Are Swimming Pool Filters Really Removing *Cryptosporidium*?

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ABSTRACT

Cryptosporidium is chlorine-resistant protozoan parasite that causes the majority of waterborne disease outbreaks in swimming pools in the U.S. Recent research has shown that free chlorine can take more than 10 days to inactivate 99.9% of *Cryptosporidium* oocysts (Ct=15,300 mg/L*min) at pH 7.5 with 1 mg/L of free chlorine, but a lot of people can swim in a pool during that 10-day period. Sand filters are commonly used as secondary barriers to *Cryptosporidium* in U.S. pools, but sand filters alone typically only remove about 25% of oocysts per passage through the filter. Additional measures appear necessary to effectively safeguard public health. Prior research has shown that sand filters can remove greater than 99% of oocysts per passage when a coagulant is added prior to filtration, but the results did not scale up to spa-scale or full-scale experiments. In the current study, sand filter removals of *Cryptosporidium*-sized microsphere surrogates will be reported for a variety of coagulants, experimental conditions, and scales of size. Aluminum sulfate, polyaluminum chloride, and cationic polymers were all capable of achieving *Cryptosporidium*-sized microsphere removals in excess of 90% in spa-scale and/or full-scale pools. Polyaluminum chloride and cationic polymers were shown to remove greater than 99% of *Cryptosporidium*-sized microspheres with filtration rates of up to 24 m/h and sand bed depths of 600 mm. Bed depth appeared to be more important than filtration rate in increasing particle removal. A streaming current monitor showed promise a means of controlling coagulant dosage and interpreting experimental results where coagulants are used. A full-scale swimming pool experiment with cationic polymer coagulation produced *Cryptosporidium* removals in the 90 to 99% range. Hopefully, this information will help empower operators, managers, and regulators to be able to develop better operating procedures and design standards to further reduce the risk of waterborne disease outbreaks associated with recreational water activities.

KEYWORDS: *Cryptosporidium*, Coagulation, Filtration, Pathogens, and Microspheres

INTRODUCTION

Cryptosporidium is chlorine-resistant protozoan pathogen that causes the majority of waterborne disease outbreaks in swimming pools in the U.S. as shown in Figure 1. Surveillance for *Cryptosporidium* in the United States indicates that the reported incidence of infection has increased dramatically since 2004 (Yoder & Beach, 2010). Figures 2 and 3 demonstrate the increased incidence and number of outbreaks of cryptosporidiosis since 2004, respectively (Yoder et al, 2010).

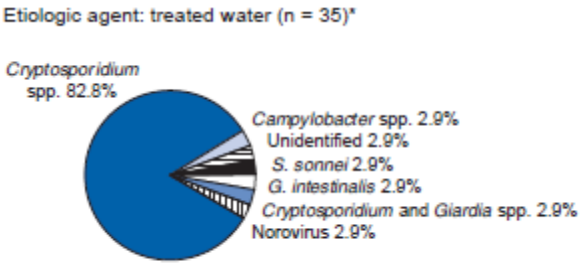
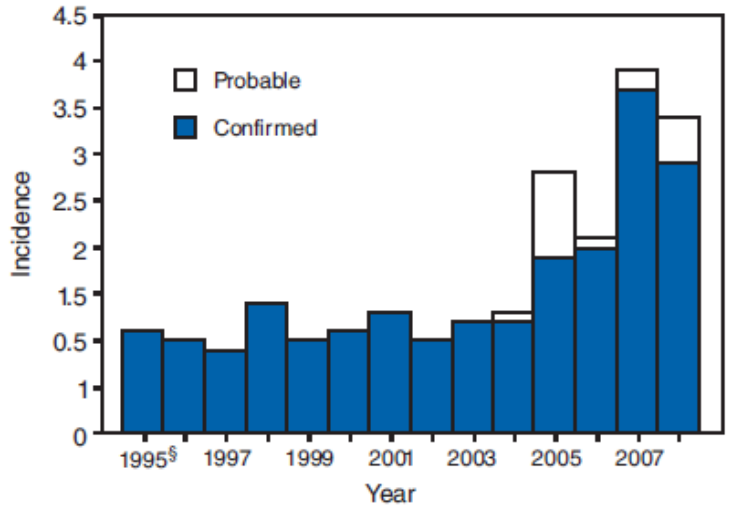


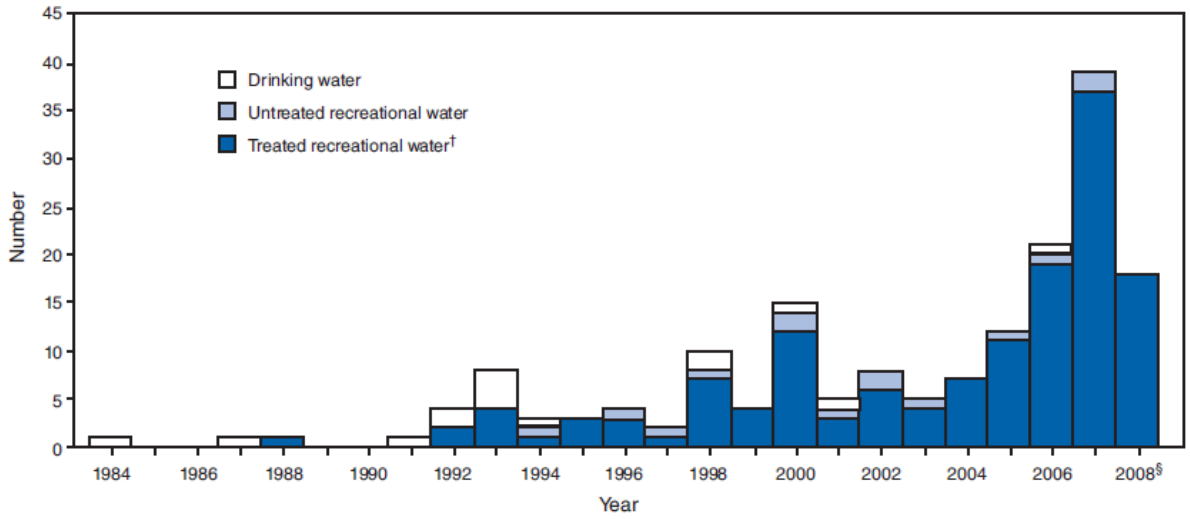
FIGURE 1. Recreational water-associated outbreaks of gastroenteritis, by etiologic agent for treated water — United States, 2005–2006 (Source: Yoder et al., 2008).



* Per 100,000 population.
† N = 68,907.
§ First full year of national reporting.

FIGURE 2. Incidence* of cryptosporidiosis, by year — National Notifiable Disease Surveillance System, United States, 1995–2008† (Source: Yoder et al., 2010).

The current Ct values for a 3-Log reduction in viability of fresh *Cryptosporidium* oocysts with free chlorine are 10,400 mg/L·min (Iowa-isolate) and 15,300 mg/L·min (Maine-isolate) at pH 7.5 (Shields et al., 2008b). At a concentration of 1 mg/L, free chlorine can take more than 10 days to inactivate 99.9% of *Cryptosporidium* oocysts (Ct=15,300 mg/L·min), but a lot of people will be swimming in the pool during that 10-day period. Sand filters are commonly used as secondary barriers to *Cryptosporidium* in U.S. pools, but sand filters alone typically only remove about 25% of oocysts per passage through the filter (Amburgey et al, 2007, 2008, 2009ab). Based on the slow kinetics of chlorine inactivation of *Cryptosporidium*, the known inefficiency of sand filter to remove oocysts, and the recent incidence of cryptosporidiosis in the U.S., additional measures appear necessary to effectively safeguard public health.



* N = 172.
† Water that has undergone a treatment process (e.g., chlorination and filtration) to make it safe for recreation.
§ Data for 2007 and 2008 are provisional.

FIGURE 3. Number* of outbreaks of cryptosporidiosis associated with water, by water type — Waterborne Disease and Outbreak Surveillance System, United States, 1988–2008 (Source: Yoder et al., 2010).

Figure 3 shows that the majority of outbreaks of cryptosporidiosis occur in treated recreational water. Figure 4 shows a drastic increase in the number of cases of cryptosporidiosis during the warmer months of the year when outdoor public pools are normally open in the U.S. While it is challenging to assess the prevalence of protozoan parasites in public pools during normal operation, a study of 160 filter backwash water samples from Atlanta, GA, USA showed that 13 (8.1%) were positive for *Giardia* or *Cryptosporidium* or both (Shields et al., 2008a).

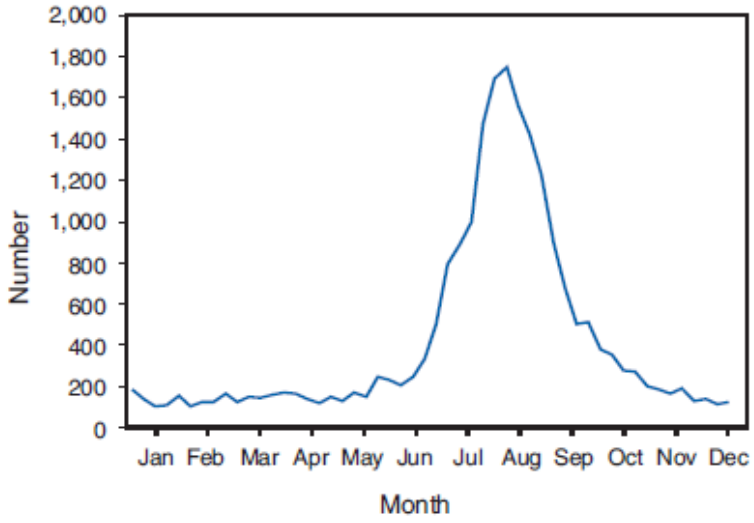


FIGURE 4. Number* of cryptosporidiosis case reports, by date of illness onset — National Notifiable Disease Surveillance System, United States, 2006–2008 (Source: Yoder et al., 2010)

Previous research has shown that sand filters can remove greater than 99% of oocysts per passage through the filter when a coagulant is added prior to filtration in lab-scale filtration systems, but the removals in full-scale trials with coagulation were only slightly higher than 25% (Amburgey et al., 2007). In later experiments, the removals in a spa-scale sand filtration system with coagulant addition only averaged 61% (Amburgey et al., 2009a). In trying to determine why the earlier lab-scale *Cryptosporidium* removal experiments with coagulant addition and sand filtration at 37 m/h did not scale up to spa-scale or full-scale pools, Amburgey and coworkers (2009b) constructed a spa-scale sand filter proportioned for a 4.4 hr turnover of a 757 L spa at 37 m/h (instead on the commercial pool filter operating at 49 m/h for a 5.3 min turnover). By changing the filter diameter from 47.7 cm to 7.6 cm and increasing the depth of the sand from 300 mm to 600 mm, they achieved removals greater than 99.9% with continuous feed of clarifier for up to 3 days (Amburgey et al., 2009b). Others have also reported excellent performance of sand filters for removing *Cryptosporidium*-sized particles from pool water with proper coagulation and filtration conditions (Croll et al., 2007). The necessity of coagulation prior to sand filtration in pools as well as the potential benefits of lower filtration rates and deeper beds of sand have recently been reported (Amburgey, 2010).

The massively overdesigned filter originally installed (Amburgey et al., 2009a) with approximately 40-fold greater filter surface area than required on the spa was thought to be primary cause of the poor performance in the earlier coagulation trials (due to coagulant demand exerted by the negatively charged sand grains at startup). However, the filter loading rate was also reduced by 25%, the depth of sand was increased by 100%, and the shear forces in the system were reduced by switching from a centrifugal pump throttled back with a ball valve to a gear pump controlled by a variable frequency drive. Further research will be required to determine precisely how changes in design, water quality, and operational variables impact the overall rate of removal of *Cryptosporidium*-sized particle in pool water.

Cryptosporidium oocysts (Iowa-isolate from the CDC) and fluorescent polystyrene microspheres (Polysciences, Inc., Warrington, PA) were not shown to have statistically significant differences in zeta potentials in simulated pool water with organics (i.e., artificial sweat and urine) (Amburgey et al, 2007). However, this was not the case for other water matrices tested. While heat-inactivated and viable *Cryptosporidium* were shown to have a statistically significant difference in zeta potential in simulated pool water between pH 2 and 8, there was no statistically significant difference between pH 7 and 8 where pools normally operate (Amburgey et al., 2007). The chemicals used in the processing and storage of *Cryptosporidium* oocysts purified from calf stool have demonstrated potential to drastically alter their zeta potential of oocysts (Amburgey et al., 2008). The optional "defatting agents" ethyl acetate or diethyl ether appear to have the greatest potential to move the zeta potential from the unprocessed levels (typically -20 to -25 mV in simulated pool water) closer to zero (-8 mV to 0 mV) after processing (Amburgey et al, 2008). Based on the observed similarity in removals between *Cryptosporidium* oocysts and polystyrene microspheres (Amburgey et al., 2007; 2009a), recent research has been conducted exclusively with polystyrene microspheres (Amburgey et al., 2009b; Amburgey, 2010).

METHODS

A 200 gallon (757 L) spa with 3-inch (7.6 cm) inner diameter sand filter was used at room temperature (20° C) for the alum and polyaluminum chloride experiments. The filter was constructed out of clear PVC with a piece of integral media support (IMS) cap (ITT Water & Wastewater USA, Inc./ F.B. Leopold Co., Zelienople, PA, USA) instead of gravel to support the filter media and a regenerative turbine pump (Speck Pumpen GmbH). The spa system was capable of pumping water at 1.9 to 2.9 L/min, and the flow was measured with a Coriolis flow meter (Endress+Hauser, Model Promass 83M flow meter) and controlled with a variable frequency drive (Lenze AC Tech Corp., SMVector) through 0.5-inch (13 mm) diameter schedule 40 PVC pipe. Inline feeding of the oocyst/microsphere suspensions was made possible by a digital peristaltic pump (Rainin, Model Rabbit-Plus) feeding directly into the PVC pipe just upstream of the pump and filter. The oocyst-sized microsphere suspensions were made in a 1-L glass Wheaton media bottle of simulated pool water and stirred continuously with an ultraflat magnetic stirrer (IKA Works, Inc., Wilmington, NC, USA) and a Teflon®-coated stir bar prior to and during the experiments. Sand filters were backwashed prior to each of the experiments to ensure the media was clean and stratified. The pool filter sand (approximately 16/40 US Standard Mesh) had an effective size (ES) of 0.49 mm and uniformity coefficient (UC) of 1.5 (Pavestone Inc., Pool filter sand).

A 1,450 gallon (5,500 L) spa with 6-inch (15.2 cm) inner diameter sand filter was used at room temperature (20° C) for the spa-scale cationic polymer experiments. The filter was constructed out of clear PVC with a piece of integral media support (IMS) cap (ITT Water & Wastewater USA, Inc./ F.B. Leopold Co., Zelienople, PA, USA) instead of gravel to support the filter media and a regenerative turbine pump (Speck Pumpen, GmbH). The spa system was capable of pumping water at 11.4 L/min, and the flow was measured with a magnetic flow meter (Model 10D1475, ABB, Inc.) and controlled with a via a 0.5-inch (13 mm) diameter schedule 40 PVC ball valve. Inline feeding of the oocyst/microsphere suspensions was made possible by a digital peristaltic pump (Watson Marlow, Model 505Di) feeding directly into the PVC pipe just upstream of the pump and filter. The coagulant was also fed upstream of the pump and filter by a peristaltic pump (Larox, Inc., Model LPP-M). The streaming current monitor (Model SCM-1, Micrometrix, Corp., Suwanee, GA USA) was installed on the filter influent line, and a computerized controller (Model PC5000, Chemtrol, Inc., Santa Barbara, CA, USA) was installed on the filter effluent line to automatically adjust the pH and free chlorine level. The pool filter sand (approximately 16/35 US Standard Mesh) had an ES of 0.58 mm and UC of 1.36 (US Silica Inc., Mystic White II).

A 10-L cubitainer and 2-inch (5.1 cm) inner diameter sand filter was used at room temperature (20° C) for the lab-scale cationic polymer experiments. The filter was constructed out of clear PVC with a piece of integral media support (IMS) cap (ITT Water & Wastewater USA, Inc./ F.B. Leopold Co., Zelienople, PA, USA) instead of gravel to support the filter media. Flow was

produced via gravity without the aid of a pump, and the flow was measured with a graduated cylinder and stopwatch. The microsphere suspensions were added to mock pool water and shaken vigorously prior to cationic polymer addition. A delay of approximately 10 min occurred between adding the cationic polymer and the start of the filtration run. Three filter effluent samples were collected for each experiment. The pool filter sand (approximately 16/40 US Standard Mesh) had an ES of 0.49 mm and UC of 1.5 (Pavestone Inc., Pool filter sand).

Simulated pool water was created for each experiment from Charlotte, NC (US) tap water supplemented with sodium bicarbonate to an alkalinity of 150 mg/L as $CaCO_3$, with calcium chloride to a hardness of 250 mg/L as $CaCO_3$, with sodium hypochlorite to a free chlorine concentration of 2 mg/L, with hydrochloric acid to a pH of 7.5, and with a mixture of artificial sweat and urine to a final total organic carbon concentration of 10 mg/L as C. Duplicate samples were collected during each experiment from the filter influent and filter effluent sample lines. A maximum of approximately 10^8 YG fluorescent carboxylate-modified polystyrene microspheres (Polysciences, Inc, Cat. #16592, 4.869 µm, std. dev. 0.246 µm) were used in each experiment to achieve a maximum filter influent concentration of approximately 132 oocysts/microspheres per mL of water. Influent samples of 50 mL were collected in sterile 50 mL conical-bottomed polypropylene centrifuge tubes (Corning® CentriStar™ Order #430828), and the volume of the effluent samples varied from 50 mL to 1 L with the larger samples collected in Wheaton glass media bottles.

A 10,000 gallon (37,850 L) outdoor pool located in Conley, GA, USA using a sand filter (Model S220T Pro Series, Hayward Pool Products Inc., Clemmons, NC, USA) was used at 29° C for the full-scale cationic polymer experiment. The approximate bed depth was 300 mm of sand. A centrifugal pump (WhisperFlo Model, Pentair Inc., Sanford, NC) was operated at 35 gpm (132 L/min) by adjusting a ball valve on the filter effluent pipe to achieve a filter loading rate of 33 m/h. The flow was measured with an ultrasonic flow meter (Model TransPort PT878, GE Measurement and Control Solution, Inc., Billerica, MA). Inline feeding of the oocyst/microsphere suspensions was made possible by a digital peristaltic pump (Cole Parmer, Inc., Vernon Hills, IL, Digital Masterflex L/S Drive with EasyLoad II pumphead) feeding directly into the 3.8 cm diameter PVC pipe just upstream of the pump and filter. The cationic polymer was dosed with the same pump at the same location over approximately 10 minutes prior to the initiation of seeding the oocysts and microspheres with the intent of conditioning the filter media to enhance pathogen capture. The pool filter sand ES of 0.58 mm and UC of 1.36 (US Silica Inc., Mystic White II).

Sample volumes analyzed were adjusted to obtain between 10 and 150 oocysts and/or microspheres per sample. Samples were filtered through 3-µm polycarbonate track-etched (PCTE) filters (GE, Order #K30CP02500) in 25-mm glass microanalysis filter funnels (Millipore Model xx10 025 00) by a regulated 3-place vacuum manifold. The filters were mounted on glass micro slides (Gold Seal® Order #3058) with one drop of polyvinyl alcohol-DABCO solution (Freer, 1984) and a glass cover slip (Corning, 25-mm square, No. 1.5) for enumeration under epifluorescent microscope (Zeiss Standard 25 microscope) at 100X total magnification. The fluorescent filter set had a 450-490-nm excitation wavelength range, a 510-nm dichroic filter, and a 520-nm emission filter. The spa system was thoroughly cleaned between experiments with a minimum of three drain-and-fill rinses with recirculation. Control experiments were used to determine whether or not the microspheres were lost due to surface attachment within the system.

RESULTS AND DISCUSSION

The first group of results was obtained with a 7.6 cm diameter sand filter attached to a 757 L spa. Sand filter removals of a *Cryptosporidium*-sized microsphere surrogates less than 2% for the filter system without any sand, which is defined a Condition 0 in Table 1. Conditions 1-4 refer to different combinations of the filter loading rate (24 or 37 m/h) and sand depth (300 mm or 600 mm), which might be helpful in comparing results in the first three tables. The control experiments with sand yielded removals between 24 and 33%, which are in agreement with previously reported swimming pool research.

Table 2 shows the removals obtained with polyaluminum chloride dosed at 0.1 mg/L as Al for the four combinations of filter loading rate and sand depth mentioned above. Condition 4 represents the worst-case scenario (i.e., the highest filtration rate and lowest sand depth), and the removals were initially only slightly better than the control experiments at 56%. Each decrease in filtration rate or increase in bed depth improved the removal efficiency for this dosage of PACl. The bed depth appeared to be more important than filtration rate for improving removal since the highest removals occurred with the deeper sand beds. Condition 1 removals were greater than 99.3% and are very close to removals reported by other researchers for the same filtration conditions and similar PACl dosages of 0.21 to 0.45 mg/L as Al (Croll et al., 2007). Croll and coworkers (2007) did report poorer performance at both higher and lower dosages of PACl. Dosing 0.1 mg/L as Al of PACl is approximately 20-fold greater than normal and could lead to faster increases in differential pressure across filters (PWTAG, 2009, p. 62).

Table 3 indicates that the initial results for filtration with aluminum sulfate (alum) at 0.1 mg/L were virtually identical to the control experiments, but the removals did improve over time. The removals for condition 4 showed only modest improvement, but the removals for condition 1 were noticeably higher. Overall, alum did not perform as well as the PACl under these conditions. Croll and coworkers (2007) also reported Condition 1 removals of 92-95% for alum at 0.1 to 0.12 mg/L as Al, which are close to the 24 hr removals in Table 3. The time-varying nature of the alum removals may be a cause for concern that could warrant further research. Dosing alum at approximately double the normally required minimum rate could lead to more frequent backwashing or treatment system upgrades (PWTAG, 2009, p. 62).

Table 4 provides some microsphere removal data for a 10-L bench-scale batch filtration system using cationic polymer (BioLab, Inc., A Chemtura Company, Lawrenceville, GA, USA) as the coagulant. The cationic polymer dosage was held constant at 2 mg/L, but the filtration rates and bed depths were again varied. While there was a clear trend toward lower filtration rates producing better removals, the effect of bed depth appeared greater with all three experiments with the deeper sand producing higher removals than the shallower bed at even the lowest filtration rate. The removals with cationic polymer were quite similar to the PACl removals for similar bed depths and filtration rates as shown in Table 2.

TABLE 4. Percent Microsphere Removal vs. Filtration Rate in 10L Batch Lab-scale Filtration Experiments (Filtration at 15-37 m/h with 300-600 mm of sand[#] after dosing 2 mg/L of cationic polymer)

Filtration Rate (m/h)	% Removal (300 mm Sand)	% Removal (600 mm Sand)
15	97.0	99.8
24	95.0	99.7
37	90.0	99.0

[#] *Pool Filter Sand (ES= 0.49 mm; UC= 1.5) (approximately 16/40 Mesh)*

TABLE 1. Control Experiments: 4.5-Micron Fluorescent Particle Removals without coagulation with varying sand depths

Coagulant	Dose (mg/L)	BFA (mg/L)	Bed Depth (mm)	SLR (m/hr)	Time (hr)	delta P (KPa)	Removal (%)	Notes
Control	None	10	0	24	0.25	3.4	1.3	**Condition 0:** No Media; Medium Rate
Control	None	10	300	37	0.25	3.4	32.9	**Condition 4:** Shallow Bed; High Rate
Control	None	10	600	24	0.25	10.3	24.5	**Condition 1:** Moderate Bed; Medium Rate

TABLE 2. Polyaluminum Chloride Experiments: 4.5-Micron Particle Removals with 0.1 mg/L of PACl as Al and varying sand depths and filtration rates

Coagulant	Dose (mg/L)	BFA (mg/L)	Bed Depth (mm)	SLR (m/hr)	Time (hr)	delta P (KPa)	Removal (%)	Notes
PAX-XL19	0.10	10	300	37	0	3.4	56.0	**Condition 4:** Shallow Bed; High Rate
PAX-XL19	0.10	10	300	37	23	4.1	87.5	**Condition 4:** Shallow Bed; High Rate
PAX-XL19	0.10	10	300	24	0	3.4	92.0	**Condition 3:** Shallow Bed; Medium Rate
PAX-XL19	0.10	10	300	24	24	8.3	95.7	**Condition 3:** Shallow Bed; Medium Rate
PAX-XL19	0.10	10	600	37	0	3.4	99.2	**Condition 2:** Moderate Bed; High Rate
PAX-XL19	0.10	10	600	37	24	19.3	98.1	**Condition 2:** Moderate Bed; High Rate
PAX-XL19	0.10	10	600	24	0	5.5	99.7	**Condition 1:** Moderate Bed; Medium Rate
PAX-XL19	0.10	10	600	24	24	20.7	99.3	**Condition 1:** Moderate Bed; Medium Rate

Coagulant: PAX-XL19 (Aluminum chlorohydrate is a PACl with approximately 82% basicity distributed by: Kemira Water US, Lawrence, KS).

TABLE 3. Aluminum Sulfate Experiments: 4.5-Micron Particle Removals with 0.1 mg/L of Alum as Al and varying sand depths and filtration rates

Coagulant	Dose (mg/L)	BFA (mg/L)	Bed Depth (mm)	SLR (m/hr)	Time (hr)	delta P (KPa)	Removal (%)	Notes
Alum	0.10	10	300	37	0	3.4	31	**Condition 4:** Shallow Bed; High Rate
Alum	0.10	10	300	37	24	>69	49	**Condition 4:** Shallow Bed; High Rate
Alum	0.10	10	600	24	0	6.9	33.0	**Condition 1:** Moderate Bed; Medium Rate
Alum	0.10	10	600	24	24	10.3	94.8	**Condition 1:** Moderate Bed; Medium Rate
Alum	0.10	10	600	24	48	44.1	89.8	**Condition 1:** Moderate Bed; Medium Rate
Alum	0.10	10	600	24	72	92.4	75.1	**Condition 1:** Moderate Bed; Medium Rate

Coagulant: Reagent Grade Aluminum Sulfate Octadecahydrate.

Figure 5 shows the Log removal of microspheres by a sand filter over time in a 5,500 L swim spa. The filter contained 300 mm of sand and was operated at 37 m/h. Both the dosage and type of polymer are different from Table 4, but the principle was the same. The cationic polymer **(**Arch Chemicals Inc., Norwalk, CT, USA) feed was continuous at 3.1 mg/L (with the dosage based on manufacturer's label) for the first 8 hours. Samples were collected at 30 and 60 minutes after turning off the coagulant feed. All removals were greater than 2 Log (or 99%) during this experiment. Figure 6 shows output from a streaming current monitor (SCM) sampling the filter influent stream during this same experiment. From Figure 6, it appears that the coagulant could have been overdosed resulting in a positive charge on the influent particles (even 1 hour after the feed of coagulant was stopped). Overdosing coagulant might work in the short-term, but long-term performance may not be sustained as all system surfaces could become positively charged and repel each other like negatively charged surfaces do in the control experiments. An SCM appears to be a useful tool for evaluating coagulant dosage and interpreting experimental results, but more research is necessary to fully evaluate its capabilities.

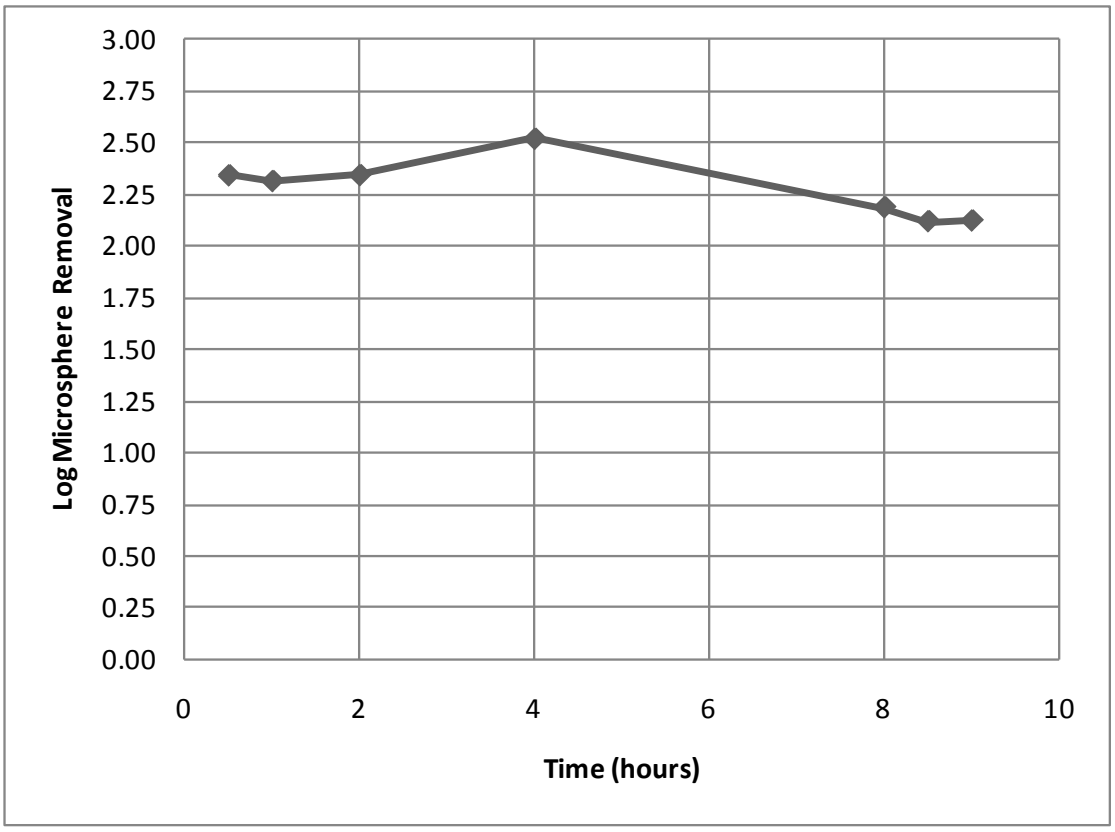


FIGURE 5. Log Microsphere Removal vs. Time in a 5,500 L Swim Spa (Filtration at 37 m/h with 300 mm of sand while dosing 3.12 mg/L of cationic polymer)

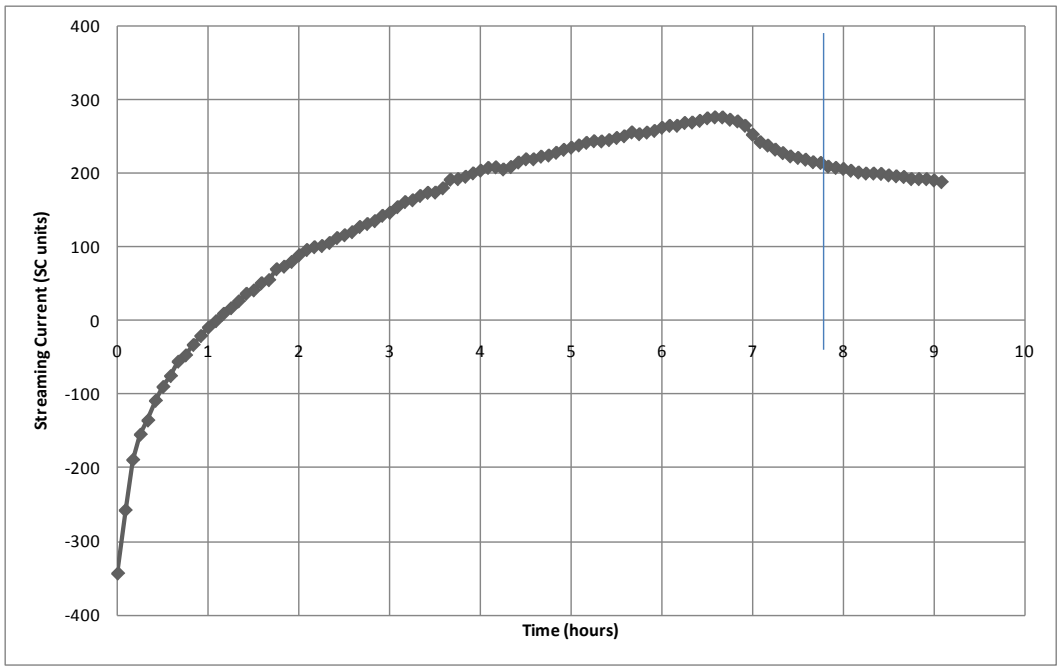


FIGURE 6. Streaming Current vs. Time for Swim Spa Experiment (Polymer feed stopped at 7.8 hrs)

Figure 7 shows the removal results for polystyrene microspheres and heat-inactivated *Cryptosporidium* oocysts in a full-scale (37,800 L) swimming in Conley, GA, USA. A cationic polymer **(**Arch Chemicals Inc., Norwalk, CT, USA) was fed as a pulse dosage of 3.1 mg/L (based on the volume of the pool). Instead of a continuous dosing of coagulant, the recommended dosage of was applied ahead of the filter for approximately 10 min. just prior to the start of the pathogen seeding. The *Cryptosporidium* removals were consistently between 1 and 2 Log (90-99%). The removals of microspheres trended closely with the oocysts further indicating its usefulness as a surrogate. This is the first full-scale experiment with *Cryptosporidium* oocysts where a coagulant has been shown to significantly enhance the removals of a sand filter that the authors are aware of.

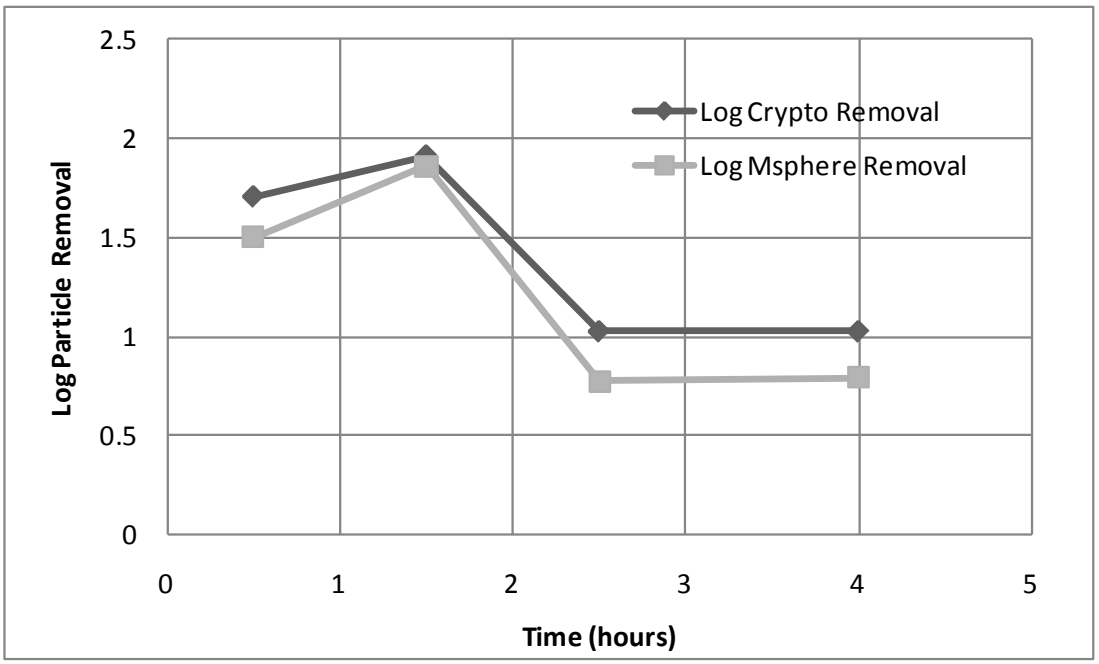


FIGURE 7. Log Removal vs. Time in 38,000 L Outdoor Pool (Filtration at 37 m/h with 300 mm of sand after dosing 3.12 mg/L of cationic polymer)

CONCLUSIONS

After considerable early success with coagulants in the laboratory enhancing the performance of swimming pool sand filters, a series of failures emerged as scale-up experiments were attempted. In short, coagulants that worked effectively in the pristine lab environment appeared to fail in spa-scale and full-scale trials. The design of the spa-scale system was found to be critically important for coagulant experiments even though control experiments were nearly identical at both scales. While filter surface area and turnover time are thought to be critically important, a series of other variables have emerged in terms of design and operation of swimming pools. These variables include filter loading rate, depth of the filter media, coagulant type, coagulant dosage, and potentially even how and where the coagulant is dosed.

Polyaluminum chloride and cationic polymers have now been successfully tested for enhancing the removal of *Cryptosporidium*-sized particles via swimming pool sand filters. Filter depth and filtration rate have significant influences on filter performance with each coagulant. The removals with Alum and Polyaluminum chloride were similar to the control experiments with 300 mm of sand at a filtration rate of 37 m/h. Filtration rate and sand depth also play a significant role in the performance of cationic polymers with deeper beds lower filtration rate yielding improved results. Polyaluminum chloride and cationic polymers appear to be more suited for swimming pool filters than alum based only on the limited research contained herein. Either underdosing or overdosing coagulants can be problematic based on filtration theory as well as previous swimming pool research (Croll et al., 2007), and the streaming current monitor appears thus far to be a useful tool for evaluating this situation. SCMs are used extensively in drinking water treatment practice for this purpose.

The full-scale cationic polymer trial might be the first successful trial where a coagulant has been used to significantly enhance the removal of *Cryptosporidium* with a swimming pool sand filter. When the coagulant was dosed intermittently just prior to the filter, the performance of the filter was improved for at least 4 hours (i.e., the duration of the experiment). While many questions remain unanswered and much research lies ahead, it is important that bench-scale, spa-scale, and full-scale experiments with coagulants for swimming pool applications have all been successfully completed. The answer to question of whether pool filters are removing *Cryptosporidium* is yes, but the current levels of removal may not be as high as is desired. Fortunately, there may be useful approaches presented in this paper that could help improve oocyst removals depending on your current design and operating practices. As the research progresses and more information becomes available, pool operators, managers, and regulators will be empowered to develop better standard operating procedures and design standards to further reduce the risk of waterborne disease outbreaks associated with recreational water venues.

ACKNOWLEDGEMENTS

The authors would like to thank all of the industry partners for donating portions of the research funding to the National Swimming Pool Foundation (NSPF) to make this research possible. The folks at NSPF like Tom Lachocki and Michelle Kavanaugh did so much to make this research possible. The generous donations of equipment from manufacturers have also played a significant role in improving the quality and speed of this research. Jim Brennan and Mike Unhoch of Arch Chemicals, Inc. deserve a lot of credit for their role in making the full-scale trial possible (and successful). Chuck Veal of the Micrometrix Corp. was very helpful in ensuring proper installation and startup of the streaming current monitor. Tom Getting of ITT Water and Wastewater USA was very helpful in providing the IMS cap material to allow the construction of an awesome set of filters that were used at multiple scales in this research. There are so many others that contributed that it is not possible to list them all, but those contributions are remembered and much appreciated.

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