DE) Filtration

Figure 5.20 displays the *Cryptosporidium parvum* and microsphere removals by DE filtration (0.7 kg·DE/m^2, and filtration rate of 3.6 m/h). Microsphere removal was more than 99.8% (2.7 log), and *Cryptosporidium parvum* removal was also above 99.8% (2.7 log), which were similar to pilot-scale removals (99.5% to 99.7% for the same amount of precoat and filtration rate, 3.6 m/h).

The filter was restarted after a 15-minute stop without flow (or a 30-minute stop without flow) to evaluate "bumping" impact on performance. The removals after bumping were not significant decreased by bumping with a 15-minute stop of DE filter with filtration rate of 3.6 m/h (1.5 gpm/ft^2). Removals both of *Cryptosporidium* and microsphere were decreased approximate less than 99.7% (2.5 log) after bumping with a 30-minute stop. Pilot-scale results showed the removals decreased from more than 99.5%

to 97% after bumping with a 30-minute stop of filter and filter was operated at 3.6 m/h. Removals obtained from full-scale were slightly higher than pilot-scale. Streaming current values (or CCA) for samples collected from perlite/sand and DE filtration experiments are shown in Figure 5.21. The streaming currents were in the range of -2.6 SCU to -1.5 SCU since no coagulant was fed.

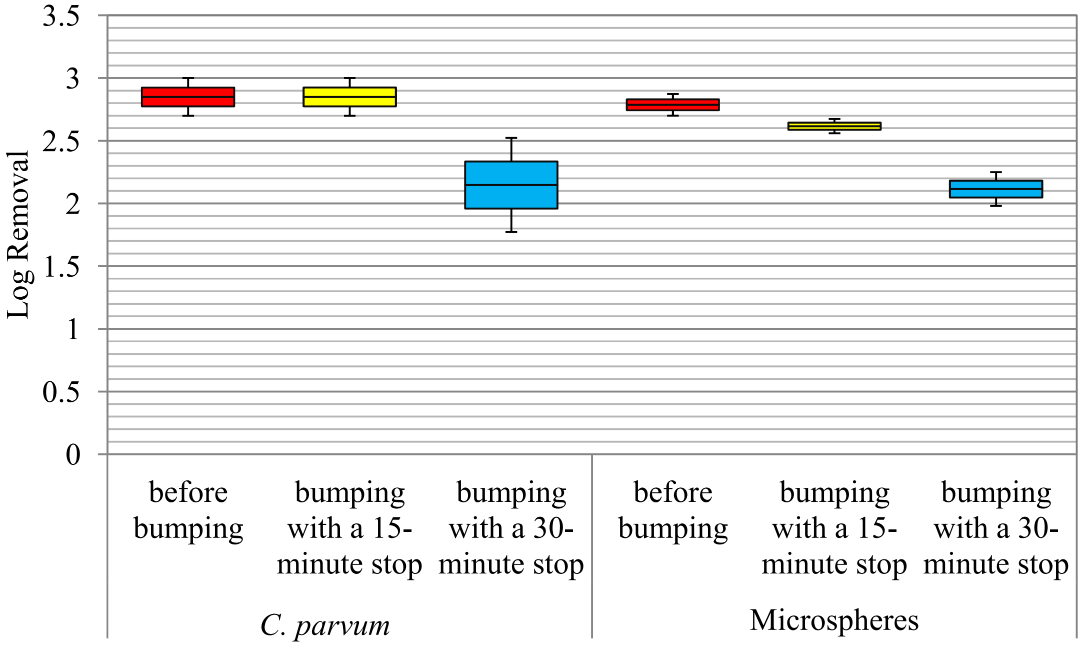


Figure 5.20 *Cryptosporidium Parvum* and Microsphere (2.56 #/mL) Removals through DE Filtration during 5 Days, 0.7 kg·DE/m^2 (0.15 lb/ft^2), SLR 3.6 m/h (1.5 gpm/ft^2) (Red color box removals by DE before bumping; Yellow color box — removals after bumping with a 15-minute filter stop; Blue color box — removals after bumping with a 30-minute filter stop) (number of experiments = 1, number of samples = 3)

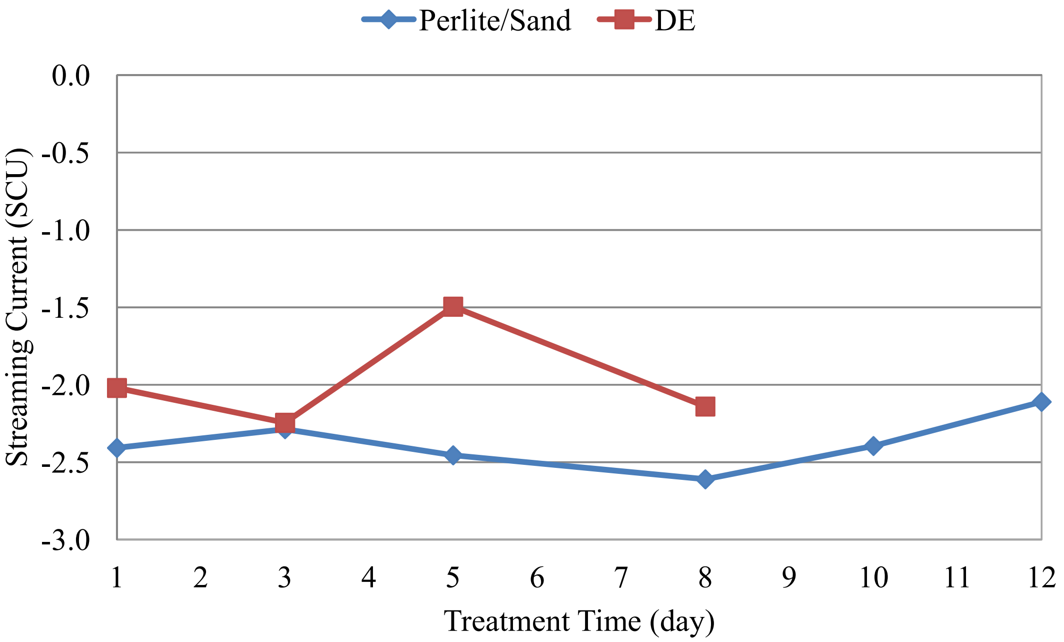


Figure 5.21 Streaming Current of Samples for Perlite/Sand and DE Filtration

5.4 Conclusions

Cryptosporidium parvum and microsphere removals from full-scale swimming pools were evaluated. The following results were obtained.

(1) Remediation dosage of coagulants

Majority of *Cryptosporidium parvum* and microspheres (approximately 90%) were removed by filtration with remediation dosage of coagulant B, D or F from swimming pool. Filtration with 0.1 mg·Al/L coagulant E achieved 82% of *Cryptosporidium* and 97% of microspheres removals.

(2) Maintenance dosage and excess dosage of coagulants

Up to 93% of (1.2 log) *Cryptosporidium* and 77% of (0.64 log) microspheres were removed with coagulant B. As high as 99% (2 log) *Cryptosporidium* and 98% (1.7 log) microspheres were removed with coagulant D. Up to 98% (1.7 log) of

Cryptosporidium and 93% (1.1 log) of microspheres were removed by coagulant E at 27 m/h. Eighty five percent of *Cryptosporidium* (0.84 log) and 82% (0.73 log) of microspheres were removed by coagulant F with maintenance dosage. Overdose conditions for coagulant B and F led to lower removals for *Cryptosporidium* and microsphere than in pilot-scale studies.

(3) Perlite/sand filtration and DE filtration

Full-Scale *Cryptosporidium parvum* removals by perlite/sand filter was 88%. Microsphere removals were 99.8%, compared with 99.7% in pilot-scale trials at 0.5 kg·perlite/m^2 (0.1 lbs·perlite /ft^2). Above 99.8% of *Cryptosporidium parvum* oocysts and microspheres were removed by DE filtration with 0.7 kg·DE/m^2 at 3.6 m/h.

Results indicated above 99% of *Cryptosporidium parvum* oocyst and/or microsphere removals were achieved by perlite/sand and DE filtration. Above 90% removals were obtained by high-rate sand filtration with coagulant D and E. Coagulants B and F had a tendency to overdose and did not consistently achieve removals greater than 90%.

CHAPTER 6: FULL-SCALE EVALUATION OF *CRYPTOSPORIDIUM*-SIZED MICROSPHERE REMOVALS FROM HOT SPA USING CARTRIDGE FILTER WITH AND WITHOUT COAGULATION

6.1 Introduction

Cartridge filters can be effective for removal of particles and natural organic matter (Wang, et al., 2008), or as pretreatment for membrane filtration (Vial and Doussau, 2002). Some unique features include: (1) compact, lightweight, easy to install, and no backwashing required; (2) more effective filtration area in a very compact system; and (3) less maintenance (Perkins, 2000). The National Sanitation Foundation (NSF) Standard for commercial pools specifies a maximum flow rate of 1.42 L/min (0.375 gallons per minute) for all cartridge filter types. Flow rates greater than 1.42 L/min (0.375 gallons per minute) through a cartridge filter reduces the filter cycle and therefore reduces filtration effectiveness (NSPF, 2009). In terms of particle size filtered out, pore size of cartridge installed in swimming spa is somewhere between sand and DE, and is usually larger than 5 µm to prevent severe clogging of the element (Perkins, 2000). Cartridges filter fabric material is used to make up the cartridge filter cells and specifically designed to trap dirt down to around 20-35 µm (from Roy Vore, NSPF®I, CPO®, 2012).

6.2 Materials and Methods

6.2.1 Research Objectives

The objectives of this chapter included evaluation of *Cryptosporidium*-sized microsphere removals from a full-scale hot spa with a cartridge filter to verify field-relevant performance with and without coagulant addition, as well the cartridge filter performance with DE.

First use of cartridge filter required adding 37 g/m^2 diatomaceous earth (DE) to enhance the filtration (PentairPools, 2008), but the actually DE added was 49 g/m^2 in this experiment. The performance with DE on removal of *Cryptosporidium*-sized microspheres was tested.

6.2.2 Experimental Setup

A 5,500 L swimming pool was built with filtration system and chemical control system. Pool water can be pumped through the cartridge filter as shown in Figure 6.1. Detailed information about the materials used in this research is listed in Appendix G. All chemicals and microspheres were fed using peristaltic or metering pumps. These sensors were connected to a controller (CAT 5000, Poolcomm, Rockville, MD, USA) for monitoring and chemical feed control. Coagulants and microspheres were fed into the pipe ahead of the pump and pre-filtration for a rapid coagulant mixing. Streaming current meter (Micrometrix, Suwanee, Georgia, USA) was installed in sample influent line to measure the surface charge of the water. Turbidimeters (HF scientific, Fort Myers, Florida, USA), particle counters (Chemtrac, Norcross, Georgia), UV transmission monitor (HF scientific, Fort Myers, Florida, USA, and Real Tech INC, Canada) were installed both on filter influent and effluent line. On-line data can be record and download from a computer. Particle counters collect the particle size in the following range, 2 µm - 3 µm, 3 µm - 6 µm, 6 µm - 10 µm, 10 µm - 20 µm, 20 µm - 50 µm, 50 µm - 100 µm, and the total particles from 2 µm to 100 µm.

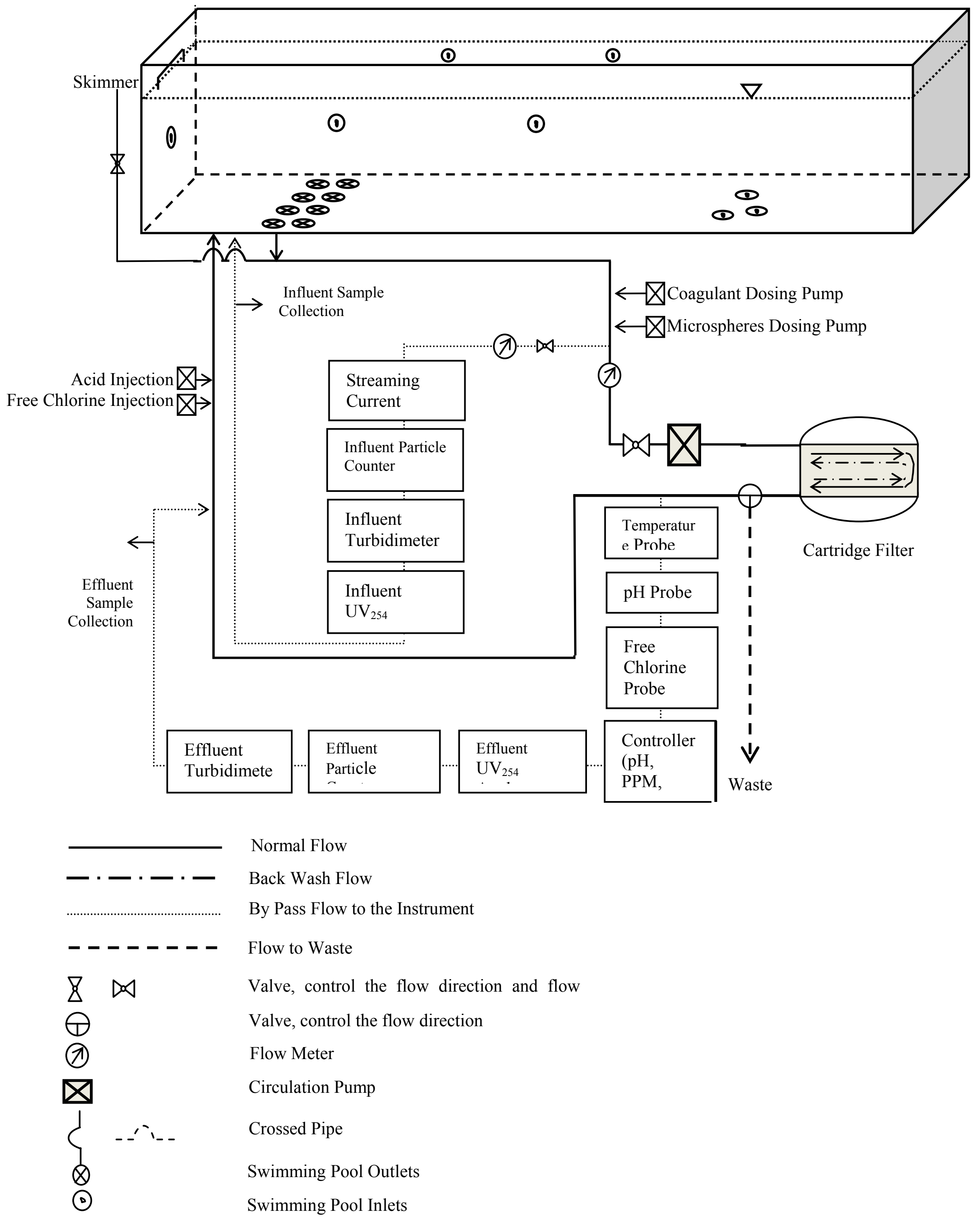


Figure 6.1 Experiment Set-up

6.2.3 Synthetic Pool Water

The synthetic pool water was generated based on previous swimming pool water quality investigation. Approximate of 5,500 L of Charlotte, NC tap water with total organic carbon (TOC) of 1 mg/L was supplemented with $NaHSO_4$ to pH 7.5, $CaCl_2$ to hardness 200 mg/L, $NaHCO_3$ to alkalinity 100 mg/L, $Ca(OCl)_2$ to chlorine 2 mg/L, to adjust pool water chemical characteristic (pH Minus, Calcium Plus, Alkalinity Plus, and TurboShock Treatment, Lonza POOLIFE®, Norwalk, Connecticut, USA).

6.2.4 *Cryptosporidium*-sized Polystyrene Microspheres

The use of polystyrene microspheres as an oocyst surrogate has been done by multiple researchers, and it was used in this study (Amburgey, 2002; Amburgey, et al., 2004; Amburgey, et al., 2005; Brown and Emelko, 2009; Dai and Hozalski, 2003; Emelko and Huck, 2003; Emelko, et al., 2005; Li, et al., 1997). Microspheres with diameter of 4.5 μm were used as the surrogate (Fluorsebrite™ Carboxylate YG 4.5 micron microspheres, Cat. #16592, Polysciences, Inc., Warrington, Pennsylvania, USA). The concentration of stock was 4.37×10^{11} #/L. The diluted solution with microspheres concentration of 4.37×10^{8} #/L was prepared by 1 to 1,000 dilutions of stock solution. Approximately 1.0×10^{7} *Cryptosporidium*-sized microspheres were used for each sample period during experiments. Microsphere samples were mixed by vortexing and hand shaking for at least two minutes each before analyzing. Samples were assay for microsphere by passing through 3.0 μm pore size polycarbonate filters (Product # K30CP02500, GE Osmonics, Minnetonka, Minnesota, USA). Each polycarbonate filter was mounted on a glass microscope slide (Gold Seal® Product # 3058, Erie Scientific Corp., Portsmouth, New Hampshire, USA) with a polyvinyl alcohol-DABCO solution, covered with a glass cover slip (25-mm square, No. 1.5, Corning, Inc., Corning, New York, USA) and counter under an epifluorescence microscope (Zeiss Standard 25 microscope, Carl Zeiss MicroImaging, LLC, Thornwood, New York, USA) (Freer, 1984). For ease of counting and to obtain statistically valid data, microscope slides needed to contain between 10 and 150 microspheres. Removal efficiency was calculated by comparing the concentrations between influent and effluent samples.

6.2.5 General Experimental Approach

Simulated spa water was heated and maintained at 38 °C, with aeration by turning on all of the jets of the swimming spa. Cartridge filter filtration rate was 0.17 L/s/m^2 (0.25 gpm/ft^2). A control experiment without DE or coagulant was conducted. Cartridge filtration with DE was performed by adding 49 g/m^2 (0.01 lbs/ft^2) DE. Coagulant B was fed at 1.56 mg/L every turnover time for total 6 turnover times (1 turnover time was 25 min). Amount of 10^7 (1.82 #/mL) microspheres were fed. Filter influent and effluent samples were taken for removal calculation. Microspheres were seeding 5 minutes before each sample collection, and the hydraulic detention time was 11 second.

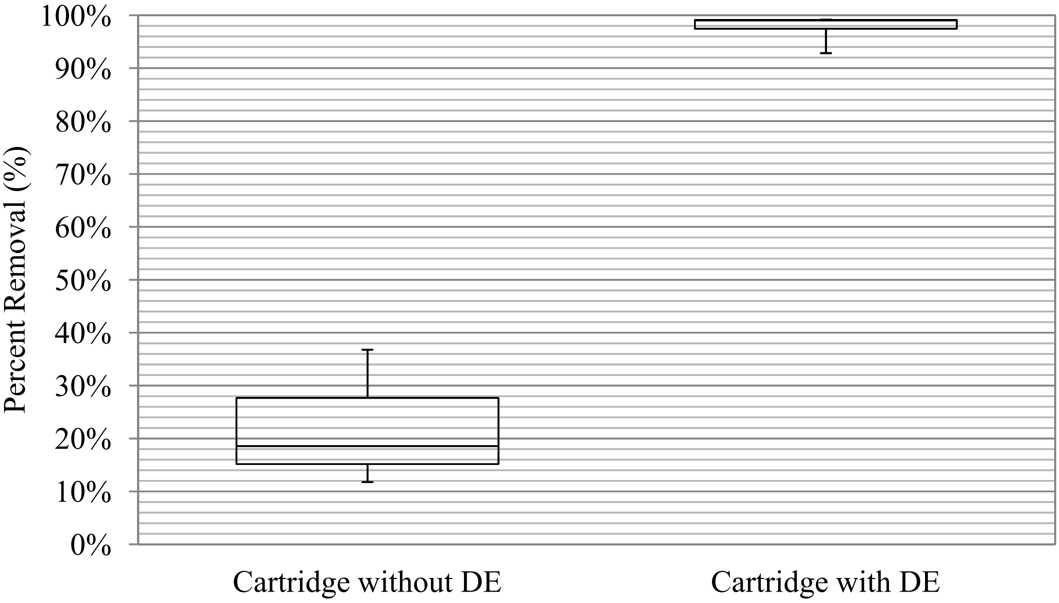
6.2.6 Quality Assurance and Quality Control

Duplicate experiments were conducted. Triplicate samples were taken for each. The swim spa was rinsed, filled, and drained with tap water at least three times between experiments to limit the amount of cross-contamination between experiments.

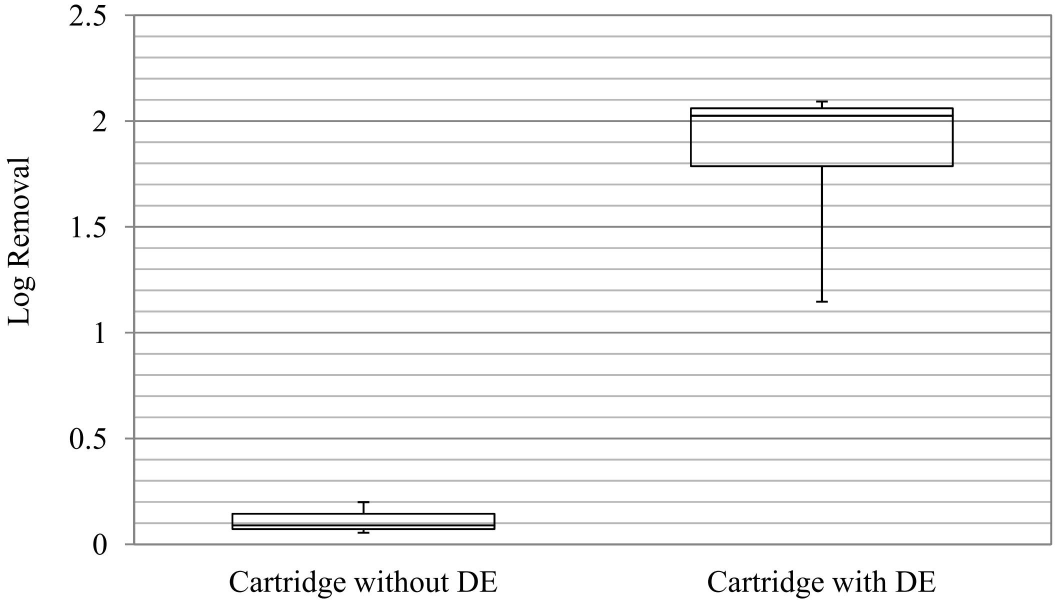
6.3 Results and Discussions

6.3.1 Cartridge Filtration with and without DE

Figure 6.2 shows the microsphere removals with and without DE addition on the surface of the cartridge filter. *Cryptosporidium*-sized microsphere removal was 22% by a cartridge filter and 98% by a cartridge filter with DE. (Raw data for microsphere removals from full-scale spa are shown in Appendix P.)



(a. Percent Removal)



(b. Log Removal)

Figure 6.2 *Cryptosporidium*-sized Microsphere (1.8 #/mL) Removals by Cartridge Filter with and without 49 g/m^2 (0.01 lbs/ft^2) DE Addition, 0.63 m/h (0.25 gpm/ft^2) (number of experiments = 2, number of samples = 3)

6.3.2 Cartridge Filtration with Coagulation

Figure 6.3 illustrates the removals at each turnover with coagulation. The *Cryptosporidium*-sized microsphere removals were up to 88% by coagulation compared to 22% with no coagulation prior cartridge filtration. The same coagulant applied in high-rate sand filtration achieved 99% *Cryptosporidium*-sized microspheres removal at room temperature (25 °C).

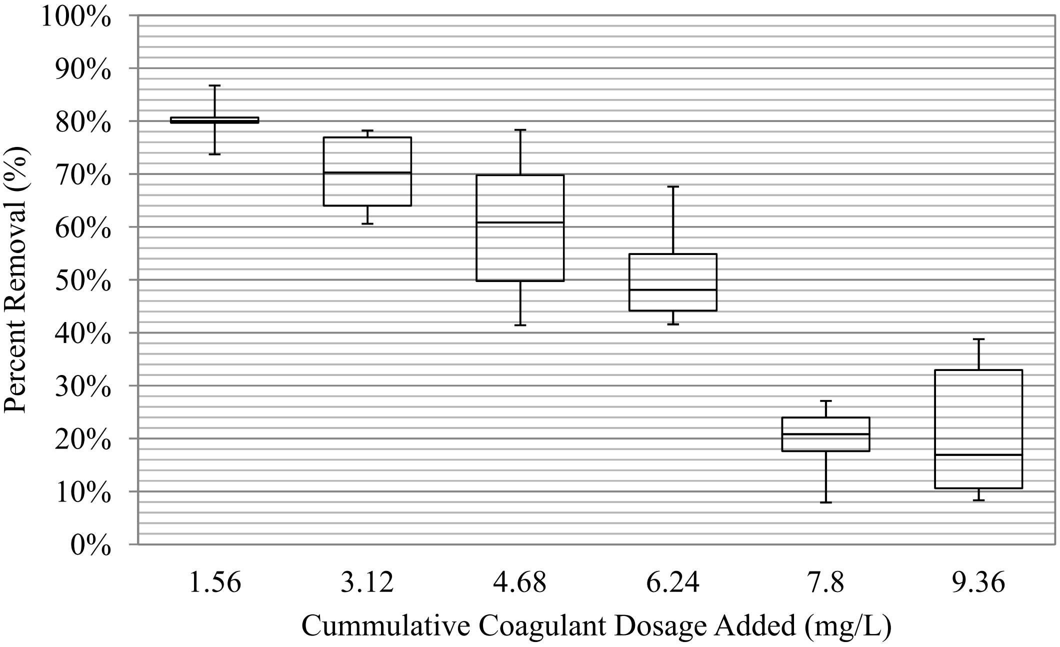


Figure 6.3 *Cryptosporidium*-sized Microsphere (1.8 #/mL) Removals by Cartridge Filter with 1.56 mg/L Coagulant B, 0.63 m/h (0.25 gpm/ft^2) (number of experiments = 2, number of samples = 3)

Filter influent and effluent particle counts were monitored and are shown in Figures 6.4 and 6.5. Total particle counts (from 2-100 μm) are shown as the light blue line at the top, among which, particles in the 3-6 μm range dominated, followed by 2-3 μm, 6-10 μm and 10-20 μm. Influent and effluent particle counts in 2-100 μm and

3-6 µm are shown in Figure 6 and Figure 7. Effluent particle counts were only lower than influent particle counts both in the first 25 min by comparing the influent and effluent particle counts in 2-100 µm and 3-6 µm ranges. The particle counts data was helpful to interpret the low removals obtained.

Figure 6.8 shows the turbidity data for cartrideg filter. Turbidity was in the range of 0.04 NTU to 0.06 NTU. The peaks for particle counts were microsphere seeding events. Microspheres were seeding 5 mins for each sample trial, and hydraulic detention time was 11 second. Turnover time of the pool was 25 mins treated by cartridge filter at 147 m/h (13.6 m^3/h or 60 gallon per minute).

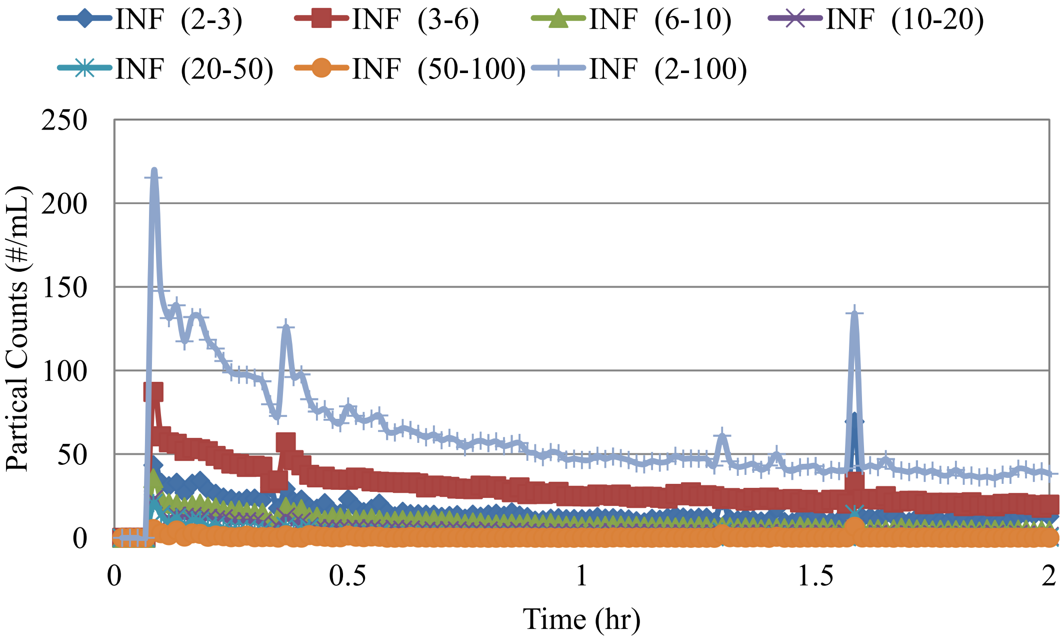


Figure 6.4 Filter Influent Particle Counts Variation over Time, 1.8 #/mL *Cryptosporidium*-sized Microspheres, 1.56 mg/L Coagulant B, 0.63 m/h (0.25 gpm/ft^2)

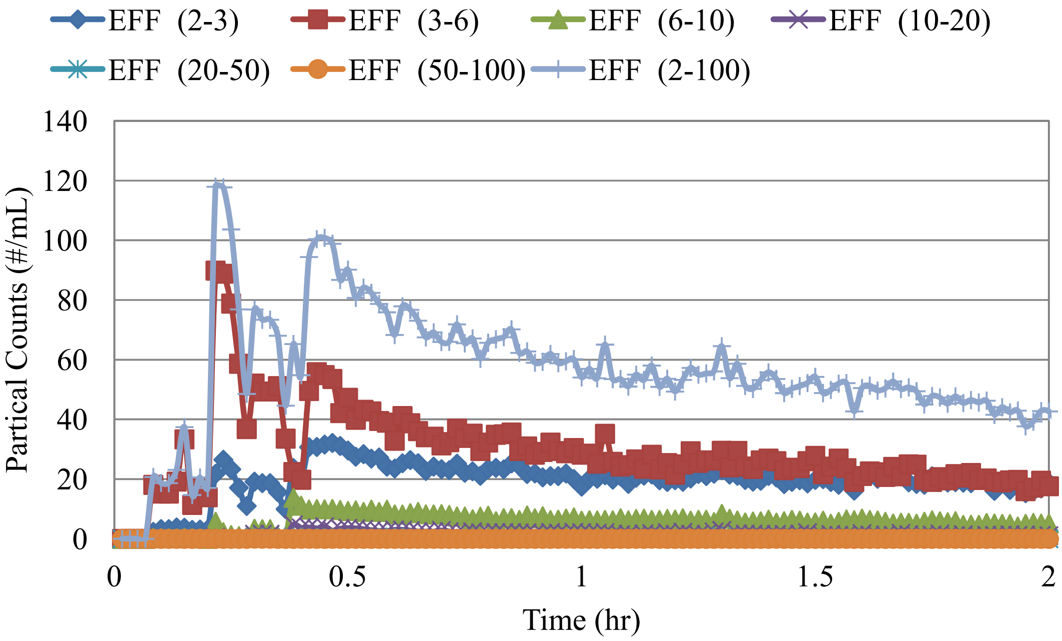


Figure 6.5 Filter Effluent Particle Counts Variation over Time, 1.8 #/mL *Cryptosporidium*-sized Microspheres, 1.56 mg/L Coagulant B, 0.63 m/h (0.25 gpm/ft^2)

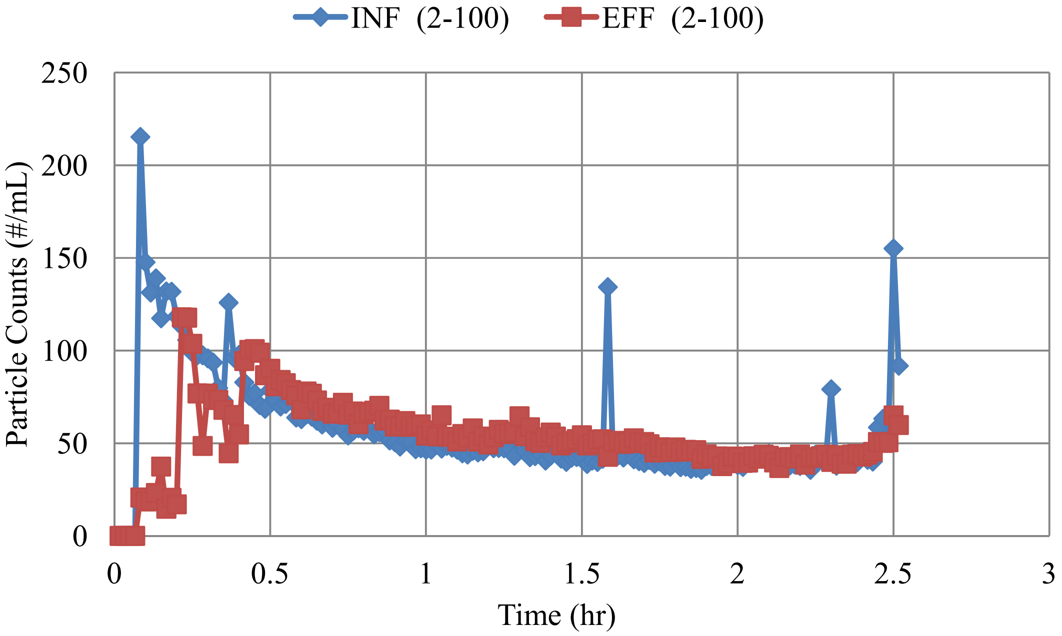


Figure 6.6 Total Filter Influent and Effluent Particle Counts (2-100 µm) Variation over Time, 1.8 #/mL *Cryptosporidium*-sized Microspheres, 1.56 mg/L Coagulant B, 0.63 m/h (0.25 gpm/ft^2)

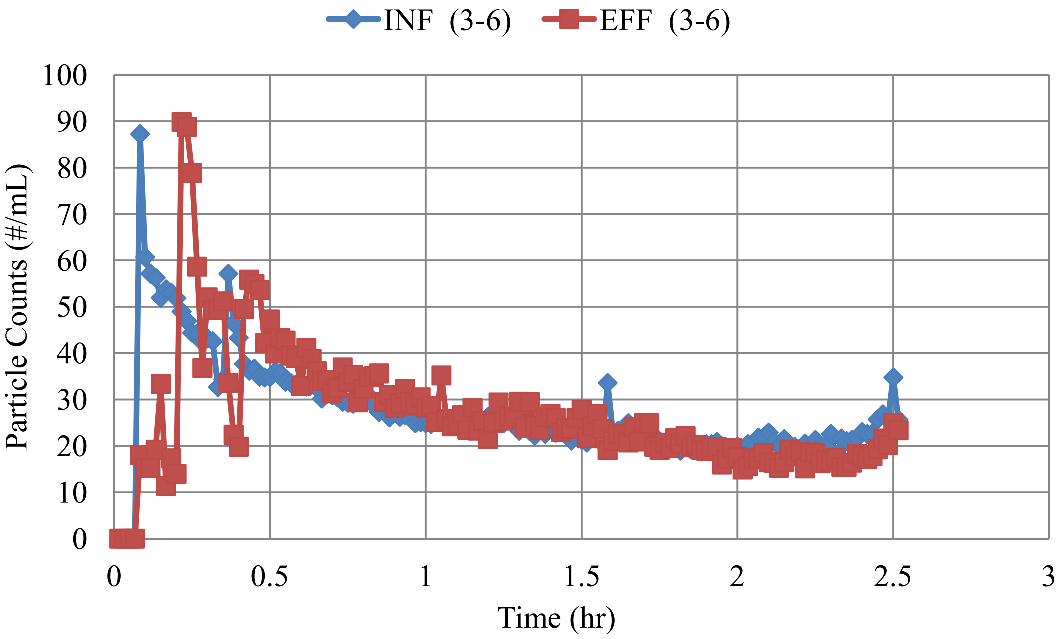


Figure 6.7 Filter Influent and Effluent Particle Counts (3-6 μm) Variation over Time, 1.8 #/mL *Cryptosporidium*-sized Microspheres, 1.56 mg/L Coagulant B, 0.63 m/h (0.25 gpm/ft^2)

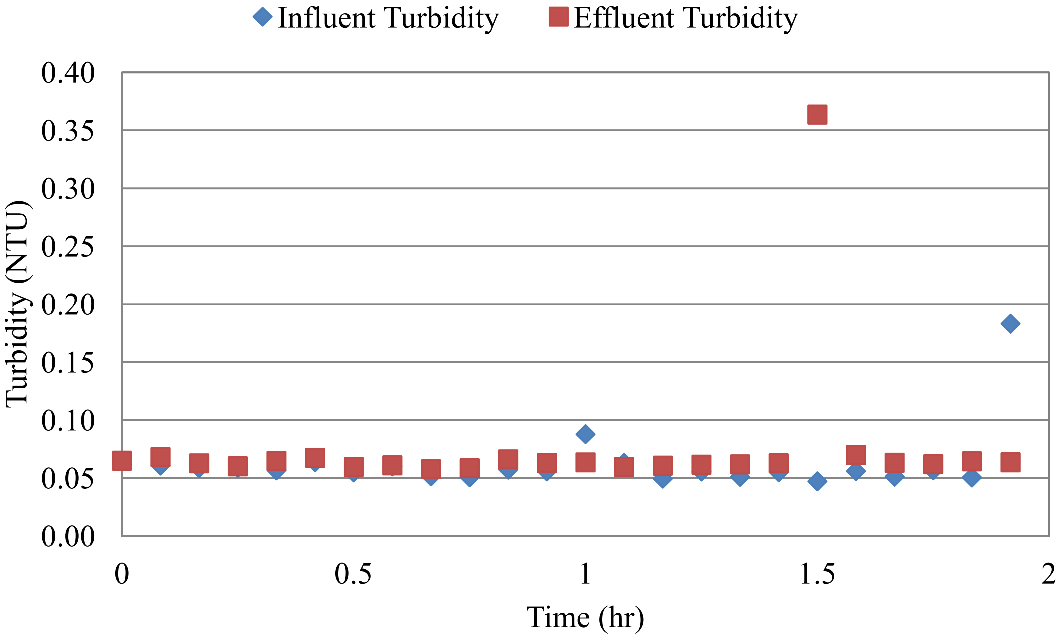


Figure 6.8 Turbidity of Filter Influent and Effluent Variation over Time, 1.8 #/mL *Cryptosporidium*-sized Microspheres, 1.56 mg/L Coagulant B, 0.63 m/hr 0.25 gpm/ft^2

Streaming current increased over time with coagulant feeding (Figure 6.9), which was similar to the pilot-scale experiments. The raw water streaming current was adjusted to -200 streaming current unit (SCU), and it increased to 380 SCU, suggesting the coagulant accumulated in the spa. Influent and effluent UV_{254} transmission are shown in Figure 6.10. The raw water UV_{254} transmission was in the range of 96% to 97%. There was no significant removal of UV_{254} in this system by comparing the influent and effluent UV_{254} transmission value.

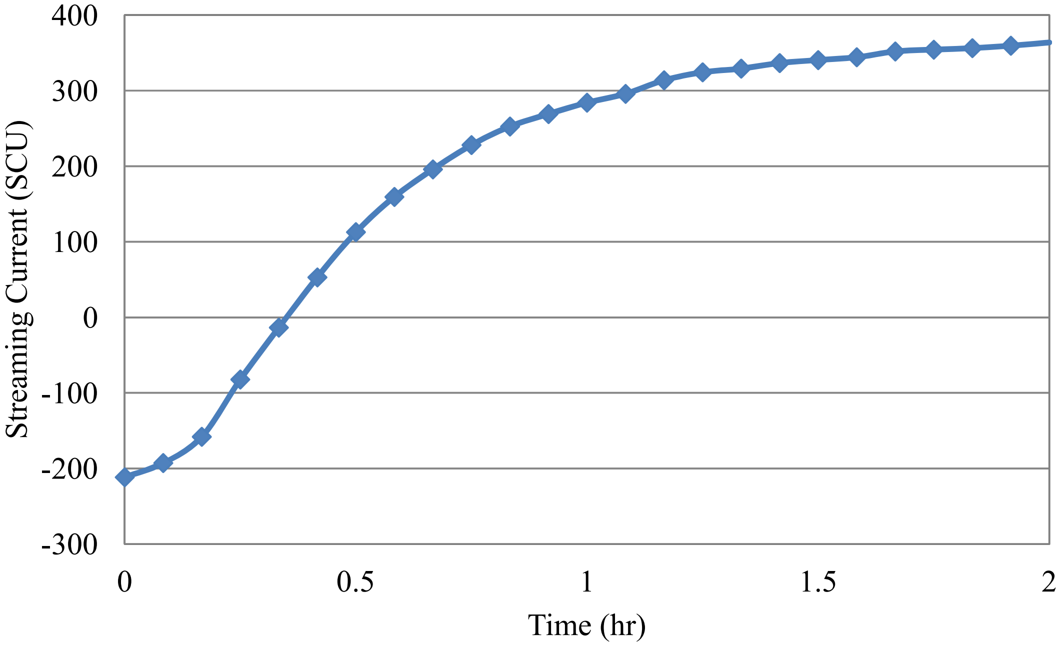


Figure 6.9 Streaming Current Variation over Time, 1.8 #/mL *Cryptosporidium*-sized Microspheres, 1.56 mg/L Coagulant B, 0.63 m/h (0.25 gpm/ft^2)

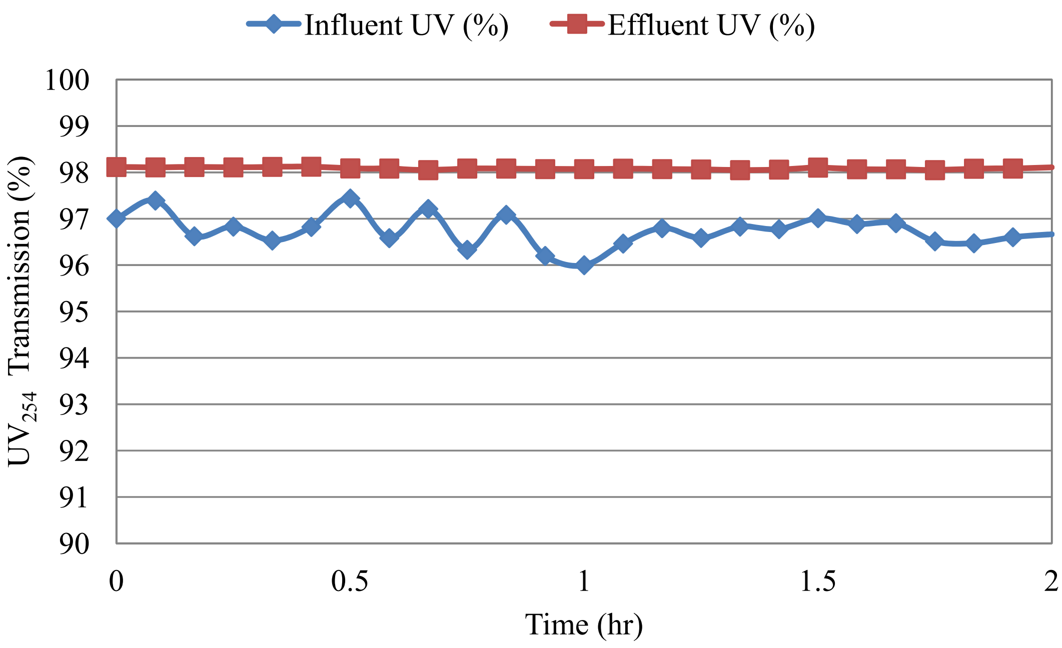


Figure 6.10 Filter Influent and Effluent UV_{254} Transmission Variation over Time, 1.8 #/mL *Cryptosporidium*-sized Microspheres, 1.56 mg/L Coagulant B, 0.63 m/h (0.25 gpm/ft^2)

6.4 Conclusions

All experiments were performed with filtration rate of 0.63 m/h (0.25 gpm/ft^2) under 38 °C with aeration. Cartridge filter could remove 22% of *Cryptosporidium*-sized microspheres. A cartridge filter with 1.1 kg DE (49 g·DE/m^2) achieved 98% microsphere removal. Coagulants B at 1.56 mg/L increased the removal up to 88% in the first 25 minutes then decreased. Streaming current increased as coagulant concentration increased. Particle counts in the 3-6 μm range dominated. Turbidity was < 0.1 NTU obtained by cartridge filter. There was no significant reduction of UV_{254} under experimental condition.

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APPENDIX A: ABSTRACT FOR EACH CHAPTER

Chapter 1

Swimming pool water samples were collected and analyzed for chemical constituents, organic matter, and particle size distributions from thirty-five swimming pools geographically distributed around the US, over the course of the spring and summer of 2010 (including both indoor and outdoor pools). Water quality varied seasonally with lower contaminant concentrations in spring compared with summer. The mean values for water chemistry parameters were, pH of 7.5, free chlorine of 1.5 mg/L, alkalinity of 94 mg/L, and hardness of 238 mg/L. The average turbidity would be 0.33 NTU, and the DOC concentration would be 5 mg/L. Based on the preceding data, three representative swimming pool waters were developed using cluster analysis, to span the range these chemical parameter commonly encountered in US swimming pools.

Chapter 2

Zeta potential titrations were conducted to evaluate six cationic coagulants for coagulation of *Cryptosporidium*-sized microsphere surrogates in three synthetic swimming pool waters. Coagulant A and B were comprised polydiallyl dimethyl ammonium chloride (polyDADMAC), coagulant C was chitosan, coagulant D was aluminum based coagulant, and coagulant E was polyaluminum chloride. Formulation of coagulant F is proprietary. Coagulants were individually titrated into three representative simulated pool water samples to develop a dose-response relationship. Results showed the zeta potential increased in the positive direction as the coagulant dose increased. No significant differences were observed for coagulant performance in different water types. Overdosing of coagulants A, B, and F were possible. Coagulant C did not behave similarly in the recommended dose range. Coagulant A, B, and F dosages between 0.5 mg/L to 3 mg/L, coagulant D dosages between 6 mg/L and 12 mg/L, and coagulant E dosages between 1 mg/L and 20 mg/L as product resulted in microsphere zeta potentials of -10 mV to 10 mV. Dissolved organic carbon (DOC) concentration did not appear to impact the zeta potential of coagulant A destabilized microspheres.

Chapter 3

Cryptosporidium outbreaks in swimming pool threaten public health. A novel evaluation procedure was developed that would produce reliable results applicable in field-relevant swimming pools. Experiments were conducted in a 5,500 L swimming pool with 30 cm dry sand. Filtration rate was 37 m/h for all the experiments. Results indicated that the maximum *Cryptosporidium*-sized microsphere removals were achieved by continuously feeding coagulant. However, extended/excessive feeding coagulant A (the only coagulant used in this part of the study) led to coagulant A build up in the system and reduced removal efficiency. Microspheres concentration impacted the system performance as higher coagulants dosages were required for higher microsphere concentrations. No significant differences in microsphere removals were observed between large sand filter and small sand filter.

Chapter 4

Cryptosporidium species are the most common cause of gastrointestinal illness in treated recreational water venues in the US. Numerous waterborne outbreaks of cryptosporidiosis have been linked to recreational waters (such as swimming pools) worldwide for several decades. *Cryptosporidium*-sized microsphere removals from a pilot-scale swimming pool through high-rate sand filtrations with six coagulants, perlite/sand filtration, and diatomaceous earth (DE) filtration were evaluated. Filter influent and effluent particle counts, turbidity, UV_{254} transmittance, pressure, and filter influent streaming current were monitored during each experiment. High-rate sand filtration results showed that up to 99% (2 log) of *Cryptosporidium*-sized microspheres were removed by filtration with coagulant A, B, D, E, and F. Continuously feeding coagulant (coagulant A, B, and F) led to coagulant accumulation in the system and further resulted in the average removal decreasing to 83% to 87% range for coagulant A, B, and F. At least 0.37 kg·perlite/m^2 for perlite/sand filtration or 0.7 kg·DE /m^2 for DE filtration were required to achieve 99% (2 log) of microsphere removals.

Chapter 5

Removals of *Cryptosporidium parvum* and *Cryptosporidium*-sized microspheres were evaluated in full-scale swimming pools through high-rate sand filtration, perlite/sand filtration, and diatomaceous earth (DE) filtration. Results showed that 90% of *Cryptosporidium parvum* and microsphere were removed by filtration with remediation dosage of coagulant B, D or F from swimming pool. Filtration with remediation dosage of coagulant E (0.1 mg·Al/L) achieved 82% of *Cryptosporidium* and 97% of microsphere removals. Coagulants B and F had a tendency to overdose and did not consistently achieve removals greater than 90%. Overdose conditions for coagulant B and F led to lower removals for *Cryptosporidium* and microsphere than in pilot-scale studies. As high as 99% of *Cryptosporidium* and 98% of microspheres were removed with maintenance dosage of coagulant D. Up to 98% (1.7 log) *Cryptosporidium* and 93% (1.1 log) of microspheres were removed by maintenance dosage of coagulant E at 27 m/h. Performance of coagulant D and E tended to decrease with increased filter pressure, which could warrant additional research. Eighty eight percent of *Cryptosporidium parvum* was removed, and 99.8% of microspheres were removed by perlite/sand filtration at 0.5 kg·perlite/m^2. Above 99.8% of *Cryptosporidium parvum* and microspheres were removed by DE filtration.

Chapter 6

Cryptosporidium-sized microsphere removals by a cartridge filter from a full-scale hot spa (38 °C) was evaluated. Results showed that 22% of *Cryptosporidium*-sized microspheres were removed by cartridge filter without coagulant. Ninety eight percent of microspheres were removed by cartridge filter with 49 g·DE/m^2. Cartridge filter with coagulation B at 1.56 mg/L per turnover achieved up to 88% removals in the first turnover (turnover time was 25 minutes) then decreased.

APPENDIX B: POOL SURVERY QUESTIONS AND RESPONSES

	Pool 1	Pool 2	Pool 3	Pool 4	Pool 5
1. Do you use a coagulant or Clarifer to Treat your pool?	No	No	No	No	
2. Filter type, Square ft, number of filters	4 high rate sand filters (Triton TR 100C) . 4.91 sq. ft.	Sand	Sand, 4.91 sq. ft., 4 filters	Defender, 1274 sq ft.	Two Sand Filters (Pressure Increase 25 on either filter
3. How do you determine when to backwash a filter (Pressure limit or time limit). List Limit	7-10 psi over starting pressure or 3 weeks	Pressure Limit	Pressure Limit (25 psi)	"Bump" the filter each night, media change once/month	Twice weekly usually 4-7 minutes after vaccuming
4. Backwash procedure and frequency.	At 7-10 psi over starting pressure or after 3 weeks at 300 gpm for 3-	Weekly at 200 gpm until water is clear.	As needed until it looks clear	N/A	
5. Oxidizer: name, dosage, and frequency.	No	No	No	No	No
6. Shock Product: name, dosage, and frequency.	No. We shock with liquid Cl over night by raising to 5 ppm Cl when combined chlorine > .5 ppm	Granular Chlorine, 1 scoop per 10,000 gallons of water when	Only use product if having trouble with controllers		Outdoor private activity pool, average depth 4 ft.
7. Discription of pool: (indoor/outdoor, lap/activity, public private, average depth.	Primarily a lap pool with Avg depth 6 ft., built in 1959, 3 ft shallow and 9 ft deep end.	Indoor, lap/activity	Swimming lessons, 4ft deep, rim flow	Indoor Activity Pool	
8. Comments (anything unique about the pool)	Use liquid chlorine and CO_2		Recently added UV	Combustion Sulfuric Acid and CO_2 for pH control, Sodium hypochlorite for	

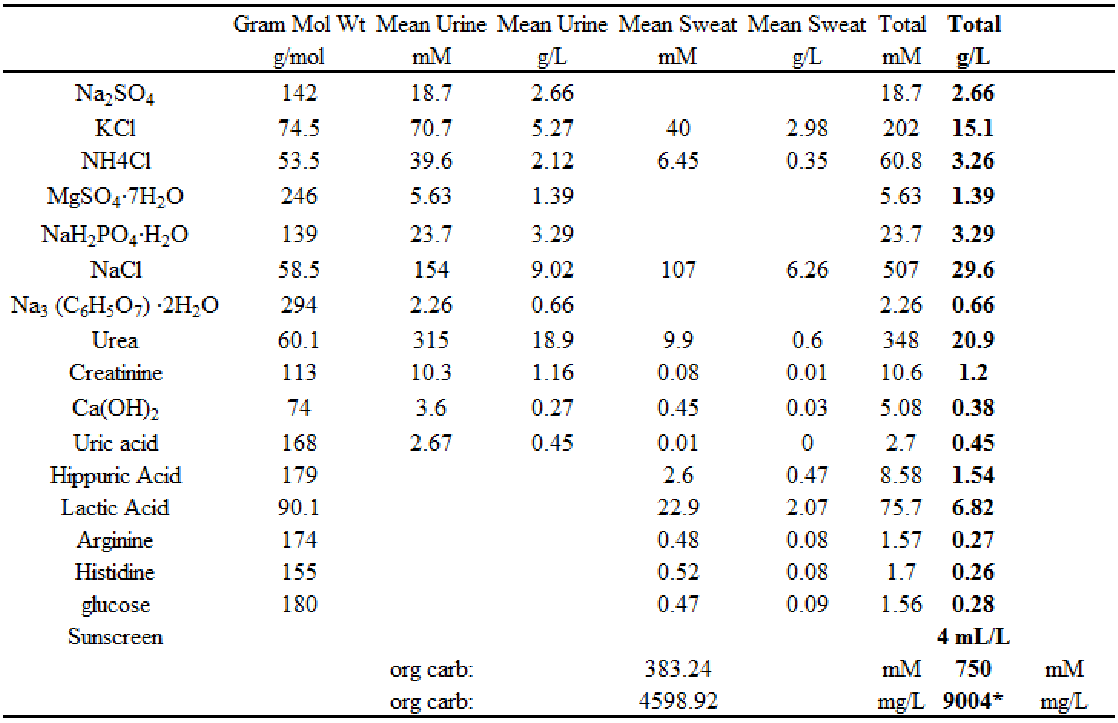
	Pool 1	Pool 2	Pool 3	Pool 4	Pool 5	Pool 6	Pool 7	Pool 8	Pool 9	Pool 10	Pool 11	Pool 12	Pool 13	Pool 14	Pool 15	Pool 16
Volume of Pool (gal)	51300	80,000	70,000	57,000	98,500	500,000	192,000	14000	17000	500,000	59	55,000	58,000	156,000	380,000	132,000
Avg. number of Swimmers (per day)	15-30	300	100	250-300	800-1000	60	125	10	40 to 50	1500	120	150	100	350	500	120
Max number of swimmers (per day)	36-48 (mostly weekends)	450	100	250-300		80	355	12	70	2200	500	400	300	400	950	240
Total Flow Rate (turnover time)	212 gpm	325 gpm	6 hr	2.5 hr	1650 gpm (1 hour turnover)	850	600	80	80	2500	650	4 hr	4 hr	5.7	1000	425 gpm

	Pool 1	Pool 2	Pool 3	Pool 4	Pool 5	Pool 6	Pool 7	Pool 8	Pool 9	Pool 10	Pool 11	Pool 12	Pool 13	Pool 14	Pool 15	Pool 16
Avg. pH	7.4	7.5	7.4	7.5	7.4	7.4	7.3	7.5	7.4	7.4	7.5	7.3	7.4	7.4	7.4	7.5
Avg. free chlorine concentration	4	2 mg/L	3 mg/L	2 mg/L	1.4 mg/L	3	2.4	2.6	3	5	2	3	3	2	3	1.5
Max free chlorine concentration	5	3 mg/L	5 mg/L	2 mg/L	1.6 mg/L	3.6	3.6	3	3.4	10	10	10	10	5	6	3
Avg. ORP reading	599	653	791 mV	590 mV	765 mV	760	813	725	700	720	790	820	750	810	650	720
Avg. water temperature	61 ^{0}F	80 ^{0}F	81 ^{0}F	89 ^{0}F	86 ^{0}F-88^{0}F	90	90	90	96	82	84	86	84	82	84	83
Avg. Hardness	150	250	370	250	310	400	1500	1000	875	350	400	600	580	500	300	260
Avg. Alkalinity	100	100	80 ppm	70 ppm	100-110	80	60	50	60	120	60	120	100	60	60	40
Avg. CYA	60	N/A	N/A	N/A	0	10	10	0	0	20	0	0	20	0	10	10
Approximate Total Dissolved Solids	0	17.5	100	?	N/A					500	1000	1000	1000	800	500	900
Amt. of fresh water added	Very little (5-10 gal)	1000 gal	1000 gal	1000-2000 gal	No way to find out	Auto Fill - it runs a lot	Auto Fill	Auto Fill	Auto Fill	50,000 gal	at 1200 gal	4,000 gal	2,000 gal	10,000 gal	35,000 gal	3,000 gal

APPENDIX C: COAGULANT CHARACTERISTIC

Coagulant	Product	Component	Molecular Formula
Coagulant A	Robarb Super Blue	Polydiallyl Dimethyl Ammonium Chloride (polyDADMAC)	$(C_8H_{16}NCl)_n$
Coagulant B	Polysheen Blue	polyDADMAC	$(C_8H_{16}NCl)_n$
Coagulant C	PRS-I	Chitosan	$(C_6H_{11}O_4N)_n$
Coagulant D	Poly-A	Sulfatodialuminum Disulfate Tetradecahydrate (aluminum-based)	N/A
Coagulant E	Kemira's PAX-18	Polyaluminum Chloride (PACl)	N/A
Coagulant F	*Cryptosporidium* Removal System	N/A	N/A

APPENDIX D: BODY FLUID ANALOGUE SOLUTION RECIPE



	Gram Mol Wt g/mol	Mean Urine mM	Mean Urine g/L	Mean Sweat mM	Mean Sweat g/L	Total mM	**Total g/L**	
Na_2SO_4	142	18.7	2.66			18.7	**2.66**	
KCl	74.5	70.7	5.27	40	2.98	202	**15.1**	
NH4Cl	53.5	39.6	2.12	6.45	0.35	60.8	**3.26**	
$MgSO_4 \cdot 7H_2O$	246	5.63	1.39			5.63	**1.39**	
$NaH_2PO_4 \cdot H_2O$	139	23.7	3.29			23.7	**3.29**	
NaCl	58.5	154	9.02	107	6.26	507	**29.6**	
$Na_3\ (C_6H_5O_7) \cdot 2H_2O$	294	2.26	0.66			2.26	**0.66**	
Urea	60.1	315	18.9	9.9	0.6	348	**20.9**	
Creatinine	113	10.3	1.16	0.08	0.01	10.6	**1.2**	
$Ca(OH)_2$	74	3.6	0.27	0.45	0.03	5.08	**0.38**	
Uric acid	168	2.67	0.45	0.01	0	2.7	**0.45**	
Hippuric Acid	179			2.6	0.47	8.58	**1.54**	
Lactic Acid	90.1			22.9	2.07	75.7	**6.82**	
Arginine	174			0.48	0.08	1.57	**0.27**	
Histidine	155			0.52	0.08	1.7	**0.26**	
glucose	180			0.47	0.09	1.56	**0.28**	
Sunscreen							**4 mL/L**	
		org carb:		383.24		mM	**750**	mM
		org carb:		4598.92		mg/L	**9004***	mg/L

*Calculated TOC concentration, 4 mg/L TOC was obtained by 1:2250 dilutions.

APPENDIX E: CHEMICAL CHARACTERISTIC OF EXPERIMENT WATER SAMPLES

Water Type	pH	Alkalinity (mg/L as $CaCO_3$)	Hardness (mg/L as $CaCO_3$)	Free Chlorine (mg/L)	Saturated Index
1	7.5	100	200	2	-0.20
2	7.9	200	120	3	0.30
3	7.2	60	350	1	-0.45

APPENDIX F: RECIPE OF THE THREE EXPERIMENTAL WATER (FOR 1,000 L WATER)

Water Type	31.45% muriatic acid (mL)	$NaHCO_3$ (g)	$CaCl_2$ (g)	6% bleach (mL)
1	24	18	189	16
2	22	193	100	32
3	27	0	355	8

APPENDIX G: EQUIPMENT DETAILS

Item	Model	Manufacturer	Address
Sand filter (big)	Triton II	Pentair	Sanford, NC, USA
Precoat filter	FNS Plus	Pentair	Sanford, NC, USA
Cartridge filter	Clean & Clear Plus	Pentair	Sanford, NC, USA
Magnetic Flow meter	yokogama AXF015G	Yokogawa Electric Corporation	Chandler, AZ, USA
LPP-M pump (coagulant feeding pump)	LPP-M2S	Larox Flowsys	Linthicum, MD, USA
Syringe pump	Model 100 series	kd Scientific	Holliston, MA, USA
Peristaltic pumps (Microspheres feeding pump)	505 Di	Watson Marlow	Wilmington, MA, USA
Turbidimeter	MicroTOL Series	HF scientific, inc	Myers, FL, USA
Influent UV	Real UVT online	Real Tech inc.	Canada
Effluent UV	AccUView UV online	HF scientific, inc	Fort Myers, FL, USA
Streaming current	Streaming Current Monitor Model SCM-1	Micrometrix Cororation	Suwanee, GA, USA
Influent particle counter	Laser Trac Particle Counter PC 2400	CHEMTRAC	Norcross, GA, USA
Effluent particle counter	MODEL PC 2400 D	CHEMTRAC	Norcross, GA, USA
Water quality controller	CAT 5000	Poolcomm	Rockville, MD, USA
Solenoid metering pump (Acid feeding pump)	gala 1601PVT200UDO12100	ProMinent	Heideibery, Germany
Chlorine feeding pump	SVP4	STENNER PUMP COMPANY	Jacksonville, FL, USA
Variable Speed pump	IntelliFlo VF+ SVRS	Pentair	Sanford, NC, USA
Electronic metering pump	EW-Y Series	Walchem	Holliston, MA, USA
Speck Pump (for small sand filter)	Y-2051.0185	Speck Pumpen	Jacksonville, FL, USA
ABB AquaMaster flow measurement	ABB AquaMaster	ABB Inc. Process Automation	Warminster, PA, USA

APPENDIX H: COAGULANT DEMAND CALCULATION

Assuming density of 4.5 μm microsphere is 1.06 SG, COOH at 800 μeq/g, the molecular weight of polyDADMAC ($(C_8H_{16}NCl^-)_n$) is 100,000 g/mole with a charge concentration of 1 eq/mole of DADMAC ($C_8H_{16}NCl^-$), and coagulant is 4% polyDADMAC. Coagulant demand to neutralize one microsphere is determined to be 1.63×10^{-7} mg as shown below. 10^5 microspheres will need 1.63×10^{-2} mg coagulant; 10^7 microspheres will need 1.63 mg coagulant; 10^8 microspheres will need 16.3 mg coagulant.

$$\rho_{Microsphere} = SG\times\rho_{H_2O} = 1.06SG\times 1g/cm^3 = 1.06g/cm^3$$

$$V_{Microsphere} = \frac{4\pi R^3}{3} = \frac{4\times 3.14\times(4.5\mu m/2)^3}{3} = 47.7\mu m^3$$

$$M_{Microsphere} = \rho_{Microsphere}\times V_{Microsphere} = 1.06g/cm^3\times 47.7\mu m^3 = 5.06\times10^{-11}g$$

$$\Delta q_{Microsphere} = 800\mu eq/g\times 5.06\times10^{-11}g = 4.05\times10^{-8}\mu eq$$

$$n = 100{,}000/(12\times8+16+14+35.5) = 619$$

$$\therefore 619 eq/mole\ for\quad polyDADMAC$$

$$polyDADMAC\quad demand:\quad 100{,}000g/mole\times(4.05\times10^{-8}\mu eq/619eq/mole) = 6.54*10^{-9}mg$$

$$Coagulant\quad demand\ for\ \ 1\ \ microsphere:\quad 6.54*10^{-9}mg/4\% = 1.63\times10^{-7}mg$$

where, $\rho_{Microsphere}$ is the density of microspheres;
$V_{Microsphere}$ is the volume of microspheres;
$M_{Microsphere}$ is the mass for one microsphere;
$\Delta q_{Microsphere}$ is the charge of the microsphere;
n is the numbers of DADMAC in one mole polyDADMAC.

APPENDIX I: FILTER MEDIA PROPERTIES AND CALCULATION OF VOLUME OF THE POOL TO SAND SURFACE AREA RATIO

Mystic White Pool Filter Sand Ratios	
Density (g/cm^3)	2.65
Porosity	0.5
Effective Size (mm)	0.49
Grain Surface Area (mm^2)	3.14
Effective Weight (g/100grains)	0.09

	Pilot Scale Swim Spa Small Filter	Pilot Scale Swim spa Big Filter	Full Scale UNCC Campus Pool
Pool Volume (gal)	1,450	1,450	322,000
Sand Volume (in^3)	339		
Sand Volume (cm^3)	5,560		2,627,803
Porous Volume	2,780		1,313,902
Actual Sand Vol (cm^3)	2,780		1,313,902
Mass Sand (g)	1,049	79,379	495,812
# of Grains	11,787	891,895	5,570,921
Total Grain Surface Area (mm^2)	37,030	2,801,971	17,501,564
Total Grain Surface Area (ft^2)	0.4	30	188
Volume/Grain Surface Area Ratio (gal/ft^2)	3,638	48	1,709
Volume/Grain Surface Area Ratio (L/m^2)	148,209	1,959	69,638

$$V_T = \pi \cdot R^2 \cdot L = 3.14 \cdot (3'')^2 \cdot 12'' = 339.3in^3 = 5560cm^3$$

$$V_{sand} = V_T \cdot (1-\varphi) = (5560cm^3)\cdot(1-0.5) = 2780cm^3$$

$$M_{sand} = V_{sand} / \rho_{sand} = (2780cm^3)/(2.65g/cm^3) = 1049.1g$$

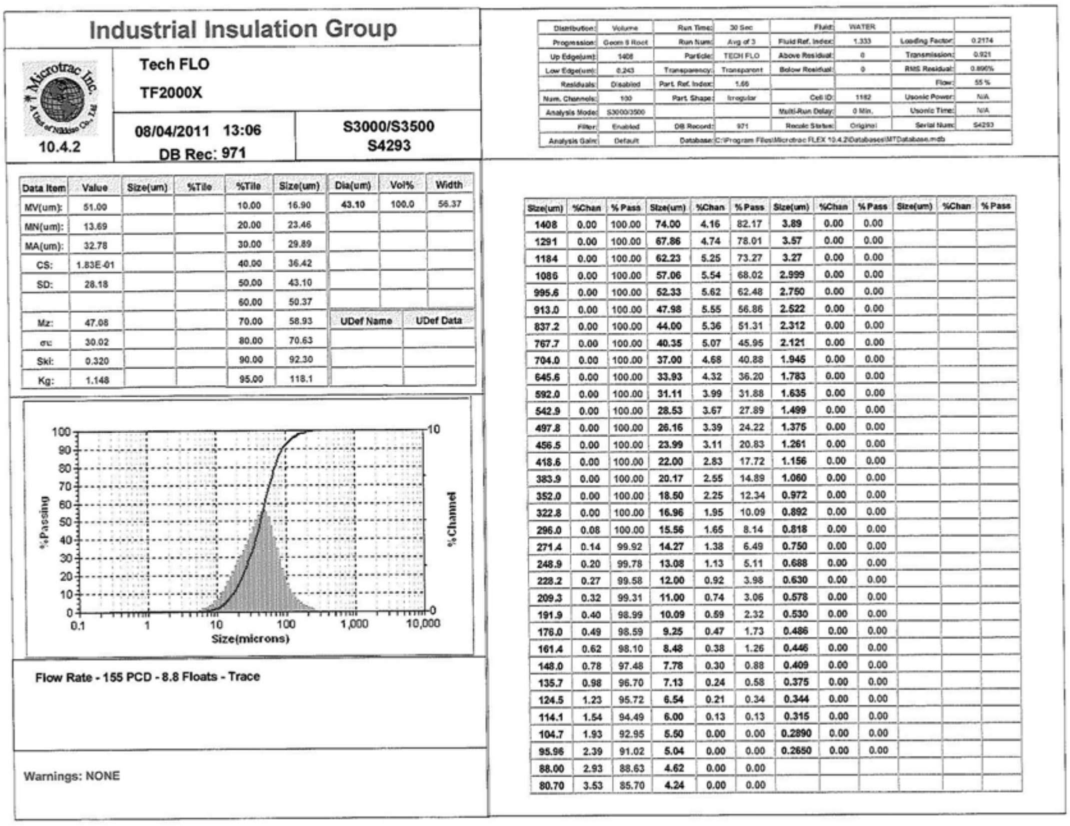
$$A_{sand} = n \cdot A_{grain} = (M_{sand}/W_e)\cdot A_{grain} = (1049.1g)/(0.089g/100grains)\cdot(3.14mm^2) = 37030mm^2$$

$$= 0.399ft^2$$

$$V_{pool} / A_{sand} = (1450\,gal)/(0.399\,ft^2) = 3638\,gal/ft^2 = 148{,}209\,L/m^2$$

where, V_T is the bulk volume of the media, including the sand and void components; R and L are bulk radius (3 in.) and depth (12 in.); V_{sand}, M_{sand} and A_{sand} are the sand volume, mass and surface area; ρ_{sand} is the sand density; n is the total count of the sand in this specific volume; V_{pool} is swimming pool volume.

APPENDIX J: PERLITE SIZE DISTRIBUTION BY MICROTRAC



Industrial Insulation Group

Microtrac Inc.
10.4.2

Tech FLO
TF2000X

08/04/2011 13:06
DB Rec: 971

S3000/S3500
S4293

Distribution:	Volume	Run Time:	30 Sec	Fluid:	WATER		
Progression:	Geom 8 Root	Run Num:	Avg of 3	Fluid Ref. Index:	1.333	Loading Factor:	0.2174
Up Edge(um):	1408	Particle:	TECH FLO	Above Residual:	0	Transmission:	0.921
Low Edge(um):	0.243	Transparency:	Transparent	Below Residual:	0	RMS Residual:	0.896%
Residuals:	Disabled	Part. Ref. Index:	1.66			Flow:	55 %
Num. Channels:	100	Part. Shape:	Irregular	Cell ID:	1182	Usonic Power:	N/A
Analysis Mode:	S3000/3500			Multi-Run Delay:	0 Min.	Usonic Time:	N/A
Filter:	Enabled	DB Record:	971	Recalc Status:	Original	Serial Num:	S4293
Analysis Gain:	Default	Database:	C:\Program Files\Microtrac FLEX 10.4.2\Databases\MTDatabase.mdb				

Data Item	Value	Size(um)	%Tile	%Tile	Size(um)
MV(um):	51.00			10.00	16.90
MN(um):	13.69			20.00	23.46
MA(um):	32.78			30.00	29.89
CS:	1.83E-01			40.00	36.42
SD:	28.18			50.00	43.10
				60.00	50.37
Mz:	47.08			70.00	58.93
σu:	30.02			80.00	70.63
Ski:	0.320			90.00	92.30
Kg:	1.148			95.00	118.1

Dia(um)	Vol%	Width
43.10	100.0	56.37

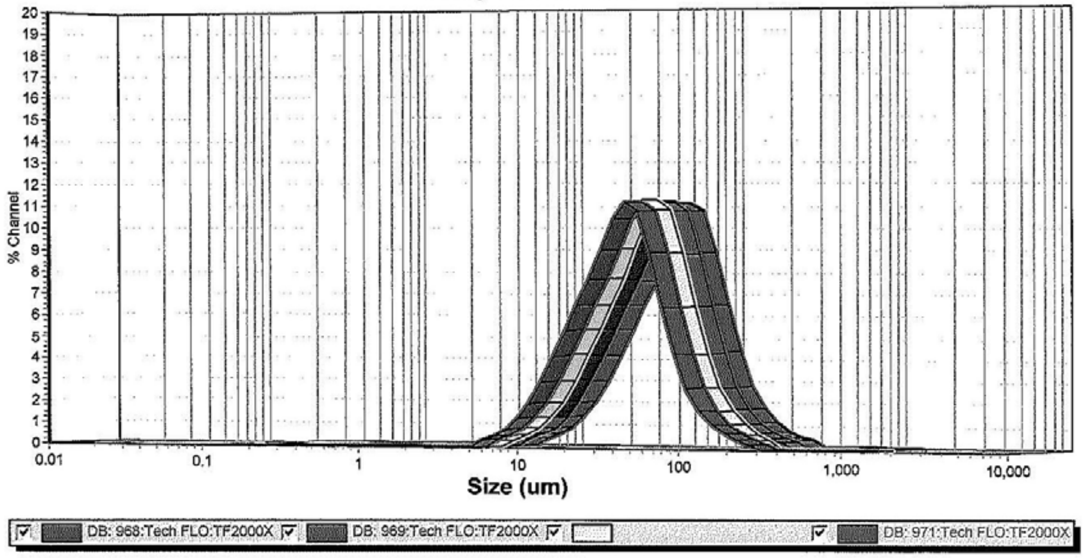
UDef Name	UDef Data

Size(um)	%Chan	% Pass	Size(um)	%Chan	% Pass	Size(um)	%Chan	% Pass	Size(um)	%Chan	% Pass
1408	0.00	100.00	74.00	4.16	82.17	3.89	0.00	0.00			
1291	0.00	100.00	67.86	4.74	78.01	3.57	0.00	0.00			
1184	0.00	100.00	62.23	5.25	73.27	3.27	0.00	0.00			
1086	0.00	100.00	57.06	5.54	68.02	2.999	0.00	0.00			
995.6	0.00	100.00	52.33	5.62	62.48	2.750	0.00	0.00			
913.0	0.00	100.00	47.98	5.55	56.86	2.522	0.00	0.00			
837.2	0.00	100.00	44.00	5.36	51.31	2.312	0.00	0.00			
767.7	0.00	100.00	40.35	5.07	45.95	2.121	0.00	0.00			
704.0	0.00	100.00	37.00	4.68	40.88	1.945	0.00	0.00			
645.6	0.00	100.00	33.93	4.32	36.20	1.783	0.00	0.00			
592.0	0.00	100.00	31.11	3.99	31.88	1.635	0.00	0.00			
542.9	0.00	100.00	28.53	3.67	27.89	1.499	0.00	0.00			
497.8	0.00	100.00	26.16	3.39	24.22	1.375	0.00	0.00			
456.5	0.00	100.00	23.99	3.11	20.83	1.261	0.00	0.00			
418.6	0.00	100.00	22.00	2.83	17.72	1.156	0.00	0.00			
383.9	0.00	100.00	20.17	2.55	14.89	1.060	0.00	0.00			
352.0	0.00	100.00	18.50	2.25	12.34	0.972	0.00	0.00			
322.8	0.00	100.00	16.96	1.95	10.09	0.892	0.00	0.00			
296.0	0.08	100.00	15.56	1.65	8.14	0.818	0.00	0.00			
271.4	0.14	99.92	14.27	1.38	6.49	0.750	0.00	0.00			
248.9	0.20	99.78	13.08	1.13	5.11	0.688	0.00	0.00			
228.2	0.27	99.58	12.00	0.92	3.98	0.630	0.00	0.00			
209.3	0.32	99.31	11.00	0.74	3.06	0.578	0.00	0.00			
191.9	0.40	98.99	10.09	0.59	2.32	0.530	0.00	0.00			
176.0	0.49	98.59	9.25	0.47	1.73	0.486	0.00	0.00			
161.4	0.62	98.10	8.48	0.38	1.26	0.446	0.00	0.00			
148.0	0.78	97.48	7.78	0.30	0.88	0.409	0.00	0.00			
135.7	0.98	96.70	7.13	0.24	0.58	0.375	0.00	0.00			
124.5	1.23	95.72	6.54	0.21	0.34	0.344	0.00	0.00			
114.1	1.54	94.49	6.00	0.13	0.13	0.315	0.00	0.00			
104.7	1.93	92.95	5.50	0.00	0.00	0.2890	0.00	0.00			
95.96	2.39	91.02	5.04	0.00	0.00	0.2650	0.00	0.00			
88.00	2.93	88.63	4.62	0.00	0.00						
80.70	3.53	85.70	4.24	0.00	0.00						

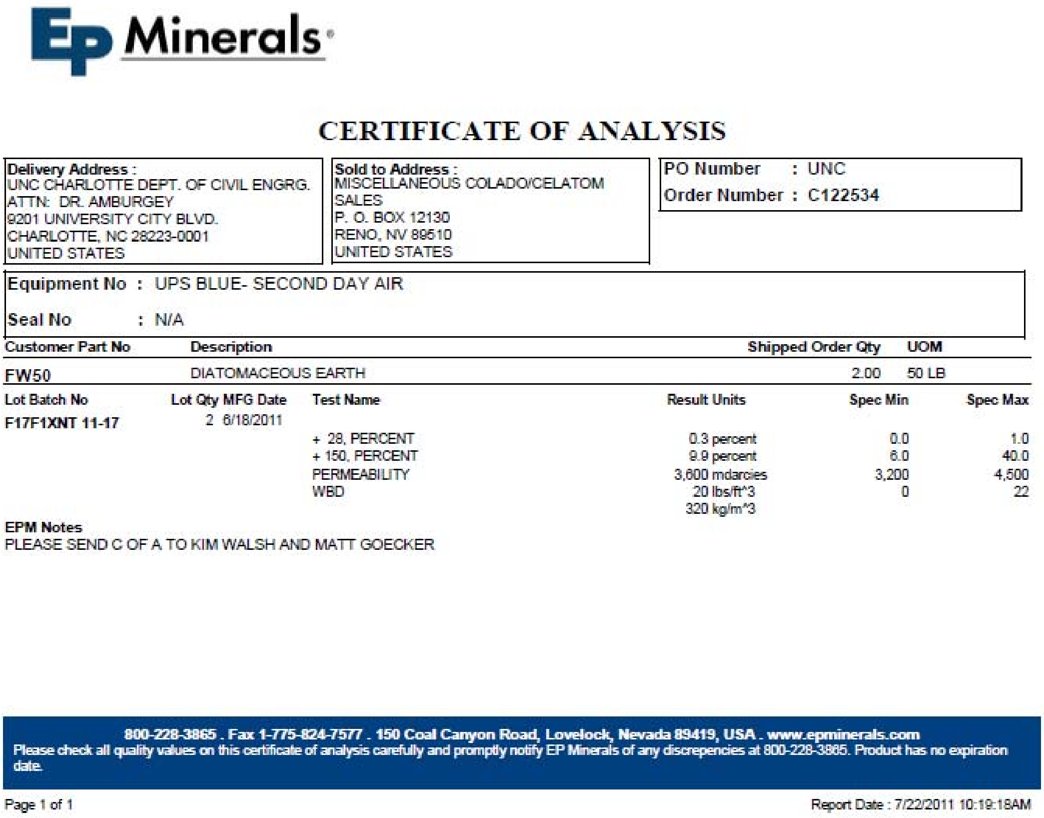
Flow Rate - 155 PCD - 8.8 Floats - Trace

Warnings: NONE

- Comparison Plot -



APPENDIX K: EP MINERALS CERTIFICATE OF ANALYSIS FOR DIATOMACEOUS EARTH



EP Minerals

CERTIFICATE OF ANALYSIS

Delivery Address :
UNC CHARLOTTE DEPT. OF CIVIL ENGRG.
ATTN: DR. AMBURGEY
9201 UNIVERSITY CITY BLVD.
CHARLOTTE, NC 28223-0001
UNITED STATES

Sold to Address :
MISCELLANEOUS COLADO/CELATOM
SALES
P. O. BOX 12130
RENO, NV 89510
UNITED STATES

PO Number : UNC
Order Number : C122534

Equipment No : UPS BLUE- SECOND DAY AIR

Seal No : N/A

Customer Part No	Description	Shipped Order Qty	UOM
FW50	DIATOMACEOUS EARTH	2.00	50 LB

Lot Batch No	Lot Qty	MFG Date	Test Name	Result Units	Spec Min	Spec Max
F17F1XNT 11-17	2	6/18/2011				
			+ 28, PERCENT	0.3 percent	0.0	1.0
			+ 150, PERCENT	9.9 percent	6.0	40.0
			PERMEABILITY	3,600 mdarcies	3,200	4,500
			WBD	20 lbs/ft^3 320 kg/m^3	0	22

EPM Notes
PLEASE SEND C OF A TO KIM WALSH AND MATT GOECKER

800-228-3865 . Fax 1-775-824-7577 . 150 Coal Canyon Road, Lovelock, Nevada 89419, USA . www.epminerals.com
Please check all quality values on this certificate of analysis carefully and promptly notify EP Minerals of any discrepencies at 800-228-3865. Product has no expiration date.

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Report Date : 7/22/2011 10:19:18AM

APPENDIX L: PILOT-SCALE SWIMMING POOL WATER CHARACTERISTICS

Coagulant	Time (hr)	OPR	Sanitizer (mg/L)	pH	Conductivity (µs)	Temperature (F)
A	0	780	1.8	7.5	1450	83
A	0.5	780	1.8	7.5	1450	83
A	1	780	1.8	7.5	1450	83
A	1.5	780	1.8	7.5	1450	83
A	2	780	1.8	7.5	1450	83
A	2.5	780	1.8	7.5	1450	83
A	3	780	1.8	7.5	1450	83
A	3.5	780	1.8	7.5	1450	83
A	4	780	1.8	7.5	1450	83
A	4.5	780	1.8	7.5	1450	83
A	5	780	1.8	7.5	1450	83
A	5.5	780	1.8	7.5	1450	83
A	6	780	1.8	7.5	1450	83
A	6.5	780	1.8	7.5	1450	83
A	7	780	1.8	7.5	1450	83
A	7.5	780	1.8	7.5	1450	83
A	8	780	1.8	7.5	1450	83
A	8.5	780	1.8	7.5	1450	83
A	9	780	1.8	7.5	1450	83
A	9.5	780	1.8	7.5	1450	83
A	10	780	1.8	7.5	1450	83
A	10.5	780	1.8	7.5	1450	83
A	11	795	0.8	7.4	1457	83
A	11.5	795	0.8	7.4	1457	83
A	12	795	0.8	7.4	1457	83
A	12.5	795	0.8	7.4	1457	83
A	13	795	0.8	7.4	1457	83
A	13.5	795	0.8	7.4	1457	83
A	14	795	0.8	7.4	1457	83
A	14.5	795	0.8	7.4	1457	83
A	15	795	0.8	7.4	1457	83
A	15.5	795	0.8	7.4	1457	83
A	16	795	0.8	7.4	1457	83
A	16.5	795	0.8	7.4	1457	83
A	17	795	0.8	7.4	1457	83
A	18	790	0.8	7.4	1457	83
A	19	790	0.7	7.4	1457	83

Coagulant	Time (hr)	OPR	Sanitizer (mg/L)	pH	Conductivity (µs)	Temperature (F)
A	19.5	790	0.7	7.4	1457	83
A	20	790	0.7	7.4	1457	83
A	20.5	790	0.7	7.4	1457	83
A	21	790	0.7	7.4	1457	83
A	21.5	790	0.7	7.4	1457	83
A	22	790	0.7	7.4	1457	83
A	22.5	790	0.7	7.4	1457	83
A	23	790	0.7	7.4	1457	83
A	23.5	790	0.7	7.4	1457	83
A	24	790	0.7	7.4	1457	83
A	24.5	790	1.5	7.4	1500	83
A	25	790	1.5	7.4	1500	83
A	25.5	790	1.5	7.4	1500	83
A	26	790	1.5	7.4	1500	83
A	26.5	790	1.5	7.4	1500	83
A	27	790	1.5	7.4	1500	83
A	27.5	790	1.5	7.4	1500	83
A	28	790	1.5	7.4	1500	83
A	28.5	790	1.5	7.4	1500	83
A	29	790	1.5	7.4	1500	83
A	29.5	790	1.5	7.4	1500	83
A	30	790	1.5	7.4	1500	83
A	30.5	790	1.5	7.4	1500	83
A	31	790	1.5	7.4	1500	83
A	31.5	790	1.5	7.4	1500	83
A	32	790	1.5	7.4	1500	83
A	32.5	790	1.5	7.4	1500	83
A	33	790	1.5	7.4	1500	83
A	33.5	800	1.5	7.4	1500	83
A	34	800	1.5	7.4	1500	83
A	34.5	800	1.5	7.4	1500	83
A	35	800	1.5	7.4	1500	83
A	35.5	800	1.5	7.4	1500	83
A	36	800	1.5	7.4	1500	83
A	36.5	800	1.5	7.4	1500	83
A	37	800	1.5	7.4	1500	83
A	37.5	800	1.5	7.4	1500	83
A	38	800	1.5	7.4	1500	83
A	38.5	800	1.5	7.4	1500	83

Coagulant	Time (hr)	OPR	Sanitizer (mg/L)	pH	Conductivity (µs)	Temperature (F)
A	39	800	1.5	7.4	1500	83
A	39.5	800	1.5	7.4	1500	83
A	40	800	1.5	7.4	1500	83
A	40.5	800	1.5	7.4	1500	83
A	41	800	1.5	7.4	1500	83
A	41.5	800	1.5	7.4	1500	83
A	42	800	1.5	7.4	1500	83
A	42.5	800	1.5	7.4	1500	83
A	43	800	1.5	7.4	1500	83
A	43.5	800	1.5	7.4	1500	83
A	44	800	1.5	7.4	1500	83
A	44.5	795	1.6	7.4	1555	83
A	45	795	1.6	7.4	1555	83
A	45.5	795	1.6	7.4	1555	83
A	46	795	1.6	7.4	1555	83
A	46.5	795	1.6	7.4	1555	83
A	47	795	1.6	7.4	1555	83
A	47.5	795	1.6	7.4	1555	83
A	48	795	1.6	7.4	1555	83
A	48.5	795	1.6	7.4	1555	83
B	0	815	0.5	7.4	1450	83
B	0.5	815	0.5	7.4	1450	83
B	1	815	0.5	7.4	1450	83
B	1.5	815	0.5	7.4	1450	83
B	2	815	0.5	7.4	1450	83
B	2.5	815	0.5	7.4	1450	83
B	3	815	0.5	7.4	1450	83
B	3.5	815	0.5	7.4	1450	83
B	4	815	0.5	7.4	1450	83
B	4.5	815	0.5	7.4	1450	83
B	5	815	0.5	7.4	1450	83
B	5.5	815	0.5	7.4	1455	83
B	6	815	0.5	7.4	1457	83
B	6.5	815	0.5	7.4	1455	83
B	7	815	0.5	7.4	1455	83
B	7.5	815	0.5	7.4	1450	83
B	8	825	0.8	7.4	1457	83
B	8.5	825	0.8	7.4	1457	83
B	9	825	0.8	7.4	1457	83

Coagulant	Time (hr)	OPR	Sanitizer (mg/L)	pH	Conductivity (µs)	Temperature (F)
B	9.5	825	0.8	7.4	1457	83
B	10	825	0.8	7.4	1457	83
B	10.5	825	0.8	7.4	1457	83
B	11	825	0.8	7.4	1457	83
B	11.5	825	0.8	7.4	1457	83
B	12	825	0.8	7.4	1457	83
B	12.5	825	0.8	7.4	1457	83
B	13	825	0.8	7.4	1457	83
B	13.5	825	0.8	7.4	1457	83
B	14	825	0.8	7.4	1457	83
B	14.5	825	0.8	7.4	1457	83
B	15	825	0.8	7.4	1457	83
B	15.5	825	0.8	7.4	1457	83
B	16	825	0.7	7.4	1457	83
B	16.5	800	1.5	7.4	1500	83
B	17	800	1.5	7.4	1500	83
B	17.5	800	1.5	7.4	1500	83
B	18	800	1.5	7.4	1500	83
B	18.5	800	1.5	7.4	1500	83
B	19	800	1.5	7.4	1500	83
B	19.5	800	1.5	7.4	1500	83
B	20	800	1.5	7.4	1500	83
B	20.5	800	1.5	7.4	1500	83
B	21	800	1.5	7.4	1500	83
B	21.5	800	1.5	7.4	1500	83
B	22	800	1.5	7.4	1500	83
B	22.5	800	1.6	7.4	1550	83
B	23	800	1.6	7.4	1550	83
B	23.5	800	1.6	7.4	1550	83
B	24	800	1.6	7.4	1550	83
B	24.5	800	1.6	7.4	1550	83
B	25	800	1.6	7.4	1550	83
B	25.5	800	1.6	7.4	1550	83
B	26	800	1.6	7.4	1550	83
B	26.5	800	1.6	7.4	1550	83
B	27	800	1.6	7.4	1550	83
B	27.5	800	1.6	7.4	1550	83
B	28	800	1.6	7.4	1550	83
B	28.5	795	1.5	7.4	1555	83

Coagulant	Time (hr)	OPR	Sanitizer (mg/L)	pH	Conductivity (µs)	Temperature (F)
B	29	795	1.5	7.4	1555	83
B	29.5	795	1.5	7.4	1555	83
B	30	795	1.5	7.4	1555	83
B	30.5	795	1.5	7.4	1555	83
B	31	795	1.5	7.4	1555	83
B	31.5	795	1.5	7.4	1555	83
B	32	795	1.5	7.4	1555	83
B	32.5	795	1.5	7.4	1555	83
B	33	795	1.5	7.4	1555	83
B	33.5	795	1.5	7.4	1555	83
B	34	795	1.5	7.4	1555	83
B	34.5	795	1.5	7.4	1555	83
B	35	795	1.5	7.4	1555	83
B	35.5	795	1.5	7.4	1555	83
B	36	795	1.5	7.4	1555	83
B	36.5	795	1.5	7.4	1555	83
B	37	795	1.5	7.4	1555	83
B	37.5	795	1.5	7.4	1555	83
B	38	795	1.5	7.4	1555	83
B	38.5	795	1.5	7.4	1555	83
B	39	815	1.4	7.4	1550	83
B	39.5	815	1.4	7.4	1550	83
B	40	815	1.4	7.4	1550	83
B	40.5	815	1.4	7.4	1550	83
B	41	815	1.4	7.4	1555	83
B	41.5	815	1.4	7.4	1555	83
B	42	815	1.4	7.4	1555	83
B	42.5	815	1.4	7.4	1555	83
B	43	815	1.4	7.4	1555	83
B	43.5	815	1.4	7.4	1555	83
B	44	815	1.4	7.4	1555	83
B	44.5	815	1.4	7.4	1555	83
B	45	815	1.4	7.4	1555	83
B	45.5	815	1.4	7.4	1555	83
B	46	815	1.4	7.4	1555	83
B	46.5	815	1.4	7.4	1555	83
C	0	800	1.5	7.4	1500	83
C	0.5	800	1.5	7.4	1500	83
C	1	800	1.5	7.4	1500	83

Coagulant	Time (hr)	OPR	Sanitizer (mg/L)	pH	Conductivity (µs)	Temperature (F)
C	1.5	800	1.5	7.4	1500	83
C	2	800	1.5	7.4	1500	83
C	2.5	800	1.5	7.4	1500	83
C	3	800	1.5	7.4	1500	83
C	3.5	800	1.5	7.4	1500	83
C	4	800	1.5	7.4	1500	83
C	4.5	800	1.5	7.4	1500	83
C	5	800	1.5	7.4	1500	83
C	5.5	800	1.5	7.4	1500	83
C	6	800	1.5	7.4	1500	83
C	6.5	800	1.5	7.4	1500	83
C	7	800	1.5	7.4	1500	83
C	7.5	800	1.5	7.4	1500	83
C	8	800	1.5	7.4	1500	83
C	8.5	800	1.5	7.4	1500	83
C	9	800	1.5	7.4	1500	83
C	9.5	830	1.8	7.5	1550	83
C	10	830	1.8	7.5	1550	83
C	10.5	830	1.8	7.5	1550	83
C	11	830	1.8	7.5	1550	83
C	11.5	830	1.8	7.5	1560	83
C	12	830	1.8	7.5	1560	83
C	12.5	830	1.8	7.5	1560	83
C	13	830	1.8	7.5	1560	83
C	13.5	830	1.8	7.5	1560	83
C	14	830	1.8	7.5	1560	83
C	14.5	830	1.8	7.5	1560	83
C	15	830	1.8	7.5	1560	83
C	15.5	830	1.8	7.5	1560	83
C	16	830	1.8	7.5	1560	83
C	16.5	830	1.8	7.5	1560	83
C	17	830	1.8	7.5	1560	83
C	17.5	830	1.8	7.5	1560	83
C	18	805	0.8	7.4	1560	83
C	18.5	805	0.8	7.4	1560	83
C	19	805	0.8	7.4	1560	83
C	19.5	805	0.8	7.4	1560	83
C	20	805	0.8	7.4	1560	83
C	20.5	805	0.8	7.4	1560	83

Coagulant	Time (hr)	OPR	Sanitizer (mg/L)	pH	Conductivity (µs)	Temperature (F)
C	21	805	0.8	7.4	1565	83
C	21.5	805	0.8	7.4	1565	83
C	22	805	0.8	7.4	1565	83
C	22.5	805	0.8	7.4	1565	83
C	23	805	0.8	7.4	1565	83
C	23.5	805	0.8	7.4	1565	83
C	24	805	0.8	7.4	1565	83
C	24.5	805	0.8	7.4	1565	83
C	25	805	0.8	7.4	1565	83
C	25.5	805	0.8	7.4	1565	83
C	26	805	0.8	7.4	1565	83
C	26.5	805	0.8	7.4	1565	83
C	27	805	0.8	7.4	1565	83
C	27.5	805	0.8	7.4	1565	83
C	28	805	0.8	7.4	1565	83
C	28.5	805	0.8	7.4	1565	83
C	29	805	0.8	7.4	1565	83
C	29.5	805	0.8	7.4	1565	83
C	30	805	0.8	7.4	1565	83
C	30.5	805	0.8	7.4	1565	83
C	31	805	0.8	7.4	1565	83
C	31.5	805	0.8	7.4	1565	83
C	32	805	0.8	7.4	1565	83
C	32.5	805	0.8	7.4	1565	83
C	33	805	0.8	7.4	1565	83
C	33.5	805	0.8	7.4	1565	83
C	34	805	0.8	7.4	1565	83
C	34.5	805	0.8	7.4	1565	83
C	35	805	0.8	7.4	1565	83
C	35.5	805	0.8	7.4	1565	83
C	36	805	0.8	7.4	1565	83
C	36.5	805	0.8	7.4	1565	83
C	37	805	0.8	7.4	1565	83
C	37.5	805	0.8	7.4	1565	83
C	38	805	0.8	7.4	1565	83
C	38.5	805	0.8	7.4	1565	83
C	39	805	0.8	7.4	1565	83
C	39.5	805	0.8	7.4	1565	83
C	40	805	0.8	7.4	1565	83

Coagulant	Time (hr)	OPR	Sanitizer (mg/L)	pH	Conductivity (µs)	Temperature (F)
C	40.5	805	0.8	7.4	1565	83
C	41	805	0.8	7.4	1565	83
C	41.5	805	0.8	7.4	1565	83
C	42	805	0.7	7.4	1565	83
C	42.5	805	0.7	7.4	1565	83
C	43	805	0.7	7.4	1565	83
C	43.5	805	0.7	7.4	1565	83
C	44	805	0.7	7.4	1565	83
C	44.5	805	0.7	7.4	1565	83
C	45	805	0.7	7.4	1565	83
C	45.5	805	0.7	7.4	1565	83
C	46	805	0.7	7.4	1565	83
C	46.5	805	0.7	7.4	1565	83
C	47	805	0.7	7.4	1565	83
C	47.5	805	0.7	7.4	1565	83
C	48	815	1.5	7.4	1565	83
C	48.5	815	1.5	7.4	1565	83
C	49	815	1.5	7.4	1565	83
C	49.5	815	1.5	7.4	1565	83
C	50	815	1.5	7.4	1565	83
C	50.5	815	1.5	7.4	1565	83
C	51	815	1.5	7.4	1565	83
C	51.5	815	1.5	7.4	1565	83
C	52	815	1.5	7.4	1565	83
C	52.5	815	1.5	7.4	1565	83
C	53	815	1.5	7.4	1565	83
C	53.5	815	1.5	7.4	1565	83
C	54	815	1.5	7.4	1565	83
C	54.5	815	1.5	7.4	1565	83
C	55	815	1.5	7.4	1565	83
C	55.5	815	1.5	7.4	1565	83
C	56	815	1.5	7.4	1565	83
C	56.5	815	1.5	7.4	1565	83
C	57	815	1.5	7.4	1565	83
C	57.5	815	1.5	7.4	1565	83
C	58	815	1.5	7.4	1565	83
C	58.5	815	1.5	7.4	1565	83
C	59	815	1.5	7.4	1565	83
C	59.5	815	1.5	7.4	1565	83

Coagulant	Time (hr)	OPR	Sanitizer (mg/L)	pH	Conductivity (µs)	Temperature (F)
C	60	815	1.5	7.4	1565	83
C	60.5	815	1.5	7.4	1565	83
C	61	815	1.5	7.4	1565	83
C	61.5	815	1.5	7.4	1565	83
C	62	815	1.5	7.4	1565	83
C	62.5	815	1.5	7.4	1565	83
C	63	815	1.5	7.4	1565	83
C	63.5	815	1.5	7.4	1565	83
C	64	815	1.5	7.4	1565	83
C	64.5	815	1.5	7.4	1565	83
C	65	815	1.5	7.4	1565	83
C	65.5	815	1.5	7.4	1565	83
C	66	815	1.5	7.4	1565	83
C	66.5	815	1.5	7.4	1565	83
C	67	815	1.5	7.4	1565	83
C	67.5	815	1.5	7.4	1565	83
C	68	815	1.5	7.4	1565	83
C	68.5	815	1.5	7.4	1565	83
C	69	815	1.5	7.4	1565	83
C	69.5	815	1.5	7.4	1565	83
C	70	815	1.5	7.4	1565	83
C	70.5	815	1.5	7.4	1565	83
C	71	815	1.5	7.4	1565	83
C	71.5	815	1.5	7.4	1565	83
C	72	815	1.5	7.4	1565	83
C	72.5	815	1.5	7.4	1565	83
C	73	815	1.5	7.4	1565	83
C	73.5	815	1.5	7.4	1565	83
C	74	815	1.5	7.4	1565	83
C	74.5	815	1.5	7.4	1565	83
C	75	815	1.5	7.4	1565	83
C	75.5	815	1.5	7.4	1565	83
C	76	815	1.5	7.4	1565	83
C	76.5	815	1.5	7.4	1565	83
C	77	815	1.5	7.4	1565	83
C	77.5	815	1.5	7.4	1565	83
C	78	815	1.5	7.4	1565	83
C	78.5	815	1.5	7.4	1565	83
C	79	815	1.5	7.4	1565	83

Coagulant	Time (hr)	OPR	Sanitizer (mg/L)	pH	Conductivity (µs)	Temperature (F)
C	79.5	815	1.5	7.4	1565	83
C	80	815	1.5	7.4	1565	83
C	80.5	815	1.5	7.4	1565	83
C	81	815	1.5	7.4	1565	83
C	81.5	815	1.5	7.4	1565	83
C	82	815	1.5	7.4	1565	83
C	82.5	815	1.5	7.4	1565	83
C	83	815	1.5	7.4	1565	83
C	83.5	815	1.5	7.4	1565	83
C	84	815	1.5	7.4	1565	83
C	84.5	815	1.5	7.4	1565	83
C	85	815	1.5	7.4	1565	83
C	85.5	815	1.5	7.4	1565	83
C	86	815	1.5	7.4	1565	83
C	86.5	815	1.5	7.4	1565	83
C	87	815	1.5	7.4	1565	83
C	87.5	815	1.5	7.4	1565	83
C	88	815	1.5	7.4	1565	83
C	88.5	815	1.5	7.4	1565	83
C	89	815	1.5	7.4	1565	83
C	89.5	815	1.5	7.4	1565	83
C	90	815	1.5	7.4	1565	83
C	90.5	815	1.5	7.4	1565	83
C	91	815	1.5	7.4	1565	83
C	91.5	815	1.5	7.4	1565	83
C	92	815	1.5	7.4	1565	83
C	92.5	815	1.5	7.4	1565	83
C	93	815	1.5	7.4	1565	83
C	93.5	815	1.5	7.4	1565	83
C	94	815	1.5	7.4	1565	83
C	94.5	815	1.5	7.4	1565	83
C	95	815	1.5	7.4	1565	83
C	95.5	815	1.5	7.4	1565	83
C	96	815	1.5	7.4	1565	83
C	96.5	815	1.5	7.4	1565	83
C	97	815	1.5	7.4	1565	83
C	97.5	815	1.5	7.4	1565	83
C	98	815	1.5	7.4	1565	83
C	98.5	815	1.5	7.4	1565	83

Coagulant	Time (hr)	OPR	Sanitizer (mg/L)	pH	Conductivity (µs)	Temperature (F)
C	99	815	1.5	7.4	1565	83
C	99.5	815	1.5	7.4	1565	83
C	100	815	1.5	7.4	1565	83
C	100.5	815	1.5	7.4	1565	83
C	101	815	1.5	7.4	1565	83
C	101.5	815	1.5	7.4	1565	83
C	102	815	1.5	7.4	1565	83
C	102.5	815	1.5	7.4	1565	83
C	103	815	1.5	7.4	1565	83
C	103.5	815	1.5	7.4	1565	83
C	104	815	1.5	7.4	1565	83
C	104.5	815	1.5	7.4	1565	83
C	105	815	1.5	7.4	1565	83
C	105.5	815	1.5	7.4	1565	83
C	106	815	1.5	7.4	1565	83
C	106.5	815	1.5	7.4	1565	83
C	107	815	1.5	7.4	1565	83
C	107.5	815	1.5	7.4	1565	83
C	108	815	1.5	7.4	1565	83
C	108.5	815	1.5	7.4	1565	83
C	109	815	1.5	7.4	1565	83
C	109.5	815	1.5	7.4	1565	83
C	110	815	1.5	7.4	1565	83
C	110.5	815	1.5	7.4	1565	83
C	111	815	1.5	7.4	1565	83
C	111.5	815	1.5	7.4	1565	83
C	112	815	1.5	7.4	1565	83
C	112.5	815	1.5	7.4	1565	83
C	113	815	1.5	7.4	1565	83
C	113.5	815	1.5	7.4	1565	83
C	114	815	1.5	7.4	1565	83
C	114.5	815	1.5	7.4	1565	83
C	115	815	1.5	7.4	1565	83
C	115.5	815	1.5	7.4	1565	83
C	116	815	1.5	7.4	1565	83
C	116.5	815	1.5	7.4	1565	83
C	117	815	1.5	7.4	1565	83
C	117.5	815	1.5	7.4	1565	83
C	118	815	1.5	7.4	1565	83

Coagulant	Time (hr)	OPR	Sanitizer (mg/L)	pH	Conductivity (µs)	Temperature (F)
C	118.5	815	1.5	7.4	1565	83
C	119	815	1.5	7.4	1565	83
C	119.5	815	1.5	7.4	1565	83
C	120	815	1.5	7.4	1565	83
D	0	780	1.8	7.5	1450	83
D	1	780	1.8	7.5	1450	83
D	2	780	1.8	7.5	1450	83
D	3	780	1.8	7.5	1450	83
D	4	780	1.8	7.5	1450	83
D	5	780	1.8	7.5	1450	83
D	6	780	1.8	7.5	1450	83
D	7	780	1.8	7.5	1450	83
D	8	780	1.8	7.5	1450	83
D	9	780	1.8	7.5	1450	83
D	10	780	1.8	7.5	1450	83
D	11	780	1.8	7.5	1450	83
D	12	780	1.8	7.5	1450	83
D	13	780	1.8	7.5	1450	83
D	14	780	1.8	7.5	1450	83
D	15	780	1.8	7.5	1450	83
D	16	780	1.8	7.5	1450	83
D	17	780	1.8	7.5	1450	83
D	18	780	1.8	7.5	1450	83
D	19	780	1.8	7.5	1450	83
D	20	780	1.8	7.5	1450	83
D	21	780	1.8	7.5	1450	83
D	22	780	1.8	7.5	1450	83
D	23	780	1.8	7.5	1450	83
D	24	780	1.8	7.5	1450	83
D	25	780	1.8	7.5	1450	83
D	26	780	1.8	7.5	1450	83
D	27	780	1.8	7.5	1450	83
D	28	780	1.8	7.5	1450	83
D	29	780	1.8	7.5	1450	83
D	30	780	1.8	7.5	1450	83
D	31	780	1.8	7.5	1450	83
D	32	780	1.8	7.5	1450	83
D	33	780	1.8	7.5	1450	83
D	34	780	1.8	7.5	1450	83

Coagulant	Time (hr)	OPR	Sanitizer (mg/L)	pH	Conductivity (µs)	Temperature (F)
D	35	780	1.8	7.5	1450	83
D	36	795	0.8	7.4	1457	83
D	37	795	0.8	7.4	1457	83
D	38	795	0.8	7.4	1457	83
D	39	795	0.8	7.4	1457	83
D	40	795	0.8	7.4	1457	83
D	41	795	0.8	7.4	1457	83
D	42	795	0.8	7.4	1457	83
D	43	795	0.8	7.4	1457	83
D	44	795	0.8	7.4	1457	83
D	45	795	0.8	7.4	1457	83
D	46	795	0.8	7.4	1457	83
D	47	795	0.8	7.4	1457	83
D	48	795	0.8	7.4	1457	83
D	49	795	0.8	7.4	1457	83
D	50	795	0.8	7.4	1457	83
D	51	795	0.8	7.4	1457	83
D	52	795	0.8	7.4	1457	83
D	53	795	0.8	7.4	1457	83
D	54	795	0.8	7.4	1457	83
D	55	795	0.8	7.4	1457	83
D	56	795	0.8	7.4	1457	83
D	57	795	0.8	7.4	1457	83
D	58	795	0.8	7.4	1457	83
D	59	795	0.8	7.4	1457	83
D	60	795	0.8	7.4	1457	83
D	61	795	0.8	7.4	1457	83
D	62	795	0.8	7.4	1457	83
D	63	795	0.8	7.4	1457	83
D	64	795	0.8	7.4	1457	83
D	65	795	0.8	7.4	1457	83
D	66	795	0.8	7.4	1457	83
D	67	795	0.8	7.4	1457	83
D	68	795	0.8	7.4	1457	83
D	69	795	0.8	7.4	1457	83
D	70	795	0.8	7.4	1457	83
D	71	795	0.8	7.4	1457	83
D	72	795	0.8	7.4	1457	83
D	73	795	0.8	7.4	1457	83

Coagulant	Time (hr)	OPR	Sanitizer (mg/L)	pH	Conductivity (µs)	Temperature (F)
D	74	795	0.8	7.4	1457	83
D	75	795	0.8	7.4	1457	83
D	76	795	0.8	7.4	1457	83
D	77	795	0.8	7.4	1457	83
D	78	795	0.8	7.4	1457	83
D	79	795	0.8	7.4	1457	83
D	80	795	0.8	7.4	1457	83
D	81	795	0.8	7.4	1457	83
D	82	795	0.8	7.4	1457	83
D	83	790	0.8	7.4	1457	83
D	84	790	0.7	7.4	1457	83
D	85	790	0.7	7.4	1457	83
D	86	790	0.7	7.4	1457	83
D	87	790	0.7	7.4	1457	83
D	88	790	0.7	7.4	1457	83
D	89	790	0.7	7.4	1457	83
D	90	790	0.7	7.4	1457	83
D	91	790	0.7	7.4	1457	83
D	92	790	0.7	7.4	1457	83
D	93	790	0.7	7.4	1457	83
D	94	790	0.7	7.4	1457	83
D	95	790	0.7	7.4	1457	83
D	96	790	1.5	7.4	1500	83
D	97	790	1.5	7.4	1500	83
D	98	790	1.5	7.4	1500	83
D	99	790	1.5	7.4	1500	83
D	100	790	1.5	7.4	1500	83
D	101	790	1.5	7.4	1500	83
D	102	790	1.5	7.4	1500	83
D	103	790	1.5	7.4	1500	83
D	104	790	1.5	7.4	1500	83
D	105	790	1.5	7.4	1500	83
D	106	790	1.5	7.4	1500	83
D	107	790	1.5	7.4	1500	83
D	108	790	1.5	7.4	1500	83
D	109	790	1.5	7.4	1500	83
D	110	790	1.5	7.4	1500	83
D	111	790	1.5	7.4	1500	83
D	112	790	1.5	7.4	1500	83

Coagulant	Time (hr)	OPR	Sanitizer (mg/L)	pH	Conductivity (µs)	Temperature (F)
D	113	790	1.5	7.4	1500	83
D	114	800	1.5	7.4	1500	83
D	115	800	1.5	7.4	1500	83
D	116	800	1.5	7.4	1500	83
D	117	800	1.5	7.4	1500	83
D	118	800	1.5	7.4	1500	83
D	119	800	1.5	7.4	1500	83
D	120	800	1.5	7.4	1500	83
D	121	800	1.5	7.4	1500	83
D	122	800	1.5	7.4	1500	83
D	123	800	1.5	7.4	1500	83
D	124	800	1.5	7.4	1500	83
D	125	800	1.5	7.4	1500	83
D	126	800	1.5	7.4	1500	83
D	127	800	1.5	7.4	1500	83
D	128	800	1.5	7.4	1500	83
D	129	800	1.5	7.4	1500	83
D	130	800	1.5	7.4	1500	83
D	131	800	1.5	7.4	1500	83
D	132	800	1.5	7.4	1500	83
D	133	800	1.5	7.4	1500	83
D	134	800	1.5	7.4	1500	83
D	135	800	1.5	7.4	1500	83
D	136	795	1.6	7.4	1555	83
D	137	795	1.6	7.4	1555	83
D	138	795	1.6	7.4	1555	83
D	139	795	1.6	7.4	1555	83
D	140	795	1.6	7.4	1555	83
D	141	795	1.6	7.4	1555	83
D	142	795	1.6	7.4	1555	83
D	143	795	1.6	7.4	1555	83
D	144	795	1.6	7.4	1555	83

APPENDIX M: RAW DATA OF PILOT-SCALE SWIMMING POOL EXPERIMENTS

Coagulant A						
Time (hr)	8	16	24	32	40	48
dose (X)	1	2	3	4	5	6
Coagulant concentration (mg/L)	1.56	3.12	4.68	6.24	7.8	9.36
Removal	98.70%	98.90%	84.24%	80.98%	72.52%	65.63%
	98.80%	98.78%	84.00%	82.09%	65.03%	59.27%
	98.79%	99.02%	82.97%	81.15%	62.97%	58.37%
	98.50%	98.86%	86.44%	85.00%	63.52%	47.83%
	99.10%	98.74%				
	98.98%	98.65%				

Coagulant B						
Time (hr)	8	16	24	32	40	48
dose (X)	1	2	3	4	5	6
Coagulant Concentration (mg/L)	1.56	3.12	4.68	6.24	7.8	9.36
Removal	99.05%	98.57%	88.24%	83.03%	67.39%	54.12%
	99.06%	98.41%	88.75%	82.78%	67.26%	46.88%
	98.95%	98.57%	87.82%	82.61%	66.74%	44.33%
	98.98%	98.86%	86.44%	85.00%	63.52%	66.29%
	99.10%	98.74%	86.89%	83.52%	70.45%	64.04%
	98.98%	98.65%	83.11%	84.57%	67.89%	61.11%

Coagulant C					
Time (hr)	24	48	96	144	176
dose (X)	3	6	12	18	22
Coagulant concentration (mg/L)	4.68	9.36	18.72	28.08	34.32
Removal	69.41%	65.47%	63.07%	72.41%	64.84%
	68.54%	68.33%	59.78%	72.22%	57.00%
	67.47%	63.64%	66.14%	70.79%	69.57%
	66.67%	64.55%	69.32%	61.11%	69.23%
	66.07%	67.42%	69.66%	65.00%	58.89%
	64.44%	60.23%	68.18%	66.29%	54.46%

Coagulant D																		
Time (hr)	8	16	24	32	40	48	56	64	72	80	88	96	104	112	120	128	136	144
dose (X)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
coag. conc	1.01	2.02	3.03	4.04	5.05	6.06	7.07	8.08	9.09	10.1	11.11	12.12	13.13	14.14	15.15	16.16	17.17	18.18
Removal	98.51%	99.15%	98.55%	97.95%	98.92%	96.98%	96.02%	84.00%	78.41%	81.19%	75.00%	73.63%	75.00%	73.49%	72.83%	70.00%	61.54%	49.44%
	97.81%	98.88%	98.71%	97.92%	98.66%	96.67%	96.00%	84.92%	78.65%	79.77%	73.26%	72.22%	75.56%	71.11%	67.47%	69.57%	67.39%	50.55%
	98.04%	99.01%	98.26%	98.09%	98.57%	97.50%	95.80%	84.88%	77.27%	81.01%	75.58%	71.74%	71.91%	75.82%	63.41%	69.23%	63.33%	53.85%
	98.35%	99.21%	98.59%	97.33%	98.92%	96.98%		88.89%		78.02%		76.27%						
	97.22%	98.97%	98.76%	97.25%	98.66%	96.67%		89.57%		76.67%		76.06%						
	97.83%	99.10%	98.19%	97.61%	98.57%	97.50%		89.55%		76.09%		75.84%						

Coagulant E	37	37	37	33	33	33	30	30	30	30	30	30	30	30	30	30	30	30
Flow rate																		
PAX conc. (m	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
removal	67.00%	36.00%	57.00%	83.00%	91.90%	89.56%	98.80%	98.56%	98.80%	99.16%	98.86%	97.71%	98.33%	92.34%	98.33%	96.78%	98.68%	98.68%
	51.00%	39.00%	54.00%	89.00%	95.50%	80.90%	93.62%	98.91%	93.62%	98.88%	98.98%	96.74%	98.56%	98.82%	98.54%	98.37%	98.09%	98.37%
	68.00%	60.00%	47.00%	81.00%	92.60%	90.52%	97.89%	93.52%	97.89%	99.06%	98.84%	96.70%	98.70%	98.28%	98.17%	98.59%	98.78%	98.60%

Coagulant F								
Dose	0.16	0.78	1.56	3.12	4.68	6.24	7.8	9.36
% removal	92.61%	99.19%	97.44%	98.90%	84.24%	80.98%	59.82%	45.98%
	91.82%	99.66%	96.86%	98.78%	84.00%	82.09%	65.03%	38.91%
	92.47%	99.43%	97.79%	99.02%	82.97%	81.15%	62.97%	41.51%
	97.16%	99.43%	91.28%					
	97.08%	99.10%	91.46%					
	96.32%	99.43%	91.84%					
	97.13%	97.47%	98.70%					
	97.33%	98.28%	98.80%					
	97.01%	97.91%	98.79%					
	98.02%							
	97.93%							
	97.91%							

APPENDIX N: FULL-SCALE SWIMMING POOL WATER CHARACTERISTICS

Pool #1	Filter Pressure (psi)			Pool measurements				
	pre-bw	post-bw	pre-seeding	pH	FC (mg/L)	Turbidity (NTU)	Conductivity (µs)	Temp (°C)
	ND	17		ND	ND	ND	ND	ND
	17.5	17.5		ND	0.58	0.303	1366	32.8
			17.5	7.615	3.02	0.169	1389	32.5
	18	17.5		ND	4.3	1.41	1491	32.9
			17.5	7.2	3.4	2.74	1467	32.1
			17.5	7.103	4.07	0.248	ND	32.2
	17.8	17.4		6.948	5.22	5.6	1562	32.1
			16	7.121	4.28	6.8	1550	31.4
	16	16.3		7.153	4.5	2	1680	31.8
			16.5	7.133	2.5	0.595	2170	29.4

	Filter Pressure (psi)			Pool measurements				
Pool #2	pre-bw	post-bw	pre-seeding	pH	FC (mg/L)	Turbidity (NTU)	Conductivity (µs)	Temp (°C)
	ND	22		ND	ND	ND	ND	ND
	23	20		ND	0.93	0.656	1206	33.1
			22.5	7.4	3	1.26	1189	33
	24.5	23.5		7.7	5.64	7.01	1259	32.7
			17	7	3.63	1.5	1308	31.9
			18	7	5.29	2.41	ND	32.2
	17	17		7	5.92	3.18	1389	31.8
			16	7	4.37	0.37	1346	31.3
	16	16		7.1	5.45	3.05	1553	31.9
			16	6.9	2.56	1.62	1774	31.6

	Filter Pressure (psi)			Pool measurements				
Pool #3	**pre-bw**	**post-bw**	**pre-seeding**	**pH**	**FC (mg/L)**	**Turbidity (NTU)**	**Conductivity (µs)**	**Temp (°C)**
	ND	21		ND	ND	ND	ND	ND
	22.3	22.3		ND	2.62	0.192	1088	35
			22	7.679	3.26	0.433	1214	32.6
	22.2	22.2		7.137	1.56	5.4	1215	32.8
			22	7.235	1.92	1.58	1289	32.1
			22	ND	1.23	0.362	ND	32.1
	22.7	22		6.983	2.28	3.67	1342	32
			23	7.048	1.88	1.54	1334	31.2
	22	21.8		7.069	2.31	2.7	1495	31.8
			22	7.14	2.21	0.837	1687	31.6

	Filter Pressure (psi)			Pool measurements				
Pool #4	**pre-bw**	**post-bw**	**pre-seeding**	**pH**	**FC (mg/L)**	**Turbidity (NTU)**	**Conductivity (µs)**	**Temp (°C)**
	ND	20.5		ND	ND	ND	ND	ND
	23	20		ND	2.93	4.02	1253	35.1
			23.5	7.394	3.31	1	1344	32.7
	24.8	20		6.745	2.52	0.588	1394	32.7
			23	7.307	2.57	8.64	1505	31.1
	23.9	20		7.322	3.46	6.24	1633	31.8
	23	20		7.431	3.11	3.89	1662	31.7

Pool #1	Measurements pre-seeding						
	pH - ctlr	ORP (mV) - ctlr	filter flow rate (gpm	CCA #1	CCA #2	CCA #3	CCA #4
	7.7	677	28.1	-3.28	-2.96	-2.93	
	7.6	574	28	-2.28	-2.27		
	7.7	652	29.9	-2.75	-2.64	-2.57	-2.54
	7.2	705	29.5	-0.1	-1.65	-2.33	-2.27
	7.2	706	30.2	-2.52	-2.25	-2.17	-1.96
	7.2	700	30.2	-2	-1.9		
	7.2	712	29.5	-1.87	-1.77		
	7.2	699	34.5	-1.87	-1.64	-1.58	
	7.2	700	32.3	-2.26	-2.16		
	7.2	678	34.4	-0.6	0.01	0.32	0.53

	Measurements pre-seeding						
Pool #2	pH - ctlr	ORP (mV) - ctlr	filter flow rate (gpm	CCA #1	CCA #2	CCA #3	CCA #4
	6.2	728	33.1	-2.87	-2.71	-2.67	
	7.5	700	38.8	-3.04	-2.71	-2.44	-2.4
	7.4	697	33.7	-3.07	-2.99	-3.02	
	7.2	781	27	-2.8	-2.74		
	7.2	740	27.4	-3.07	-2.94	-2.96	
	7.3	777	27.6	-2.4	-2.4		
	7.2	789	26.7	-1.52	-1.5		
	7.2	772	33.3	-2.09	-2.06		
	6.9	797	33.3	-2.45	-2.42		
	7.1	752	32.6	-0.62	-0.61		

	Measurements pre-seeding						
Pool #3	**pH - ctlr**	**ORP (mV) - ctlr**	**filter flow rate (gpm**	**CCA #1**	**CCA #2**	**CCA #3**	**CCA #4**
	7.4	728	37.2	-3.21	-3.04	-3.01	
	7.4	735	32.3	-2.5	-2.3	-2.22	
	7.6	764	32.7	-2.63	-2.38	-2.26	-2.22
	7.3	736	32.8	-2.64	-2.55	-2.47	-2.44
	7.4	706	32.3	-2.57	-2.13	-1.72	-1.65
	7.2	704	32.2	-2.28	-2.14	-2.09	
	7.2	728	33	-1.64	-1.54		
	7.2	722	34.1	-2.09	-2.05		
	7.2	716	34.4	-2.62	-2.59		
	7.2	715	35	-0.03	0.26	0.42	

	Measurements pre-seeding						
Pool #4	**pH - ctlr**	**ORP (mV) - ctlr**	**filter flow rate (gpm**	**CCA #1**	**CCA #2**	**CCA #3**	**CCA #4**
	7.2	682	29	-2.55	-2.42	-2.18	-2.17
	7.2	707	37.2	-2.34	-1.85	-1.8	
	7.4	700	18	-2.72	-2.45	-2.36	-2.31
	7	736	32.2	-2.32	-2.19	-2.2	
	7.4	726	28	-2.05	-1.94		
	7.3	754	34.2	-1.91	-1.8		
	7.4	750	34.2	-0.56	-0.58		

Pool #1	Measurements pre-seeding						
	pH - ctlr	ORP (mV) - ctlr	filter flow rate (gpm)	CCA #1	CCA #2	CCA #3	CCA #4
	7.7	677	28.1	-3.28	-2.96	-2.93	
	7.6	574	28	-2.28	-2.27		
	7.7	652	29.9	-2.75	-2.64	-2.57	-2.54
	7.2	705	29.5	-0.1	-1.65	-2.33	-2.27
	7.2	706	30.2	-2.52	-2.25	-2.17	-1.96
	7.2	700	30.2	-2	-1.9		
	7.2	712	29.5	-1.87	-1.77		
	7.2	699	34.5	-1.87	-1.64	-1.58	
	7.2	700	32.3	-2.26	-2.16		
	7.2	678	34.4	-0.6	0.01	0.32	0.53

	Measurements pre-seeding						
Pool #2	pH - ctlr	ORP (mV) - ctlr	filter flow rate (gpm)	CCA #1	CCA #2	CCA #3	CCA #4
	6.2	728	33.1	-2.87	-2.71	-2.67	
	7.5	700	38.8	-3.04	-2.71	-2.44	-2.4
	7.4	697	33.7	-3.07	-2.99	-3.02	
	7.2	781	27	-2.8	-2.74		
	7.2	740	27.4	-3.07	-2.94	-2.96	
	7.3	777	27.6	-2.4	-2.4		
	7.2	789	26.7	-1.52	-1.5		
	7.2	772	33.3	-2.09	-2.06		
	6.9	797	33.3	-2.45	-2.42		
	7.1	752	32.6	-0.62	-0.61		

	Measurements pre-seeding						
Pool #3	**pH - ctlr**	**ORP (mV) - ctlr**	**filter flow rate (gpm)**	**CCA #1**	**CCA #2**	**CCA #3**	**CCA #4**
	7.4	728	37.2	-3.21	-3.04	-3.01	
	7.4	735	32.3	-2.5	-2.3	-2.22	
	7.6	764	32.7	-2.63	-2.38	-2.26	-2.22
	7.3	736	32.8	-2.64	-2.55	-2.47	-2.44
	7.4	706	32.3	-2.57	-2.13	-1.72	-1.65
	7.2	704	32.2	-2.28	-2.14	-2.09	
	7.2	728	33	-1.64	-1.54		
	7.2	722	34.1	-2.09	-2.05		
	7.2	716	34.4	-2.62	-2.59		
	7.2	715	35	-0.03	0.26	0.42	

	Measurements pre-seeding						
Pool #4	**pH - ctlr**	**ORP (mV) - ctlr**	**filter flow rate (gpm)**	**CCA #1**	**CCA #2**	**CCA #3**	**CCA #4**
	7.2	682	29	-2.55	-2.42	-2.18	-2.17
	7.2	707	37.2	-2.34	-1.85	-1.8	
	7.4	700	18	-2.72	-2.45	-2.36	-2.31
	7	736	32.2	-2.32	-2.19	-2.2	
	7.4	726	28	-2.05	-1.94		
	7.3	754	34.2	-1.91	-1.8		
	7.4	750	34.2	-0.56	-0.58		

	Measurements pre-seeding						
Pool #5	**pH - ctlr**	**ORP (mV) - ctlr**	**filter flow rate (gpm)**	**CCA #1**	**CCA #2**	**CCA #3**	**CCA #4**
	7.4	570	ND	-2.52	-2.41	-2.35	-2.35
	7.7	649	27.2	-2.38	-2.27	-2.21	
	7.4	651	25	-2.47	-2.44		
	7.2	695	25.2	-2.69	-2.58	-2.56	
	7.2	685	15.3	-2.4	-2.39		
	7.2	686	9.2	-2.13	-2.09		

Measurements post-sampling		Seeding (time)	
Pool #5	**ORP (mV) - ctlr**	**Start**	**End**
	547	2:50	3:46
	654	12:07	1:05
	652	9:24	10:13
	704	12:25	1:14
	681	10:57	11:41
	685	10:31	11:15

			Pool measurements				
Pool #5		**Filter Pressure (psi)**	**pH**	**FC (mg/L)**	**Turbidity (NTU)**	**Conductivity (µs)**	**Temp (°C)**
	pre-DE	16			ND		
	pre-bump	18	6.954	1.83		1535	31.2
	post-bump	26.2					
	pre-bump	25.4			1.89		
	post-bump	28.7	6.869	2.25		1642	31.4
	pre-bw	17			ND		
	pre-DE	16					
	pre-bump		7.04	2.37		1672	32
	post-bump						
	pre-bump	17	7.019	1.08	1.09	1731	30.5
	post-bump	17					
	post-seeding	16					

	Measurements pre-seeding							
Pool #5	**pH - ctlr**	**ORP (mV) - ctlr**	**filter flow rate (gpm)**	**CCA #1**	**CCA #2**	**CCA #3**	**CCA #4**	**Pool #5**
			26					
	7.2	680	27.2	-2.03	-2.01			
	7.2	686	16	-2.28	-2.21			
	7.2	688	29	-1.52	-1.47			
	7.2	653	29.3	-2.21	-2.07			
			25.9					
			27.7					

Measurements post-sampling		Seeding (time)	
pH - ctlr	**ORP (mV) - ctlr**	**Start**	**End**
7.1	676	12:16	12:58
7.2	680	1:15	1:58
7.2	688	11:10	11:57
7.2	685	12:12	1:08
7.2	685	1:39	2:25
7.2	661	10:44	11:31

APPENDIX O: RAW DATA OF FULL-SCALE SWIMMING POOL EXPERIMENTS MEASURED BY CDC

INFLUENT					
		C. parvum		Microspheres	
Sample	Vol analyzed (ml)	Slide count	Conc (oocysts/100 ml)	Slide count	Conc (#/100 ml)
B1 inf 1	5	0	<20	4	80
B1 inf 2	5	0	<20	0	<20
B1 inf 3	100	5	5	27	27
B2 inf 1	5	0	<20	1	20
B2 inf 2	5	0	<20	1	20
B2 inf 3	100	9	9	14	14
B3 inf 2	100	8	8	10	10
B6 inf 2	100	55	55	122	122
B7 inf 2	100	68	68	139	139
B8 inf 2	100	88	88	115	115
B9 inf 1	450	347	77	439	98
B10 inf 1	450	506	112	630	140
B11 inf 1	450	121	27	133	30
B12 inf 1	100	8	8	17	17
B12 inf 2	300	179	60	327	109
B13 inf 1	100	118	118	167	167

D1 inf 1	5	0	<20	6	120
D1 inf 2	5	0	<20	2	40
D1 inf 3	100	2	2	20	20
D3 inf 2,3	100	12	12	43	43
D6 inf 2	100	116	116	104	104
D7 inf 2	100	112	112	203	203
D8 inf 2,3	100	28	28	56	56
D9 inf 1	450	429	95	81	18
D10 inf 1	450	1050	233	1864	414
D11 inf 1	450	582	129	858	191
D12 inf 1	100	132	132	230	230
D13 inf 1	100	190	190	275	275
F1 inf 1	5	1	20	0	<20
F1 inf 2	5	0	<20	5	100
F1 inf 3	100	16	16	26	26
F2 inf 1	5	0	<20	0	<20
F2 inf 2	5	0	<20	1	20
F2 inf 3	100	11	11	34	34
F3 inf 2	100	9	9	44	44
F6 inf 1, 2	100	119	119	227	227
F7 inf 1,2	100	88	88	174	174
F8 inf 1,2	100	60	60	108	108
F9 inf 1	450	560	124	846	188
F10 inf 1	450	258	57	500	111
F11 inf 1	450	293	65	664	148
F12 inf 1	100	139	139	179	179
F13 inf 1	100	194	194	297	297

E1 inf 1	5	1	20	0	<20
E1 inf 2	5	0	<20	3	60
E1 inf 1,2,3	127.5	22	17	44	35
E2 inf 1	5	1	20	2	40
E2 inf 2	5	0	<20	0	<20
E2 inf 1,2,3	140	5	4	40	29
E3 inf 1,2	100	12	12	38	38
E6 inf 1,2	100	43	43	209	209
E7 inf 1,2	100	37	37	150	150
E8 inf 1	100	159	159	316	316
E9 inf 1	100	22	22	45	45
E10 inf 1	100	49	49	67	67
Perlite inf 1,2	100	8	8	29	29
DE 1 inf 1	450	239	53	296	66
DE 2 inf 1	450	216	48	207	46
DE 3 inf	100	65	65	67	67
DE 4 inf	100	87	87	95	95
DE 5 inf	100	55	55	75	75
DE 6 inf	100	39	39	84	84

EFFLUENT							
		C. parvum		Microspheres		Estimated Removal (%)	
Sample	Vol analyzed (ml)	Slide count	Conc (oocysts/100 ml)	Slide count	Conc (#/100 ml)	*C. parvum*	Microspheres
B1 eff 1	1000	24	2	35	4	61	88
B1 eff 2	1000	15	2	28	3		
B2 eff 1	1000	9	1	13	1	88	89
B2 eff 2	1000	12	1	18	2		
B3 eff 1	1000	0	<0.1	5	1		94
B3 eff 2	1000	2	<0.1	7	1		
B6 eff 1	1000	147	15	580	58	73	52
B7 eff 1	1000	189	19	441	44	72	68
B8 eff 1	1000	63	6	113	11	93	90
B9 eff 1	1000	139	14	471	47	82	52
B8 eff 1	1000	63	6	113	11	93	90
B9 eff 1	1000	139	14	471	47	82	52
B10 eff 1	1000	335	34	977	98	70	30
B11 eff 1	1000	97	10	382	38	64	
B12 eff 1	1000	149	15	602	60	75	45
B13 eff 1	1000	842	84	1832	183	24	
B13 eff 3	250	239	96	604	242		

D1 eff 1	1000	12	1	83	8	50	38
D1 eff 2	1000	8	1	165	17		
D3 eff 1	1000	0	<0.1	14	1	>92	96
D3 eff 2	1000	0	<0.1	23	2		
D6 eff 1	1000	30	3	656	66	96	
D6 eff 2	1000	71	7	1607	161		
D7 eff 1	1000	15	2	26	3	99	99
D8 eff 1	1000	14	1	387	39	89	25
D8 eff 2	1000	46	5	455	46		
D9 eff 1	1000	63	6	195	20	96	27
D9 eff 2	1000	17	2	69	7		
D10 eff 1	1000	23	2	43	4	99	99
D11 eff 1	1000	52	5	156	16	96	92
D12 eff 1	1000	21	2	28	3	98	99
D13 eff 1	1000	125	13	248	25	93	91
F1 eff 1	1000	96	10	107	11	58	48
F1 eff 2	1000	40	4	164	16		
F2 eff 1	1000	5	1	17	2	91	92
F2 eff 2	1000	14	1	36	4		
F3 eff 1	1000	7	1	38	4	92	91
F6 eff 1	1000	228	23	1488	149	83	41
F6 eff 3	250	44	18	293	117		
F7 eff 1	1000	448	45	1686	169	65	29
F7 eff 3	250	44	18	192	77		
F8 eff 1	1000	211	21	670	67	65	38
F9 eff 1	1000	444	44	1622	162	79	49
F9 eff 3	250	17	7	74	30		
F10 eff 1	1000	410	41	1714	171	43	
F10 eff 3	250	60	24	196	78		
F11 eff 1	1000	312	31	1237	124	62	34
F11 eff 3	250	47	19	175	70		
F12 eff 1	1000	201	20	442	44	86	75
F13 eff 1	1000	984	98	2664	266	53	12
F13 eff 3	250	210	84	642	257		
E1 eff 1	1000	77	8	181	18	70	71
E1 eff 2	1000	27	3	20	2		
E2 eff 1	1000	3	<0.1	12	1	>72	97
E2 eff 2	1000	2	<0.1	8	1		
E3 eff 1	1000	1	<0.1	4	<0.1	>92	>97

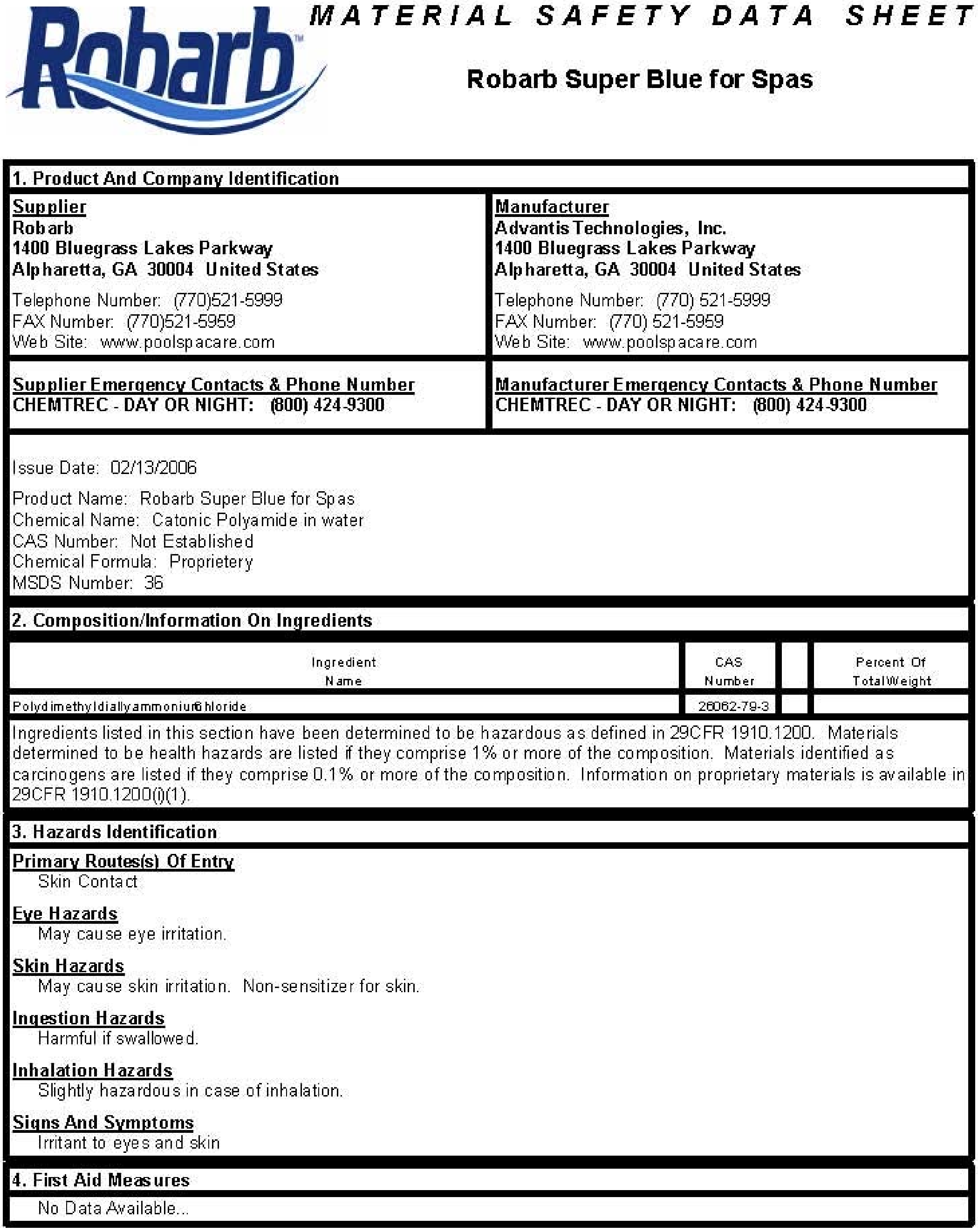
E3 eff 2	1000	2	<0.1	7	1		
E6 eff 1	1000	16	2	795	80	96	62
E7 eff 1	1000	99	10	816	82	73	46
E8 eff 1	1000	28	3	1127	113	98	64
E9 eff 1	1000	112	11	783	78	43	
E9 eff 2	1000	140	14	719	72		
E10 eff 1	1000	384	38	674	67	48	
E10 eff 3	1000	121	12	821	82		
Perlite eff 1	1000	4	<0.1	4	<0.1	>88	>97
DE 1 eff 1	1000	0	<0.1	2	<0.1	>99.8	>99.8
DE 2 eff 1	1000	0	<0.1	3	<0.1	>99.8	>99.8
DE 3 eff 1	1000	11	1	13	1	98	98
DE 4 eff 1	1000	0	<0.1	0	<0.1	>99.9	>99.9
DE 5 eff	1000	0	<0.1	1	<0.1	>99.8	>99.9
DE 6 eff	1000	1	<0.1	1	<0.1	>99.7	>99.9

APPENDIX P: RAW DATA OF FULL-SCALE SWIMMING SPA EXPERIMENTS

Cartridge Filter with Coagulant						
Does (mg/L)	1.56	3.12	4.68	6.24	7.8	9.36
Removal	86.73%	73.20%	69.80%	67.61%	22.54%	38.79%
	79.59%	62.89%	41.41%	56.19%	27.10%	10.19%
	80.91%	78.16%	69.71%	41.58%	24.44%	36.54%
	73.74%	67.35%	49.02%	43.81%	17.12%	8.33%
	80.00%	78.22%	78.35%	45.26%	7.89%	22.08%
	80.00%	60.61%	51.96%	50.94%	19.09%	11.71%

Control	with DE
36.79%	99.00%
18.56%	99.19%
11.76%	99.11%
	92.86%

APPENDIX Q: MATERIAL SAFETY DATA SHEETS



Robarb™

MATERIAL SAFETY DATA SHEET

Robarb Super Blue for Spas

1. Product And Company Identification

Supplier **Robarb** **1400 Bluegrass Lakes Parkway** **Alpharetta, GA 30004 United States** Telephone Number: (770)521-5999 FAX Number: (770)521-5959 Web Site: www.poolspacare.com	**Manufacturer** **Advantis Technologies, Inc.** **1400 Bluegrass Lakes Parkway** **Alpharetta, GA 30004 United States** Telephone Number: (770) 521-5999 FAX Number: (770) 521-5959 Web Site: www.poolspacare.com
Supplier Emergency Contacts & Phone Number **CHEMTREC - DAY OR NIGHT: (800) 424-9300**	**Manufacturer Emergency Contacts & Phone Number** **CHEMTREC - DAY OR NIGHT: (800) 424-9300**

Issue Date: 02/13/2006

Product Name: Robarb Super Blue for Spas
Chemical Name: Catonic Polyamide in water
CAS Number: Not Established
Chemical Formula: Proprietery
MSDS Number: 36

2. Composition/Information On Ingredients

Ingredient Name	CAS Number		Percent Of Total Weight
PolydimethyldiallyammoniumChloride	26062-79-3		

Ingredients listed in this section have been determined to be hazardous as defined in 29CFR 1910.1200. Materials determined to be health hazards are listed if they comprise 1% or more of the composition. Materials identified as carcinogens are listed if they comprise 0.1% or more of the composition. Information on proprietary materials is available in 29CFR 1910.1200(i)(1).

3. Hazards Identification

Primary Routes(s) Of Entry
Skin Contact

Eye Hazards
May cause eye irritation.

Skin Hazards
May cause skin irritation. Non-sensitizer for skin.

Ingestion Hazards
Harmful if swallowed.

Inhalation Hazards
Slightly hazardous in case of inhalation.

Signs And Symptoms
Irritant to eyes and skin

4. First Aid Measures

No Data Available...

MATERIAL SAFETY DATA SHEET

Robarb Super Blue for Spas

4. First Aid Measures - Continued

Eye

In case of contact, hold eyelids apart and immediately flush eyes with plenty of water for at least 15 minutes.

Skin

Remove contaminated clothing and shoes.Rinse the affected area with tepid water for at least 15 minutes.

Ingestion

DO NOT INDUCE VOMITING. Drink large amounts of water or milk. Contact a physician or poison control. In cases where individual is semi-comatose, comatose, or convulsing, DO NOT GIVE FLUIDS BY MOUTH.

Inhalation

If inhaled, remove to fresh air.

Fire Fighting (Pictograms)

5. Fire Fighting Measures

Flash Point: >100 °C
Flash Point Method: Closed Cup
Flammability Class: NOT FLAMMABLE

Fire And Explosion Hazards

In a fire situation, may liberate oxides of nitrogen or carbon, and hydrogen chloride.

Extinguishing Media

Use the appropriate extinguishing media for the surrounding fire.

Fire Fighting Instructions

CAUTION Surfaces wet with this product are slippery. Keep containers cool by spraying with water if exposed to fire.

6. Accidental Release Measures

Clean up spill immediately. Contain and/or absorb spill with inert material (e.g. sand, vermiculite). Flush spill area with water. Use appropriate containers to avoid environmental contamination.
CAUTION Surfaces wet with this product are slippery.

7. Handling And Storage

Handling And Storage Precautions

Keep out of reach of children. Store material in a cool and dry place. Wash thoroughly after handling.

Storage Precautions

Avoid contact with skin and clothing.

Work/Hygienic Practices

Wash thoroughly with soap and water after handling.

MATERIAL SAFETY DATA SHEET

Robarb Super Blue for Spas

7. Handling And Storage - Continued

Protective Clothing (Pictograms)

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8. Exposure Controls/Personal Protection

Engineering Controls

Local exhaust acceptable. Special exhaust not required.

Eye/Face Protection

Safety glasses with side shields or goggles recommended.

Skin Protection

Chemical-resistant gloves.

Respiratory Protection

None normally required.

9. Physical And Chemical Properties

Appearance

Clear Blue

Odor

Mild amine

Chemical Type: Mixture
Physical State: Liquid
Melting Point: NOT APPLICABLE °F
Boiling Point: 212 °F
Specific Gravity: 1.0-1.1
Molecular Weight: Proprietary
Percent Volitales: NEGLIGIBLE
Packing Density: NOT DETERMINED
Vapor Pressure: NOT DETERMINED
Vapor Density: NOT DETERMINED
pH Factor: 2-3
Solubility: Soluble in Water
Viscosity: NOT DETERMINED
Evaporation Rate: <1

10. Stability And Reactivity

Stability: Stable
Hazardous Polymerization: will not occur

Conditions To Avoid (Stability)

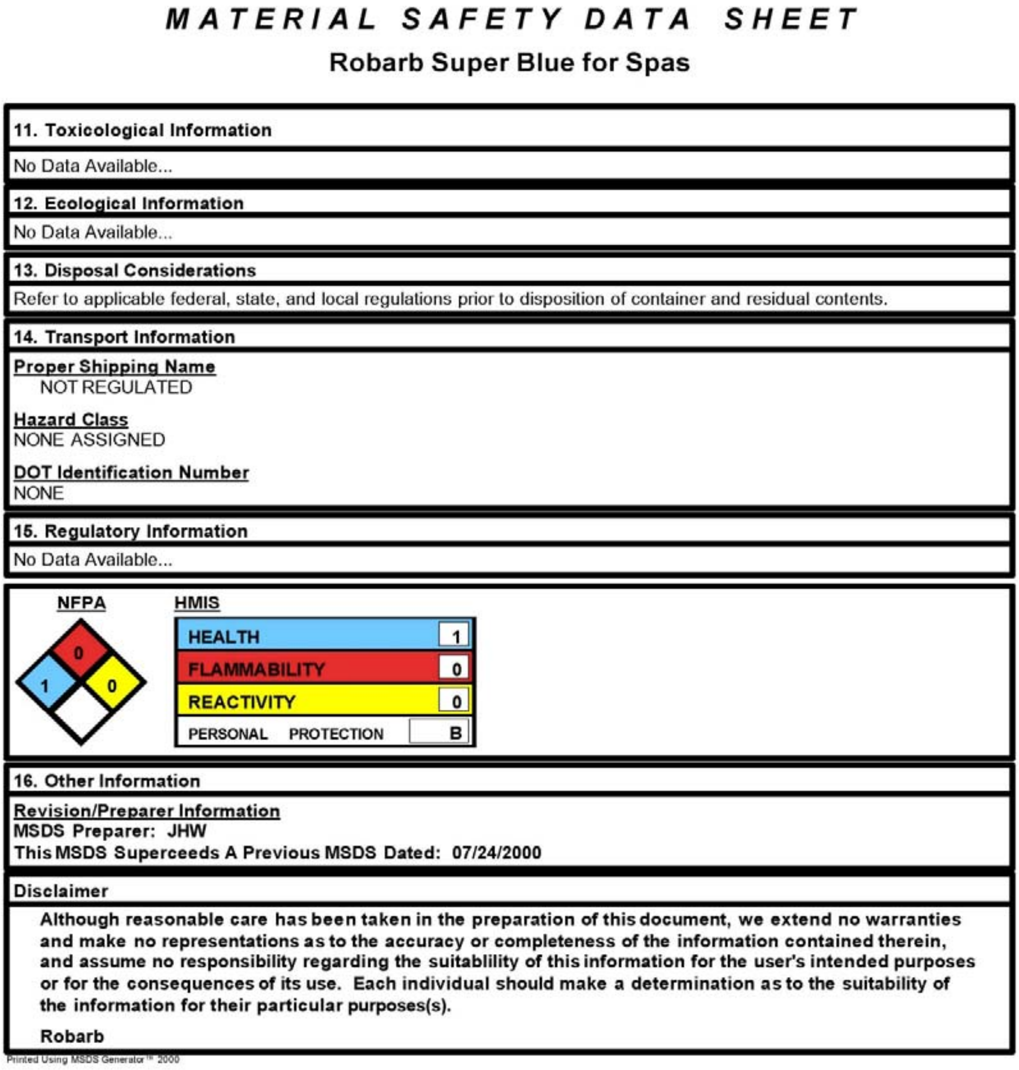
Strong Oxidizers

Incompatible Materials

Avoid contact with strong oxidizers

Hazardous Decomposition Products

When heated toxic fumes such as Oxides of Carbon, Nitrogen and Hydrogen chloride may be present



MATERIAL SAFETY DATA SHEET

Robarb Super Blue for Spas

11. Toxicological Information

No Data Available...

12. Ecological Information

No Data Available...

13. Disposal Considerations

Refer to applicable federal, state, and local regulations prior to disposition of container and residual contents.

14. Transport Information

Proper Shipping Name
NOT REGULATED

Hazard Class
NONE ASSIGNED

DOT Identification Number
NONE

15. Regulatory Information

No Data Available...

NFPA

HMIS

HEALTH	1
FLAMMABILITY	0
REACTIVITY	0
PERSONAL PROTECTION	B

16. Other Information

Revision/Preparer Information
MSDS Preparer: JHW
This MSDS Superceeds A Previous MSDS Dated: 07/24/2000

Disclaimer

Although reasonable care has been taken in the preparation of this document, we extend no warranties and make no representations as to the accuracy or completeness of the information contained therein, and assume no responsibility regarding the suitablility of this information for the user's intended purposes or for the consequences of its use. Each individual should make a determination as to the suitability of the information for their particular purposes(s).

Robarb

Printed Using MSDS Generator™ 2000

MATERIAL SAFETY DATA SHEET

MSDS

BioGuard Polysheen Blue

Date-Issued:01/20/1997
MSDS Ref. No:BBIO23721
Date-Revised:11/28/2001
Revision No:6

1. PRODUCT AND COMPANY IDENTIFICATION

PRODUCT NAME: BioGuard Polysheen Blue
GENERAL USE: Water clarifier

MANUFACTURER
Bio-Lab, Inc.
BioGuard
P.O. Box 1489
Decatur, GA 30031
Customer SERVICE: 800-859-7946

24 HR. EMERGENCY TELEPHONE NUMBERS
CHEMTREC (Transportation) (800) 424-9300
Poison Control Center (Medical) 877-800-5553

2. COMPOSITION / INFORMATION ON INGREDIENTS

Chemical Name	CAS#	Wt.%
Contains less than 1% of a Hazardous Material.		

COMMENTS: Ingredients listed in this section have been determined to be hazardous as defined in 29 CFR 1910.1200. Materials determined to be health hazards are listed if they comprise 1% of more of the composition. Materials identified as carcinogens are listed if they comprise 0.1% or more of the composition. Information on proprietary materials is available as provided in 29 CFR 1910.1200.

3. HAZARDS IDENTIFICATION

EMERGENCY OVERVIEW
PHYSICAL APPEARANCE: Blue liquid.

IMMEDIATE CONCERNS: CAUTION: Avoid contact with eyes, skin and clothing. Do not mix with other chemicals.

POTENTIAL HEALTH EFFECTS
EYES: This product is not expected to cause eye irritation. However, in accordance with good personal hygiene practices, avoid contact with eyes.

SKIN: This product is not expected to cause skin irritation. However, in accordance with good personal hygiene practices, avoid contact with skin or clothing.

INGESTION: No evidence of adverse effects from available information.

INHALATION: May be irritating to nose and throat. Avoid breathing vapors.

ROUTES OF ENTRY: Skin Contact, Eye Contact, Inhalation.

COMMENTS HEALTH: There are no known chronic hazards.

4. FIRST AID MEASURES

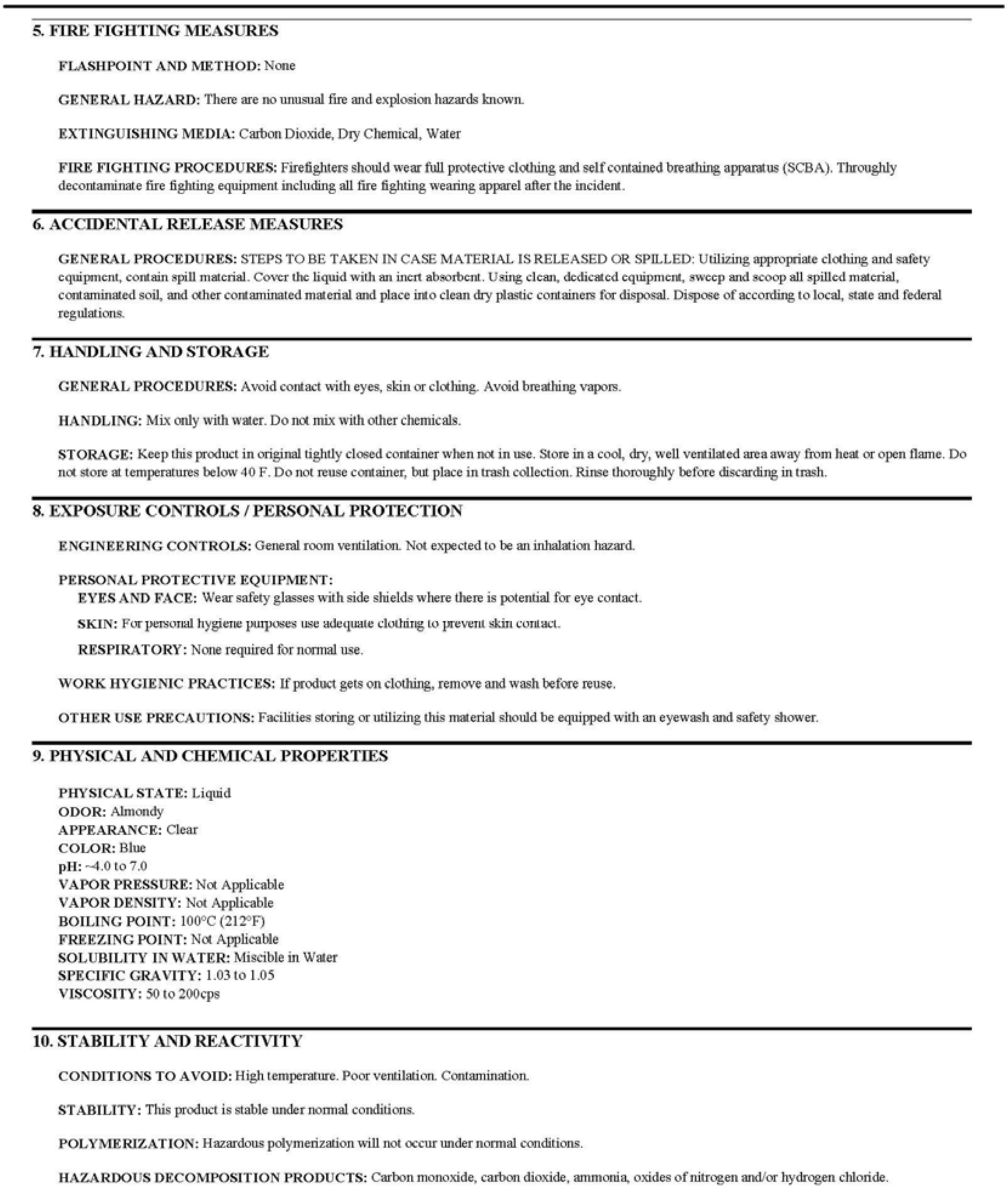
EYES: If in eyes: Flush eyes with plenty of water. Get medical attention if irritation persists.

SKIN: If on skin: Wash with plenty of soap and water. Get medical attention if irritation develops.

INGESTION: Not an expected route of overexposure.

INHALATION: If inhaled: Remove to fresh air. If breathing is difficult, have trained person administer oxygen. If not breathing, give artificial respiration. Call a physician immediately.

BioGuard Polysheen Blue



5. FIRE FIGHTING MEASURES

FLASHPOINT AND METHOD: None

GENERAL HAZARD: There are no unusual fire and explosion hazards known.

EXTINGUISHING MEDIA: Carbon Dioxide, Dry Chemical, Water

FIRE FIGHTING PROCEDURES: Firefighters should wear full protective clothing and self contained breathing apparatus (SCBA). Throughly decontaminate fire fighting equipment including all fire fighting wearing apparel after the incident.

6. ACCIDENTAL RELEASE MEASURES

GENERAL PROCEDURES: STEPS TO BE TAKEN IN CASE MATERIAL IS RELEASED OR SPILLED: Utilizing appropriate clothing and safety equipment, contain spill material. Cover the liquid with an inert absorbent. Using clean, dedicated equipment, sweep and scoop all spilled material, contaminated soil, and other contaminated material and place into clean dry plastic containers for disposal. Dispose of according to local, state and federal regulations.

7. HANDLING AND STORAGE

GENERAL PROCEDURES: Avoid contact with eyes, skin or clothing. Avoid breathing vapors.

HANDLING: Mix only with water. Do not mix with other chemicals.

STORAGE: Keep this product in original tightly closed container when not in use. Store in a cool, dry, well ventilated area away from heat or open flame. Do not store at temperatures below 40 F. Do not reuse container, but place in trash collection. Rinse thoroughly before discarding in trash.

8. EXPOSURE CONTROLS / PERSONAL PROTECTION

ENGINEERING CONTROLS: General room ventilation. Not expected to be an inhalation hazard.

PERSONAL PROTECTIVE EQUIPMENT:
- **EYES AND FACE:** Wear safety glasses with side shields where there is potential for eye contact.
- **SKIN:** For personal hygiene purposes use adequate clothing to prevent skin contact.
- **RESPIRATORY:** None required for normal use.

WORK HYGIENIC PRACTICES: If product gets on clothing, remove and wash before reuse.

OTHER USE PRECAUTIONS: Facilities storing or utilizing this material should be equipped with an eyewash and safety shower.

9. PHYSICAL AND CHEMICAL PROPERTIES

PHYSICAL STATE: Liquid
ODOR: Almondy
APPEARANCE: Clear
COLOR: Blue
pH: ~4.0 to 7.0
VAPOR PRESSURE: Not Applicable
VAPOR DENSITY: Not Applicable
BOILING POINT: 100°C (212°F)
FREEZING POINT: Not Applicable
SOLUBILITY IN WATER: Miscible in Water
SPECIFIC GRAVITY: 1.03 to 1.05
VISCOSITY: 50 to 200cps

10. STABILITY AND REACTIVITY

CONDITIONS TO AVOID: High temperature. Poor ventilation. Contamination.

STABILITY: This product is stable under normal conditions.

POLYMERIZATION: Hazardous polymerization will not occur under normal conditions.

HAZARDOUS DECOMPOSITION PRODUCTS: Carbon monoxide, carbon dioxide, ammonia, oxides of nitrogen and/or hydrogen chloride.

INCOMPATIBLE MATERIALS: Other swimming pool/spa chemicals in their concentrated forms. Strong oxidizing agents. This material may react slowly with iron, copper or aluminum resulting in corrosion and/or product degradation.

11. TOXICOLOGICAL INFORMATION

EYE EFFECTS: This product may be irritating to eyes.

SKIN EFFECTS: This product may be irritating to skin.

CARCINOGENICITY:
This product is not listed as a carcinogen by IARC.

This product is not listed as a carcinogen by NTP.

This product is not listed as a carcinogen by OSHA.

GENERAL COMMENTS: This product is not a mutagen or teratogen.

12. ECOLOGICAL INFORMATION

ECOTOXICOLOGICAL INFORMATION: This product may be toxic to fish and aquatic organisms. Keep product from entering waterways and watersheds.

13. DISPOSAL CONSIDERATIONS

PRODUCT DISPOSAL: Disposal of unused, uncontaminated product is regulated according to local, state and federal regulations.

EMPTY CONTAINER: Do not reuse container. Rinse thoroughly before discarding in trash.

14. TRANSPORT INFORMATION

DOT (DEPARTMENT OF TRANSPORTATION)
PROPER SHIPPING NAME: Not Regulated.

15. REGULATORY INFORMATION

UNITED STATES
SARA TITLE III (SUPERFUND AMENDMENTS AND REAUTHORIZATION ACT)

313 REPORTABLE INGREDIENTS: This product or its components are not listed.

CERCLA (COMPREHENSIVE RESPONSE, COMPENSATION, AND LIABILITY ACT)

CERCLA REGULATORY: This product or its components are not listed.

TSCA (TOXIC SUBSTANCE CONTROL ACT)

TSCA REGULATORY: This product or its components are not subject to export notification.

TSCA STATUS: This product or its components are listed on the TSCA Inventory.

FIFRA (FEDERAL INSECTICIDE, FUNGICIDE, AND RODENTICIDE ACT): This product is not a registered pesticide.

16. OTHER INFORMATION

PREPARED BY: Regulatory Affairs Department

REVISION SUMMARY Revision #: 6

This MSDS replaces the November 24, 1997 MSDS. Any changes in information are as follows:
In Section 1
Prepared By

In Section 3
Emergency Overview - Immediate Concerns Potential Heath Effects - Eyes Potential Health Effects - Skin Potential Health Effects - Ingestion Routes of Entry

In Section 4
Firstaid - Eyes Firstaid - Skin Firstaid - Ingestion

In Section 7
Handling Storage

In Section 8
Engineering Controls Skin Protection Eyes-Face Protection Respiratory Protection Work Hygienic Practices

In Section 9
Appearance (Group Field) for Vapor Pressure (Group Field) for Vapor Pressure Density (Group Field) for Freezing Point Specific Gravity (From) Specific Gravity (To)

In Section 13
Disposal

HMIS RATING

HEALTH:		1
FLAMMABILITY:		0
PHYSICAL HAZARD:		0
PERSONAL PROTECTION:		B

NFPA RATING

HEALTH:	1
FIRE:	0
REACTIVITY:	0

Key
4 = Severe
3 = Serious
2 = Moderate
1 = Slight
0 = Minimal

MANUFACTURER DISCLAIMER: IMPORTANT: This information is given without a warranty or guarantee. No suggestions for use are intended or shall be construed as a recommendation to infringe any existing patents or violate any Federal, State or local laws. Safe handling and use is the responsibility of the customer. Read the label before using this product. This information is true and accurate to the best of our knowledge.

HALOSOURCE
Health Science Technologies

Date: 8/15/2008
Revision: 02

Material Safety Data Sheet
SeaKlear: PRS – Stage One

SECTION 1: PRODUCT AND COMPANY IDENTIFICATION

Manufacturer's Name:	HaloSource, Inc.
Corporate Address:	1631 220th St. SE, Suite 100, Bothell, WA 98021
Manufacturer's Telephone:	(425) 881-6464 (Monday-Friday, 8AM-5PM PDT)
Emergency Telephone:	**800-424-9300 Chemtrec** (24 Hours)
Material/Trade/Product Name:	**SeaKlear: PRS – Stage One**
Synonyms:	PRS 1, PRS I, Test Polymer A
Chemical Name:	Chitosan Proprietary Formula
Chemical Formula:	Not available
EPA Registration #:	Not applicable
CAS No.:	87582-10-3
Product Use:	Swimming pool water treatment.

SECTION 2: COMPOSITION/INFORMATION ON INGREDIENTS

CAS NO.	COMPONENT	%	OSHA HAZARDOUS?
64-19-7	Acetic Acid	1	YES
	All other components are non-hazardous.	99	NO

NOTE: See Section 8 for permissible exposure limits.

SECTION 3: HAZARDS IDENTIFICATION

EMERGENCY OVERVIEW

Clear to pale yellow viscous liquid with a pungent vinegar odor.

This material presents little or no health hazards, environmental hazards, and no unusual hazard if involved in a fire.

POTENTIAL HEALTH EFFECTS

EYE: May be mildly irritating to eyes.

SKIN: Not hazardous to skin.

INHALATION: Vapors may be mildly irritating to the respiratory tract.

INGESTION: May be mildly harmful if swallowed.

CHRONIC EXPOSURE/CARCINOGENICITY: This substance is not listed as a potential carcinogen by IARC.

SIGNS AND SYMPTOMS OF OVEREXPOSURE: Stinging, burning, coughing if inhaled. May irritate eyes with stinging, watering, inflammation; may cause chemical burns to eyes and surrounding tissue. May irritate skin with stinging, drying, inflammation. May irritate gastrointestinal system if ingested.

AGGRAVATION OF PRE-EXISTING CONDITIONS: None known.

POTENTIAL ENVIRONMENTAL EFFECTS: This material is readily biodegradable.

SECTION 4: FIRST AID MEASURES

FIRST AID PROCEDURES

EYE CONTACT: Remove contact lenses if worn and flush eyes with copious amounts of water or buffered saline eye wash solution. Get immediate medical attention.

SKIN CONTACT: Remove contaminated clothing and wash contact area with mild soap and plenty of water.

INHALATION: Remove person to fresh air and treat symptomatically. Get medical attention if symptoms worsen.

INGESTION: Get immediate medical attention.

NOTE TO PHYSICIANS: None.

SECTION 5: FIRE FIGHTING MEASURES

FLASH POINT: Not available
UPPER FLAMMABLE LIMIT: Not available
FLAMMABLITY CLASS (OSHA): Not applicable

AUTOIGNITION TEMPERATURE: Not available
LOWER FLAMMABLE LIMIT: Not available
FLAME PROPAGATION/BURNING RATE: Not available

UNIQUE FIRE PROPERTIES: None known.

HAZARDOUS COMBUSTION PRODUCTS: None known.

EXTINGUISHING MEDIA: Does not burn. Use water, dry chemicals, carbon dioxide, sand or foam. Use extinguishing media appropriate for surrounding fire.

PROTECTION OF FIREFIGHTERS: Do not enter confined fire space without full bunker gear (helmet with face shield, bunker coat, gloves and rubber boots), including a positive pressure NIOSH approved self-contained breathing apparatus. Water may be used to keep fire-exposed containers cool until fire is out.

SECTION 6: ACCIDENTAL RELEASE MEASURES

PERSONAL PROTECTIVE EQUIPMENT: See Section 8 (Personal Protective Equipment).

ENVIRONMENTAL PRECAUTIONS: Material is 100% biodegradable, is nontoxic and can be disposed of in any approved manner. Treatment, storage, transportation and disposal must be in accordance with applicable federal, state, and local regulations.

METHODS FOR CLEANING UP: Dilute with water and hose down.

SECTION 7: HANDLING AND STORAGE

SAFE *HANDLING* RECOMMENDATIONS

VENTILATION: Use with adequate ventilation.

FIRE PREVENTION: Material will not burn.

SPECIAL HANDLING REQUIREMENTS: Wash hands thoroughly after handling.

SAFE *STORAGE* RECOMMENDATIONS

CONTAINMENT: Keep container closed when not in use.

STORAGE ROOM RECOMMENDATIONS: 10-50ºC (will freeze @ ~ 3ºC)

INCOMPATIBLE MATERIALS: Strong oxidizing materials and strong bases.

STORAGE CONDITIONS: Shelf life is indefinite, but viscosity will decrease over time. The container should be kept covered to prevent contamination.

SECTION 8: EXPOSURE CONTROLS/PERSONAL PROTECTION

ENGINEERING CONTROLS: Good general ventilation should be sufficient to control airborne levels.

PERSONAL PROTECTIVE EQUIPMENT (PPE)

EYE/FACE PROTECTION: Wear safety glasses with side shields (or goggles) and a face shield.

SKIN PROTECTION: Wear chemical resistant clothing.

HAND PROTECTION: Wear chemical-resistant gloves.

RESPIRATORY PROTECTION: A respiratory protection program that meets OSHA's 29 CFR 1910.134 and ANSI Z88.2 requirements must be followed whenever workplace conditions warrant a respirator's use.

GOOD HYGEIENE/WORK PRACTICES: Always follow good hygiene/work practices by avoiding vapors or mists and contact with eyes and skin. Thoroughly wash hands after handling and before eating or drinking. Always wear the appropriate PPE when repairing or performing maintenance on contaminated equipment.

EXPOSURE GUIDELINES

PERMISSIBLE EXPOSURE LIMITS						
INGREDIENT CAS NO.	OSHA		WISHA		ACGIH (TLV)	
	TWA	STEL	TWA	STEL	TWA	STEL
Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable	Not Applicable

SECTION 9: PHYSICAL AND CHEMICAL PROPERTIES

COLOR: Clear to pale yellow.
PHYSICAL FORM: Viscous liquid
pH: 3.0 – 4.5
VAPOR DENSITY: Not applicable
MELTING POINT: Not available
SOLUBILITY IN WATER: Soluble

SHAPE: Viscous liquid
ODOR: Pungent vinegar
VAPOR PRESSURE: Not applicable
BOILING POINT: 211ºF
FREEZING POINT: Not available
SPECIFIC GRAVITY OR DENSITY: 1.0 – 1.1 g/mL

NOTE: These physical data are typical values based on material tested but may vary from sample to sample. Values should not be construed as a guaranteed analysis of any specific lot or as specifications.

SECTION 10: STABILITY AND REACTIVITY

CHEMICAL STABILITY: Stable

CONDITIONS TO AVOID: Strong oxidizing material and strong bases.

MATERIALS TO AVOID (INCOMPATIBILITY): Strong oxidizing material and strong bases.

HAZARDOUS DECOMPOSITION PRODUCTS: Decomposition will not occur.

HAZARDOUS POLYMERIZATION: Will not occur.

SECTION 11: TOXICOLOGICAL INFORMATION

ORAL LD_{50} (rat): Not available.

DERMAL LD_{50} (rabbit): Not available.

SKIN IRRITATION: Not available.

EYE IRRITATION: Not available.

SKIN SENSITIZATION: Not available.

ADDITIONAL INFORMATION:

SECTION 12: ECOLOGICAL INFORMATION

ECOTOXICITY: Not available.

MOBILITY: Not available.

PERSISTENCE AND DEGRADABILITY: Not available.

BIOACCUMULATIVE POTENTIAL: Not available.

ADDITIONAL INFORMATION: Not available.

SECTION 13: DISPOSAL CONSIDERATIONS

If this product as supplied becomes a waste, it does not meet the criteria of a hazardous waste as defined under the Resource Conservation and Recovery Act (RCRA) 40 CFR 261. Please be advised that state and local requirements for waste disposal may be more restrictive or otherwise different from federal regulations. Consult state and local regulations regarding the proper disposal of this material.

NOTE: Chemical additions, processing or otherwise altering this material may make the waste management information presented in this MSDS incomplete, inaccurate or otherwise inappropriate.

SECTION 14: TRANSPORT INFORMATION

U.S. DEPARTMENT OF TRANSPORTATION (DOT):

Proper Shipping Name:	Not Regulated
Hazard Class:	Not Regulated
Identification Number (UN Number):	Not Regulated
Packing Group (PG):	Not Regulated

SECTION 15: REGULATORY INFORMATION

TSCA STATUS: All ingredients are listed

CERCLA REPORTABLE QUANTITY (RQ):

CHEMICAL NAME	RQ
None	Not applicable

SARA TITLE III SECTION 302 EXTREMELY HAZARDOUS SUBSTANCES (EHS):

CHEMICAL NAME	TPQ	RQ
Not applicable	Not applicable	Not applicable

SARA TITLE III SECTION 311/312 HAZARD CATEGORIES: Does this product/material meet the definition of the following hazard classes according to the EPA ‘Hazard Categories’ promulgated under Sections 311 and 312 of SARA Title III?

ACUTE HEALTH HAZARD	CHRONIC HEALTH HAZARD	FIRE HAZARD	REACTIVE HAZARD	SUDDEN RELEASE OF PRESSURE
NO	NO	NO	NO	NO

SARA TITLE III SECTION 313 TOXIC CHEMICALS INFORMATION:

CHEMICAL NAME	CAS NO.	CONCENTRATION (%)
Not applicable	Not applicable	Not applicable

CALIFORNIA PROPOSITION 65: The following chemical(s) is/are known to the state of California to cause cancer or reproductive toxicity:

CHEMICAL NAME	CAS NO.	CONCENTRATION (%)
Not applicable	Not applicable	Not applicable

SECTION 16: OTHER INFORMATION

REVISION INFORMATION:
MSDS sections(s) changed since last revision of document: Section 2 – Components updated.

DISCLAIMER:
****
**

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****
**

MSDS PREPARED BY: Jeremy Heath, EH&S Manager

MATERIAL SAFETY DATA SHEET

I - PRODUCT IDENTIFICATION

Product: Poly-A Tablets
CAS Number: 10043-01 (Majority in Proprietary Formulation)
General Use: Highly concentrated coagulating and flocking compound.
Synonyms: Crystal Bright Filter Tabs

COMPANY IDENTIFICATION

AllChem Performance Products, LP
6010 NW First Place
Gainesville, FL 32607
Tel: 352-378-9696

24 HR EMERGENCY TELEPHONE NUMBER

INFOTRAC (Transportation): (800)535-5053

II – COMPOSITION, INFORMATION ON INGREDIENTS

Chemical or Common Name	CAS#:	Wt%
Sulfatodialuminum disulfate tetradecahydrate	10043-01-3	~97
Remainder – Proprietary Formulation		~3

III – HAZARDS IDENTIFICATION

EMERGENCY OVERVIEW
Physical Appearance: White tablets.

Immediate Concerns: CAUTION: Irritating to eyes and skin. Avoid contact with eyes, skin or clothing. Harmful if swallowed. Avoid breathing dust or vapors. Wear goggles or safety glasses and rubber gloves when handling this product. Remove and wash contaminated clothing.

Primary Route(s) of Entry:
- Ingestion: (X)
- Inhalation: (X)
- Skin Contact: (X)
- Eye Contact: (X)

Potential Health Effects (Acute and Chronic):
- Eyes: CAUTION: Causes eye irritation. Avoid contact with eyes.
- Skin: CAUTION: Skin irritation on repeated or prolonged contact or when moisture is present. Avoid contact with skin.
- Ingestion: Harmful if swallowed. Ingestion may irritate gastrointestinal tract. May cause nausea, vomiting and purging.
- Inhalation: Irritating to nose and throat. Avoid breathing dust or vapors.

IV – FIRST AID MEASURES

Eyes: If contact with eyes occurs, immediately flush with cold water for at least 15 minutes. Then get immediate medical attention.
Skin: If contact with skin, brush off excess chemical and flush skin with cold water for at least 15 minutes. If irritation persists, get medical attention.
Ingestion: Induce vomiting. Call a physician or poison control center immediately.
Inhalation: If inhaled, remove to fresh air. If breathing is difficult, have trained person administer oxygen. If not breathing, give artificial respiration. Call a physician immediately.

V – FIRE FIGHTING MEASURES

MATERIAL SAFETY DATA SHEET

FIRE AND EXPLOSION HAZARD DATA

Flash Point: (Method Used)
Extinguishing Media: Water.
Fire-fighting Procedures: Firefighters should wear full protective clothing and self contained breathing apparatus (SCBA). Thoroughly decontaminate firefighting equipment including all fire fighting wearing apparel after the incident.
Hazardous Combustion Products: Sulfur oxide gases (toxic, oxidizers and corrosive). Sulfur trioxide is a fire hazard.

VI – ACCIDENTAL RELEASE MEASURES

Steps To Be Taken In Case Material Is Spilled Or Released: Utilizing appropriate protective clothing and safety equipment, contain spilled material. Using clean dedicated equipment, sweep and scoop all spilled material, contaminated soil, and other contaminated material and place in clean dry plastic containers for disposal. Dispose of according to local, state and federal regulations.

VII – HANDLING AND STORAGE

Handling: Mix only with water. Never add water to product. Always add product to large quantities of water. Do not mix with other chemicals. Use clean dry utensils. Do not add this product to any dispensing device containing remnants of any other product. Such use may cause a violent reaction leading to fire or explosion. Contamination with other chemicals may start a chemical reaction generating heat, hazardous gases, fire and explosion. In case of contamination or decomposition, do not reseal container. If possible, isolate container in open air or well ventilated area. Flood area with large volumes of water, if necessary.
Storage: Keep this product in original closed container when not in use. Store in a cool, dry, well-ventilated area away from heat or open flame. Do not add any other product to container. Never return unused product to container; dispose of product in accordance with local, state or federal regulations.

VIII – EXPOSURE CONTROLS / PERSONAL PROTECTION

Exposure Guidelines:
OSHA Hazardous Components (29 CFR 1910.1200)

		Exposure Limits					
		OSHA PEL		ACGIH TLV		SUPPLIER OEL	
		Ppm	mg/m^3	ppm	mg/m^3	ppm	mg/m^3
Sulfatodialuminum disulfate	TWA	N/E		N/E[1]			
tetra-decahydrate	STEL				2		

OSHA TABLE COMMENTS:
1. N/E = Not Established

Respiratory Protection: A respiratory protection program that meets OSHA 1910.1314 and ANSI Z88.2 requirements must be followed whenever workplace conditions warrant a respirator's use.
Ventilation:
Local Exhaust: General room ventilation plus local exhaust should be used to minimize exposure to vapors.
Mechanical Exhaust:
Other Protective Clothing or Equipment:
Eyes and Face: Wear goggles or safety glasses with side shields when handling this product.
Skin: Wear rubber gloves when handling this product. Avoid contact with skin.
Work/ Hygienic Practices: Remove and wash contaminated clothing before reuse.
Other Use Precautions: Facilities storing or utilizing this material should be equipped with an eyewash and safety shower.

IX - PHYSICAL/CHEMICAL CHARACTERISTICS
Appearance: White tablet.

Specific Gravity:0.84 g/ml
Physical State: Solid
pH: 3.61 (1% solution)

X – STABILITY AND REACTIVITY

Stability:
() Unstable (X) Stable – under normal conditions
Conditions to Avoid: High temperature. Poor ventilation. Contamination. Moisture/highhumidity.
Hazardous Decomposition or By-Products: Sulfur oxide gases (toxic, oxidizers & corrosive). Sulfur trioxide is a fire hazard.
Hazardous Polymerization:
() May Occur (X) Will Not Occur – under normal conditions.
Conditions to Avoid:
Incompatible Materials: Alkalies and water reactive materials like oleum cause exothermic reactions. Other swimming pool/spa chemicals in their concentrated forms.

XI- TOXICOLOGICAL INFORMATION

Acute Toxicity:
 Eyes: Toxicological information indicates this product may be irritating to eyes.
 Dermal LD_{50}: Toxicological information indicates this product may be irritating to skin.
Carcinogenicity: Not listed
 OSHA: ( )
 NTP: ( )
 IARC: ( )
Mutagenicity: This product is not a mutagen or teratogen.

XII– ECOLOGICAL INFORMATION

Ecotoxicological Information: This product may be toxic to fish and aquatic organisms. Keep product from entering waterways and watersheds.

XIII – DISPOSAL CONSIDERATIONS

Disposal Method: Do not put product, spilled product, or filled or partially filled containers into the trash or waste compactor. Contact with incompatible materials could cause a reaction or fire.
Product Disposal: Disposal of unused, uncontaminated product is regulated according to local, state and federal regulations.
Empty Container: Do not reuse container. Rinse thoroughly before discarding in trash.

XIV - TRANSPORTATION DATA

Please refer to applicable regulations or call company noted under Section I.

XV - REGULATORY INFORMATION

UNITED STATES
SARA TITLE III: 313: Aluminum sulfate is a SARA Title III Section 313 Toxic Chemical
CERCLA REGULATORY: CERCLA RQ: Aluminum sulfate RQ is 5000 lb
TSCA REGULATORY: This product or its components are not subject to export notification.
TSCA Status: This product or its components are listed on the TSCA inventory.
OSHA HAZARD COMM RULE: Product is hazardous by definition of the Hazardous Communication Standard.
CLEAN WATER ACT: Aluminum sulfate is listed as a Clean Water Act Section 311 Hazardous Substance

MATERIAL SAFETY DATA SHEET

FIFRA: This product is not a registered pesticide.

HMIS Rating:	Health: 1	Fire: 0	Reactivity: 1	Special: B
NFPA Rating:	Health: 1	Fire: 0	Reactivity: 1	Protection: B

XVI - ADDITIONAL INFORMATION

This MSDS replaces the 01/18/2008 version. Any changes in information are as follows: Section III. **ALWAYS COMPLY WITH ALL APPLICABLE INTERNATIONAL, FEDERAL, STATE AND LOCAL REGULATIONS REGARDING THE TRANSPORTATION, STORAGE, USE AND DISPOSAL OF THIS CHEMICAL.**

Due to the changing nature of regulatory requirements, the REGULATORY INFORMATION listed in Section XV of this document should NOT be considered all-inclusive or authoritative. International, Federal, State and Local regulations should be consulted to determine compliance with all required reporting requirements.

The information in this MSDS was obtained from sources, which we believe are reliable. **HOWEVER, THE INFORMATION IS PROVIDED WITHOUT ANY WARRANTY, EXPRESS OR IMPLIED, REGARDING ITS CORRECTNESS**. The conditions or methods of handling, storage, use, and disposal of the product are beyond our control and may be beyond our knowledge. **FOR THIS AND OTHER REASONS, WE DO NOT ASSUME RESPONSIBILITY AND EXPRESSLY DISCLAIM LIABILITY FOR LOSS, DAMAGE OR EXPENSE ARISING OUT OF OR IN ANY WAY CONNECTED WITH THE HANDLING, STORAGE, USE OR DISPOSAL OF THE PRODUCT**. This MSDS was prepared and is to be used only for this product. If the product is used as a component in another product, this MSDS information may not be applicable.

Issue Date: 07/29/2005
Ref No. 033VTG
Revision Date: 05/14/2009
Revision No.: 3

kemira

KWS-PAX-18-10/16/08

PRODUCT INFORMATION

KEMIRA PAX-18

Polyaluminum Chloride

KEMIRA PAX-18 is a high performance liquid polyaluminum chloride coagulant that generally offers superior clarification in either potable or wastewater. The aluminum in KEMIRA PAX-18 is highly charged, enabling less of it to do more. Advantages available to many end users are ***Reduced Sludge, Minimized pH Adjustment, Longer Filter Runs, Superior Finished Water Quality, and Optimized Cold Water Performance****. KEMIRA PAX-18 is a general-purpose coagulant, versatile enough to handle any type of challenge.*

PRODUCT SPECIFICATION;

Appearance	Yellowish Liquid
Aluminum (Al)	9.0 ± 0.2%
Al_2O_3	17.1 ± 0.4%
Basicity	42 ± 2%
Specific Gravity(25°C)	1.37 ± 0.03 kg/L

TYPICAL;

Iron (Fe^{tot})	< 0.01%
pH (25°C)	0.9 ± 0.3
Viscosity (25° C)	30 ± 5 cP
Freezing Point	-20° C / -4° F

CERTIFICATION / APPROVAL

KEMIRA PAX-18 meets or exceeds all **AWWA** standards for polyaluminum chloride. KEMIRA PAX-18 is **NSF/ANSI Standard 60** certified for use in potable water treatment up to 200 mg/l.

DOSING

KEMIRA PAX-18 should be fed straight without dilution.

A diaphragm-metering pump of non-corrosive material is suitable.

STORAGE

Storage tanks and piping should be constructed of suitable non-corrosive material such as fiberglass or cross-linked polyethylene. KEMIRA PAX-18 is mildly corrosive and will attack most metals over a period of time. KEMIRA PAX-18 has a recommended shelf life of 8 months. As with any chemical, it is recommended to clean the storage tank every year.

HANDLING / SAFETY

The handling of any chemical requires care. Anyone responsible for using or handling KEMIRA PAX-18 should familiarize themselves with the full safety precautions outlined in our Material Safety Data Sheet.

DELIVERY

Shipping Instructions ; Corrosive Liquid, Acidic, Inorganic, n.o.s., 8, UN 3264, P.G. III

CUSTOMER SERVICE

If you have any questions concerning this material, please contact our Customer Service Department.

US;

Lawrence, KS	(800) 879-6353

Canada

Varennes, QC	(800) 465-6171

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CLEAN WATER IS OUR LIFE

Kemira Water - www.kemira.com
US Sales Office, 3211 Clinton Parkway Ct, Suite 1, Lawrence, KS, 66047,Tel (800) 879-6353, Fax (785) 842-3150.
Canada Sales Office, 3405 Blvd Marie-Victorin, Varennes, QC J3X 1T6, Tel (800) 465-6171, Fax (450) 652-7343