# Evaluating a composite cartridge for small system drinking water treatment

Nur Muhammad, Rajib Sinha, Radha Krishnan, Craig L. Patterson, Roy C. Haught, Harold H. Harms and Rick Seville

## ABSTRACT

A pilot-scale evaluation was conducted at the U.S Environmental Protection Agency (EPA) Test & Evaluation (T&E) Facility in Cincinnati, Ohio, on a multi-layer, cartridge-based system that combines physical filtration with carbon adsorption and ultraviolet (UV) light disinfection to serve as a home-base water treatment security device against accidental or intentional contaminant events. The system was challenged with different levels of turbidity, a number of biological contaminants including *Bacillus subtilis*, *Escherichia coli*, *MS2 bacteriophage* and Polystyrene Latex (PSL) beads as a surrogate for *Cryptosporidium* and a number of chemical contaminants including super-chlorination, methyl tertiary butyl ether (MTBE), water chlorination disinfection byproducts (DBPs) and diazinon. The results demonstrated that the performance of the system varies as a function of the specific contaminant or surrogate. The overall performance indicated the potential of the system to improve the quality and safety of household water and to serve as an additional treatment barrier in circumstances where there is little or no treatment or where the quality of treated water may have deteriorated during distribution. The results also demonstrated that *B. subtilis* spore can serve as a more conservative surrogate for *Cryptosporidium* than PSL beads.

**Key words** | *Bacillus subtilis*, composite cartridge, *Cryptosporidium*, disinfection byproducts, membrane disinfection, surrogate, UV disinfection

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## INTRODUCTION

Drinking water systems have an enormous impact on public health, and the associated benefits of a well-run system cannot be overstated. Since 1971, more than 600 water-borne disease outbreaks have been recorded in the United States. In most cases, these outbreaks result in nausea, diarrhea, and cramps; however, in some cases, they result in very serious illness and even death (U.S. EPA 2003*a*). These outbreaks serve as a constant reminder of the critical importance of ensuring safe drinking water. The events of September 11, 2001 have further emphasized the need to develop water security appliances to remove physical, biological and chemical contaminants from deliberate or accidental contamination of the drinking water supply. An approach used by the water industry to provide safe drinking water and prevent outbreaks of waterborne diseases is the concept of "multiple barriers" (Abbaszadegan *et al.* 1997; U.S. EPA 2003*a*). As a final barrier before consumption, properly designed and operated public water systems, either large or small, are required to protect public health. This paper presents the results of experiments intended to further the development of a small package plant system for drinking water treatment.

Small systems serving less than 10,000 people face many challenges in meeting regulatory compliance and providing safe drinking water. The Water Supply and Water Resources Division (WSWRD) of the U.S. Environmental

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Protection Agency's (EPA's) National Risk Management Research Laboratory (NRMRL) has been conducting research on small drinking water systems since 1997 in response to the 1996 reauthorization of the Safe Drinking Water Act (SDWA). The SDWA established standards for drinking water systems and required EPA to assess treatment technologies relevant to small systems. This study evaluated the performance of a composite cartridge (Harmsco Filtration Products, West Palm Beach, Florida) that consists of physical filtration, adsorption and UV disinfection in removing physical, chemical and biological contaminants. The study also identified areas for further improvement and critically evaluated the applicability of the small system as a home water security device. The study also compared the potential of aerobic spore *Bacillus subtilis* with PSL beads as surrogate for *Cryptosporidium*.

## METHODS AND MATERIALS

### System description

The composite cartridge filter is constructed in three layers surrounding a hollow core. Figure 1 shows a conceptual diagram, various layers of the cartridge and the direction of water flow of the system. The outer filter media is a pleated pre-filter for removing particles and sediment. The second layer consists of an activated carbon extrusion to adsorb chemicals and to improve taste. The last layer is a submicron, pleated filter media for removing finer particles and microbial contaminants. The filter system housing consists of upper and lower chambers that are connected by an internal standpipe. The upper chamber houses the composite cartridge while the lower functions as a UV sterilization chamber. The cartridge and its hollow core, fits over the standpipe. There are two O-rings in the cartridge that engage with the standpipe and establish a seal to prevent by-passing. The UV chamber performs inactivation of microbial contaminants. Water enters the upper chamber and flows through all layers of the composite cartridge, then enters the UV chamber through the standpipe. After UV treatment, the finished water exits the system housing.

The filtration system setup at the T&E Facility (Figure 2) incorporates an inlet pump, power supply panel, inlet and outlet flow valves, pressure gauges, sample ports and associated electrical and plumbing hookups.

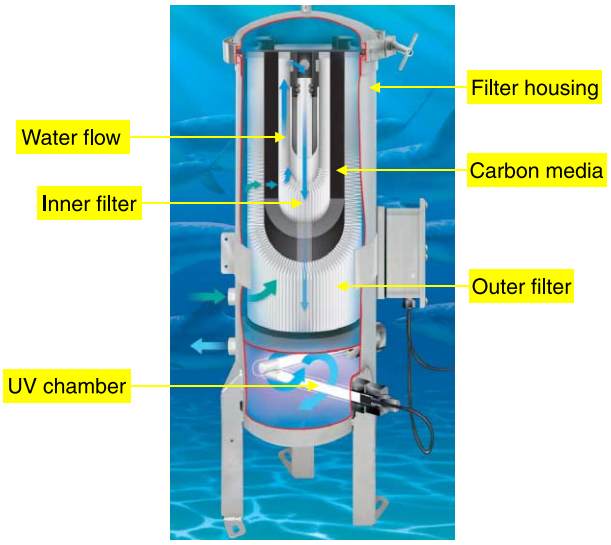


**Figure 1** | Conceptual diagram of the composite cartridge.

### Experimental challenges

#### Turbidity challenges

Turbidity is traditionally used as an indicator of water quality and a measure of effectiveness of a treatment process in removing pathogens from source water (U.S. EPA 2003*a*). Several pilot-scale and full-scale studies have demonstrated that organism-sized particles, turbidity and heterotrophic

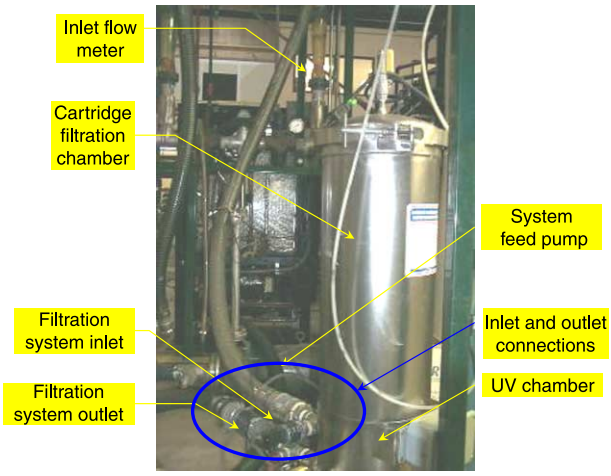


**Figure 2** | Filtration system setup at the T&E Facility.

plate count (HPC) are approximate indicators of pathogen removal by drinking water treatment processes but are not reliable quantitative surrogates (LeChevallier & Norton 1992; Nieminski & Ongerth 1995; Huck *et al.* 2001, 2002; Emelko *et al.* 2005). In this study, the system was challenged with various turbidity levels ranging from 1 Nephelometric Turbidity Unit (NTU) to 10.4 NTU to evaluate the performance of the system in meeting drinking water guidelines.

### Microbiological challenges

To evaluate specific bacteria removal, the system was challenged with two different species: 1) *Bacillus subtilis*, a predominant aerobic spore and 2) *Escherichia coli*, a human pathogen. Several studies (Yates *et al.* 1998; Dugan *et al.* 2001; Cornwell *et al.* 2003; Brown & Cornwell 2007) have demonstrated that *B. subtilis* is a conservative surrogate for *Cryptosporidium parvum* (*C. parvum*), a spore resistant to conventional disinfection by chlorination. *MS2 bacteriophage*, described as a surrogate for pathogenic enteric viruses (Harrington *et al.* 2003), was used in this study to challenge the system to evaluate the performance in removing viruses. *MS2 bacteriophage* has also been mentioned as a biological surrogate for *Cryptosporidium* (Fallon *et al.* 2007).

PSL beads with a mean size of 2.83 μm were used as a non-biological surrogate for *Cryptosporidium parvum* to evaluate the performance of the system in removing protozoa. The Long Term 2 Enhanced Surface Water Treatment Rule dictates that a surrogate must have an effective size of 3 μm or smaller to demonstrate *Cryptosporidium* removal (U.S. EPA 2005). Oocyst-sized polystyrene microspheres have been used as non-biological surrogates for oocysts removal by several researchers (Li *et al.* 1997; Swertfeger *et al.* 1998; Amburgey *et al.* 2001; Emelko *et al.* 2003; Emelko & Huck 2004). The relationship between *C. parvum* and polystyrene microspheres removal were filter-specific and affected by the operating conditions (Emelko *et al.* 2003).

During the turbidity challenges, influent and effluent concentrations of particles in the *Cryptosporidium* size range of 2 to 5 μm were measured to provide an indirect, secondary measure of protozoa removal. Heterotrophic plate counts in the influent and effluent were also monitored during the turbidity challenges to evaluate heterotrophic bacteria removal by the system (with and without UV treatment).

### Chemical challenges

The system was challenged with MTBE, a fuel additive, high chlorine concentration typical of that required to disinfect a water distribution system following a biological contamination event, disinfection byproducts from chlorination such as trihalomethanes (THMs) and haloacetic acids (HAAs) and diazinon, a pesticide.

The widespread use of MTBE combined with its high mobility, water solubility and resistance to natural attenuation has resulted in its detection in ground and surface waters (Squillace *et al.* 1996; Hartley *et al.* 1999; Fayolle *et al.* 2001). U.S. EPA has classified MTBE as a possible human carcinogen and set a drinking water advisory at 20–40 μg/L to prevent taste and odor problems and to protect against potential health effects (U.S. EPA 1997).

Chlorine is widely used in the disinfection of drinking water. Waterborne diseases, such as cholera, typhoid and dysentery have decreased dramatically due to chlorine disinfection (Moudgal *et al.* 2000; Hamidin *et al.* 2008). However, chlorine and its related species react with organic matter in water to produce chemical compounds known as disinfection byproducts. Of these, THMs and HAAs are found in the highest concentrations in treated drinking water (Richardson 2003; Hamidin *et al.* 2008). Epidemiological studies on animals have revealed adverse health effects of DBPs. such as colon cancer (King *et al.* 2000), kidney tumor (Hard *et al.* 2000) and infant growth reduction (Wright *et al.* 2004). U.S. EPA (2003*a*) has set a maximum contaminant level (MCL) for total THM and total of five regulated HAAs (HAA5) as 0.08 and 0.06 mg/L, respectively.

Diazinon is one of the most widely used organophosphorus pesticides for households as well as agricultural pest control. The extensive use of pesticides represents a water quality risk in agricultural areas since these compounds can contaminate surface and ground waters and can cause adverse health effects (Chiron *et al.* 2000). Most pesticides present in surface water are not removed by conventional treatment processes (Miltner *et al.* 1989).

Therefore, more efficient processes are required to remove pesticides during drinking water production.

## Injection, sampling and analysis

### Turbidity challenges

Feed water with the target turbidity level was prepared by mixing water from a surface water source (Mill Creek, located adjacent to the T&E Facility) with dechlorinated potable water in a 5,000-gallon tank. Although the quality of the Mill Creek water varies during different times of the year, the typical values of the general parameters are as follows: pH ≈ 8.0, dissolved oxygen ≈ 6.2 mg/L, temperature ≈ 14.5°C, bio-chemical oxygen demand (BOD5) ≈ 3.2 mg/L, chemical oxygen demand (COD) ≈ 6.2 mg/L, TOC ≈ 6.7 mg/L, conductivity ≈ 535 μmohs/cm, TSS ≈ 52 mg/L and hardness 245 mg/L. A mass-balance approach was used to determine the mixing ratio of potable water to surface water to achieve the target feed water turbidity. Automatic turbidity sensors (HACH Model:ATI 15/76) were installed in the tank as well as in the supply pipe to continuously monitor the turbidity of the feed water. Grab samples for influent and effluent were collected at hourly intervals for approximately 5 hours. The turbidity of these grab samples was determined using a HACH turbidity meter, Model 2100P. An online particle counter (HACH Model: 1900 WPC) was used to monitor the influent and effluent particle count data in the size range of 2–5 μm. Grab samples for influent and effluent HPC concentrations were collected twice during each test run. The HPC concentrations were determined using the IDEXX SimPlate method (IDEXX 2002).

### Microbiological challenges

For *B. subtilis*, *E. coli* and *MS2 bacteriophage* challenges, 1 mL of stock suspension with an approximate cell concentration of $10^9$ cells per mL was mixed with 500 mL of 0.01% polysorbate surfactant (Tween®20, Sigma-Aldrich, St. Louis, Missouri) in a 1-L glass beaker. A sub-sample was collected to determine the actual concentration of the injection suspension. The 500-mL suspension was then injected into the influent stream of the filtration system using a peristaltic pump. At the completion of the injection, the beaker was filled with an additional 500 mL of 0.01% polysorbate surfactant and injected into the feed stream. The total injection time for the suspension and the rinseate was approximately 60 minutes. Samples from the influent and effluent stream were collected at 0, 5, 10, 20, 30 and 60 minutes after the start of the injection. Duplicate samples were collected 10 minutes after the start of injection of the organism. A new cartridge was used for each of the contaminants and the system was flushed for approximately 30 minutes before and after each challenge test. Each test was conducted on the cartridge at 15 gpm for approximately one hour and the total output during each test was ≈ 900 gallons. No headloss development was observed during these challenge tests.

*B. subtilis* (Raven Laboratories, Omaha, Nebraska) and MS2 bacteriophage (BioVir Laboratories, Benifica, California) stocks were obtained from biological laboratories. *E. coli* (ATCC 15222™, American Type Culture Collection, Manassas, Virginia) stock was prepared by culturing with nutrient broth. Grab samples for *B. subtilis* were analyzed in accordance with methods described by Rice *et al.* (1994). Grab samples for *E. coli* were analyzed based on HACH microbiological methods for Total coliform and *E. coli* (HACH 1999). Grab samples for *MS2 bacteriophage* were submitted to BioVir Laboratory for analysis by EPA Method 1602 (U.S. EPA 2001*a*). Triplicate tests were conducted for each contaminant for evaluating the performance of the system. All the tests were performed using dechlorinated potable water at a flow rate of 15 gpm.

For PSL bead challenges, 1 mL of stock bead suspension with an approximate concentration of $10^9$ per mL was mixed with 500 mL of 0.01% polysorbate surfactant in a 1-L glass beaker. The 500 mL suspension was then injected into the influent stream of the system using a peristaltic pump. At the completion of the injection, the beaker was filled with an additional 500 mL of 0.01% polysorbate surfactant and injected into the feed stream. The total injection time for the bead suspension and the rinseate was 30 minutes. The system was run for 4–5 hours after completion of the injection. A slip stream of the effluent from the system was diverted through a 1 μm membrane in a manifold membrane system to collect the beads from the effluent. The beads were then eluted, and the samples were analyzed according to EPA Method 1622 (U.S. EPA 2001*b*).

A 500 μL sub-sample was also collected and analyzed to determine the total beads in the influent. Polysciences PSL beads (Fluosorbite® Plain YG, Polysciences, Inc., Warrington, Pennsylvania) (3.0 μm microspheres) were used as stock suspension for this challenge. The total output during each test was ≈ 4,500 gallons. The system was flushed for 30 minutes before and after each test. No headloss development was observed during the PSL beads challenges.

### Chemical challenges

For MTBE, super-chlorination and diazinon, the system was challenged with target feed concentrations of the appropriate chemical at 1, 4 and 0.15 mg/L, respectively. Injection solutions of the contaminants were prepared by mixing the stocks with nanopure water and fed into the influent stream using a peristaltic pump. For evaluating the removal of DBPs, the system was challenged with the THMs inherent in Cincinnati drinking water and with a spike of 15 μg/L (total) of five regulated haloacetic acids (HAA5) using a custom standard solution. In the case of THMs, the samples were analyzed for chloroform ($CHCl_3$), dichlorobromomethane ($CHBrCl_2$), dibromochloromethane ($CHBr_2Cl$) and bromoform ($CHBr_3$) and the total THMs concentrations were considered for performance evaluation. In the case of HAAs, the samples were analyzed for five regulated haloacetic acids: monochloroacetic acids (MCAA), dichloroacetic acids (DCAA), trichloroacetic acids (TCAA), monobromoacetic acids (MBAA) and dibromoacetic acids (DBAA). The total HAA5 concentration was considered for performance evaluation of the system.

For each test, influent and effluent samples were collected prior to injection. The first post-injection samples were collected 15 minutes after the start of the injection; subsequently, three additional samples were collected at hourly intervals. Duplicate samples were collected 135 minutes after the start of the injection of the contaminants. All the tests were conducted using dechlorinated potable water at a flow rate of 15 gpm. A new cartridge was used for each of the contaminants and the system was flushed for approximately 30 minutes before and after each challenge test. Each test was conducted on the cartridge at 15 gpm for approximately 3.25 hours and the total output during each test was ≈ 3,000 gallons. No headloss development was observed during these challenges.

Grab samples for MTBE were analyzed using EPA Methods 5030C (purge and trap) and 8015 [gas chromatography with flame-ionization detector (GC/FID)] (U.S. EPA 2003*b*). Grab samples for chlorine were analyzed using HACH Method 8021 (HACH 1997). Grab samples for THMs and HAAS were analyzed using EPA Method 551.1 (U.S. EPA 1995*a*) and EPA Method 552.2 (U.S. EPA 1995*b*), respectively. Diazinon samples were analyzed using EPA Method 507 (U.S. EPA 1989).

## RESULTS AND DISCUSSIONS

### Turbidity challenges

Tables 1, 2, 3 and 4 summarize turbidity, particle counts, HPC and differential pressure/run time results, respectively, during the turbidity challenges. The influent and effluent data for turbidity and particle counts represent the average of five grab samples during each test. The influent and effluent data for HPC represent the average of two grab samples during each test. The results show that the system has potential for removal of turbidity and *Cryptosporidium* size particles. A total of eight (8) turbidity challenges were conducted on the filtration system operated at 15 gpm. For influent turbidity levels between 1 and 3 NTU, effluent

**Table 1** | Summary of results for turbidity removal during turbidity challenges

| Turbidity test no. | Turbidity (NTU) Influent | Effluent | % Removal |
|---|---|---|---|
| 1 | 1.10 | 0.38 | 65.5 |
| 2 | 2.16 | 0.62 | 71.3 |
| 3 | 1.98 | 0.51 | 74.2 |
| 4 | 2.10 | 0.53 | 74.8 |
| 5 | 1.07 | 0.38 | 64.5 |
| 6 | 2.54 | 0.51 | 79.9 |
| 7 | 2.60 | 0.44 | 83.0 |
| 8 | 3.12 | 0.44 | 85.6 |
| 9* | 10.41 | 0.31 | 97.0 |
| 10* | 9.48 | 0.26 | 97.3 |

*Test conducted on a cartridge with finer inner media (1.0 μm nominal nanofiber) at a lower filtration rate of 11 gpm.

**Table 2** | Summary of results for 2–5 μm particle counts during turbidity challenges

| Turbidity test no. | Particle counts/mL Influent | Effluent | % Removal |
|---|---|---|---|
| 1 | 214 | 99 | 53.6 |
| 2 | 673 | 94 | 86.0 |
| 3 | 653 | 109 | 83.0 |
| 4 | 927 | 109 | 88.3 |
| 5 | 657 | 111 | 84.3 |
| 6 | 1,683 | 102 | 93.5 |
| 7 | 1,600 | 102 | 93.5 |
| 8 | 5,902 | 220 | 96.3 |
| 9* | 14,147 | 458 | 96.7 |
| 10* | 13,113 | 505 | 96.2 |

*Test conducted on a cartridge with finer inner media (1.0 μm nominal nanofiber) at a lower filtration rate of 11 gpm.

turbidity levels varied between 0.38 and 0.62 NTU with removal efficiencies varying from 64.5 to 85.6%. Particle count was used as a secondary indicator of the performance of the system in filtering particles in the *Cryptosporidium* size range (2–5 μm). The influent particle concentration was not controlled and was accepted as received when constituting the feed water for turbidity challenges. The feed particle counts were between 214 and 5,202 per mL and the effluent particle counts were between 94 and 220 per mL. Particle count (2–5 μm) removal varied from 53.6 to 96.3%, depending on the feed concentrations. The performance of the system in removing heterotrophic bacteria was enhanced by the integrated UV system. The influent HPC concentration was not controlled and was accepted as received when constituting the feed water for turbidity challenges. For HPC concentrations between 463 and 12,350/mL, the effluent HPC concentrations varied between 10 and 125/mL with the UV ON, and between 225 and 4,885/mL with the UV OFF. The HPC removal efficiencies ranged from 95.3 to 99.2% with the UV light ON and from 42 to 84.3% with the UV light OFF.

**Table 3** | Summary of results for heterotrophic plate count (HPC) during turbidity challenges

| Turbidity test no. | HPC/mL Influent | Effluent (with UV) | Effluent (without UV) | % Removal With UV | Without UV |
|---|---|---|---|---|---|
| 1 | 463 | 10 | 272 | 97.9 | 42.0 |
| 2 | 1,680 | 21 | 315 | 98.8 | 81.2 |
| 3 | 1,960 | 65 | 370 | 96.8 | 81.0 |
| 4 | 1,950 | 33 | 385 | 98.2 | 79.0 |
| 5 | 2,750 | 52 | 690 | 98.9 | 74.5 |
| 6 | 12,350 | 46 | 4,885 | 99.2 | 60.0 |
| 7 | 960 | 10 | 225 | 99.0 | 76.0 |
| 8 | 2,700 | 125 | 423 | 95.3 | 84.3 |

Two additional tests were conducted on a cartridge with finer inner media, operated at 11 gpm using feed water with higher turbidity. For influent turbidity levels between 9.48 and 10.4 NTU, effluent turbidity levels varied between 0.31 and 0.26 NTU with associated removal efficiencies varying between 97.0 and 97.3%. For influent particle (2–5 μm) counts between 13,113 per mL and 14,147 per mL, effluent particle counts varied between 458 and 505 per mL with removal efficiencies varying from 96.2 to 96.7%. The rate of headloss of the system, presented as differential pressure per gallon per hour, was a function of feed water quality, cartridge condition and operational filtration rate. Although the effluent quality improved significantly with finer inner media and lower filtration rate, the rate of headloss increased rapidly. This indicates the preference of the system for low turbidity feed water for the system. The effluent quality did not deteriorate due to the dirty condition of the filter and higher feed water turbidity.

## PSL bead challenges

Table 5 shows the results for PSL bead challenges, used as a surrogate for *Cryptosporidium*. A total of four tests were conducted on the cartridge operated at 15 gpm. The concentrations of beads in the injected suspensions were around $10^6$ per mL that generated a total beads count of approximately $10^9$ in the influent stream. The log removal varied from 2.3 to 2.5 with an average log removal of 2.4. Two additional tests were conducted on a cartridge with finer inner media at 11.0 gpm. The log removal values increased to 3.73 at clean conditions and 3.12 at dirty conditions. Although the removal performance for turbidity and natural particles did not deteriorate at the dirty condition of the filter, the removal performance for PSL beads deteriorated at dirty conditions. This is attributed to the higher rigidity of the PSL beads. Emelko & Huck (2004)

**Table 4** | Summary of differential pressure/headloss during turbidity challenges

| Turbidity test no. | Feed turbidity (NTU) | Filter condition | Diff. pressure (Psi) | Water treated (Gallons) | Run time (Hours) | Rate of headloss (Psi/gal/h) |
|---|---|---|---|---|---|---|
| 1 | 1.10 | Clean | 2 | 4,230 | 5.5 | 0.00009 |
| 2 | 2.16 | Dirty | 8 | 4,060 | 5.5 | 0.00040 |
| 3 | 1.98 | Clean | 3 | 3,500 | 5.0 | 0.00020 |
| 4 | 2.10 | Dirty | 8 | 3,350 | 4.0 | 0.00060 |
| 5 | 1.07 | Dirty | 25 | 3,500 | 4.25 | 0.00200 |
| 6 | 2.54 | Clean | 6 | 4,173 | 4.5 | 0.00030 |
| 7 | 2.60 | Dirty | 7 | 4,250 | 4.5 | 0.00040 |
| 8 | 3.12 | Clean | 4 | 3,830 | 4.0 | 0.00030 |
| 9* | 10.41 | Clean | 45 | 2,651 | 4.0 | 0.00424 |
| 10* | 9.48 | Dirty | 46 | 410 | 0.75 | 0.15000 |

*Test conducted on a cartridge with finer inner media (1.0 μm nominal nanofiber) at lower filtration rate of 11 gpm.

has explained that polystyrene microspheres may be more rigid than oocysts and therefore may attach and/or detach differently as filter influent particle load or composition changes.

### *Bacillus subtilis* challenges

Table 6 shows the results for the *B. subtilis* challenges. The influent and effluent data presented are the average of concentrations of the sampling events that were consistent during each test run. The log removal of *B. subtilis* varied between 1.6 and 2.0, with an average log removal of 1.75 for an influent cell concentration ranging from $10^4$ to $10^5$ cells per 100 mL. The removal of *B. subtilis* was inferior to the removal of oocyst-sized beads (2.4 log removal). This result is consistent with that reported in the literature (Yates *et al.* 1998; Dugan *et al.* 2001; Cornwell *et al.* 2003; Brown & Cornwell 2007) that aerobic spore *B. subtilis* is a conservative surrogate for *Cryptosporidium*.

### *Escherichia coli* challenges

Table 7 shows the results for the *E. coli* challenges. The influent and effluent data presented are the average of concentrations of the sampling events that were consistent during each test run. The system showed an adequate removal of *E. coli*. The log removal of *E. coli* varied between 2.97 to 3.66 with an average log removal of 3.35 for an influent cell concentration of approximately $10^5$ cells per 100 mL. The relatively higher log removal of *E. coli* compared to *B. subtilis* spore followed the trend of vegetative cells being more vulnerable to UV treatment as documented by several researchers (Chang *et al.* 1985; Sommer *et al.* 1998).

**Table 5** | Summary of PSL bead test results

| Test no. | Injection conc./mL | Total beads in influent | Total beads in effluent | Log removal |
|---|---|---|---|---|
| 1 | $2.20 \times 10^6$ | $1.10 \times 10^9$ | $3.50 \times 10^6$ | 2.50 |
| 2 | $3.40 \times 10^6$ | $1.70 \times 10^9$ | $9.30 \times 10^6$ | 2.30 |
| 3 | $3.60 \times 10^6$ | $1.80 \times 10^9$ | $8.00 \times 10^6$ | 2.40 |
| 4 | $3.68 \times 10^6$ | $1.84 \times 10^9$ | $7.50 \times 10^6$ | 2.40 |
| 5* | $3.12 \times 10^6$ | $1.56 \times 10^9$ | $2.49 \times 10^5$ | 3.73 |
| 6*,† | $3.28 \times 10^6$ | $1.64 \times 10^9$ | $1.25 \times 10^6$ | 3.12 |

*Test conducted on a cartridge with finer inner media (1.0 μm nominal nanofiber) at lower filtration rate of 11 gpm.
†Test conducted on dirty cartridge condition.

**Table 6** | Summary of *B. subtilis* test results

| Test no. | No. of cells/100 mL Influent | Effluent | Log removal |
|---|---|---|---|
| 1 | $3.78 \times 10^4$ | $9.25 \times 10^2$ | 1.61 |
| 2 | $9.10 \times 10^4$ | $1.86 \times 10^3$ | 1.70 |
| 3 | $6.25 \times 10^4$ | $1.40 \times 10^3$ | 1.65 |
| 4 | $1.10 \times 10^5$ | $1.10 \times 10^3$ | 2.00 |

## MS2 bacteriophage challenges

Table 8 shows the results for the *MS2 bacteriophage* challenges. The influent and effluent data presented are the average concentrations of the sampling events that were consistent during each test run. The log removal efficiencies varied between 1.00 to 1.20 with an average log removal of 1.10 for an influent cell concentration of approximately $10^5$ cells per 100 mL. The average log removal (1.10) approximately corresponds to 20 milliJoules per square centimeter ($mJ/cm^2$) UV intensity based on the collimated beam test conducted on the stock MS2 bacteriophage used in these experiments. The low log removal may be attributed to relatively more UV-resistant capacity of MS2 bacteriophage as described by Fallon *et al.* (2007).

## MTBE challenges

Table 9 shows the results of the MTBE challenges. For influent MTBE levels between 1.02 to 1.38 mg/L, the effluent MTBE levels varied between 0.26 to 0.93 mg/L before breakthrough occurred after approximately 8 hours of injection. Although the influent MTBE concentrations were very high, the system demonstrated adequate removal (49% overall) before breakthrough occurred in the carbon media of the cartridge. The cartridge appeared to recover following the rest period at the end of each challenge; however, such recovery was very short-lived.

**Table 7** | Summary of *E. coli* test results

| Test no. | No. of cells/100 mL Influent | Effluent | Log removal |
|---|---|---|---|
| 1 | $2.23 \times 10^5$ | $2.39 \times 10^2$ | 2.97 |
| 2 | $4.49 \times 10^5$ | $0.98 \times 10^2$ | 3.66 |
| 3 | $4.19 \times 10^5$ | $1.63 \times 10^2$ | 3.40 |

**Table 8** | Summary of *MS2 bacteriophage* test results

| Test no. | No. of cells/100 mL Influent | Effluent | Log removal |
|---|---|---|---|
| 1 | $1.10 \times 10^5$ | $7.92 \times 10^3$ | 1.10 |
| 2 | $1.63 \times 10^5$ | $1.06 \times 10^4$ | 1.20 |
| 3 | $9.6 \times 10^4$ | $9.48 \times 10^3$ | 1.00 |

## Chlorine challenges

Table 10 shows the results of super-chlorination challenges. For influent chlorine levels between 4.00 to 5.70 mg/L, the effluent chlorine levels varied between 0.02 to 0.43 mg/L. The system demonstrated excellent performance (96.2% overall) in removing free chlorine from drinking water for an influent concentration that is typical of super-chlorination of distribution systems. No breakthrough occurred during the three tests; however, the effluent chlorine concentrations increased gradually with time, indicating either a slight desorption or a low level passing of chlorine through the carbon media of the cartridge.

## DBP challenges

Tables 11 and 12 summarize the data of total THM and HAA5 for the DBP challenges. A total of three challenges were conducted on the HSC-15 cartridge operated at 15 gpm. For influent total THM concentrations between 27.7 to 45.5 μg/L, the effluent THM concentrations varied between 0 to 10.3 μg/L. Although the feed concentrations of total THM were less than the U.S. EPA MCL (80 μg/L) (U.S. EPA 2003*a*) of the contaminant, the unit performed in an excellent manner (84% overall) in reducing the THM levels available in drinking water. For influent total HAA5 concentrations between 6.53 to 15.6 μg/L, the effluent concentrations varied between 4.04 to 10.39 μg/L.

**Table 9** | Summary of MTBE test results

| Test no | MTBE concentration (mg/L) Influent | Effluent | % Removal |
|---|---|---|---|
| 1 | 1.23–1.34 | 0.63–0.93 | 26.0–48.8 |
| 2 | 1.02–1.05 | 0.26–0.67 | 34.2–75.3 |
| 3 | 1.38–1.39 | 0.45–1.35 | 3.3*–67.6 |

*Breakthrough occurred; not considered for performance evaluation.

**Table 10** | Summary of Chlorine test results

| Test no | Chlorine concentration (mg/L) Influent | Effluent | % Removal |
|---|---|---|---|
| 1 | 4.32–4.88 | 0.02–0.08 | 98.2–99.6 |
| 2 | 4.04–5.70 | 0.11–0.21 | 94.8–97.5 |
| 3 | 4.52–4.66 | 0.24–0.43 | 90.7–94.7 |

Although the feed concentrations of HAA5 were less than the U.S. EPA MCL (60 μg/L) (U.S. EPA 2003*a*) of the contaminant, the unit performed reasonably well (46% overall) in reducing the HAA5 levels available in drinking water. No overall breakthrough of HAA5 occurred during the three challenges; however, an individual component, mono-bromo acetic acid (MBAA) started breakthrough after 8 hours of filter run.

Three additional tests were conducted on the system at a lower filtration rate (11.0 gpm) using relatively higher feed concentrations of THM and HAA5. For influent total THM concentrations between 75.0 to 112.4 μg/L, the effluent THM concentrations varied between 1.3 to 10.9 μg/L. The effluent quality did not deteriorate due to higher feed concentrations of total THM. Although the feed concentrations were more than the U.S. EPA MCL (80 μg/L) in most of the sampling events, the system demonstrated excellent performance (93.9% overall) in reducing the effluent THM concentrations. Although the percent removal value (43% overall) remained similar, the effluent quality deteriorated significantly at higher feed concentration of HAA5. For influent total HAA5 concentrations between 20.7 to 66.8 μg/L, the effluent concentrations varied between 12.9 to 29.5 μg/L. Breakthrough occurred after 11 hours of filter run.

**Table 11** | Summary of THM test results

| Test no | Total THM concentration (μg/L) Influent | Effluent | % Removal |
|---|---|---|---|
| 1 | 40.8–45.5 | 0–5.7 | 86.8–100.0 |
| 2 | 27.7–29.0 | 3.2–8.6 | 70.3–88.5 |
| 3 | 33.4–36.2 | 4.5–10.3 | 69.2–87.6 |
| 4* | 85.9–95.0 | 1.3–4.2 | 95.2–98.6 |
| 5* | 75.0–90.9 | 2.6–7.2 | 90.4–97.2 |
| 6* | 89.8–112.4 | 4.2–10.9 | 87.9–94.5 |

*Test conducted at lower filtration rate of 11 gpm with higher feed concentration.

**Table 12** | Summary of HAA5 test results

| Test no | HAA5 concentration (μg/L) Influent | Effluent | % Removal |
|---|---|---|---|
| 1 | 12.2–15.1 | 4.0–7.4 | 39.3–73.5 |
| 2 | 10.9–13.7 | 5.9–7.5 | 40.5–55.5 |
| 3 | 8.4–12.8 | 4.1–9.1 | 28.9–59.4 |
| 4* | 26.0–57.7 | 12.9–19.5 | 31.0–68.5 |
| 5* | 29.0–66.8 | 22.8–29.5 | 13.9–55.8 |
| 6* | 20.7–37.4 | 19.4–21.9 | 0.0†–47.8 |

*Test conducted at a lower filtration rate of 11 gpm with higher feed concentration.
†Breakthrough occurred, not considered for performance evaluation.

**Table 13** | Summary of Diazinon test results

| Test no | Diazinon concentration (μg/L) Influent | Effluent | % Removal |
|---|---|---|---|
| 1 | 43.6–61.5 | 0.2–0.4 | 99.1–99.6 |
| 2 | 48.5–73.5 | 0.3–0.3 | 99.4–99.6 |
| 3 | 59.2–87.1 | 0.2–1.3 | 97.8–99.7 |

### Diazinon challenges

Table 13 shows the results of diazinon challenges. For influent diazinon concentrations ranging between 43.6 and 97.9 μg/L, the effluent diazinon concentration varied between 0.2 and 1.3 μg/L. The system demonstrated excellent performance (99.3%) in removing the target pesticide that is difficult to remove in a conventional treatment system. There was no breakthrough observed during the tests.

## CONCLUSIONS

Based on the data obtained from the turbidity challenge tests, the tested composite cartridge system demonstrates potential for removal of turbidity and *Cryptosporidium* size particles. For influent turbidity levels between 1 and 3 NTU, effluent turbidity levels varied between 0.38 and 0.62 NTU and overall removal efficiencies ranged between 64.5 and 85.6%. Particle count was used as a secondary indicator of the performance of the system in filtering particles in the *Cryptosporidium* size range (2–5 μm). For influent particle counts between 214 and 5,202 per mL, the effluent particle counts were between 94 and 220 per mL and the resulting

removal efficiencies varied between 53.6 and 96.3% depending on the feed concentrations. The rate of headloss of the system presented as differential pressure per gallon per hour depended on the condition of the cartridge and feed water turbidity. The effluent quality did not deteriorate due to the dirty condition of the filter and high feed water turbidity; however, the headloss increased rapidly indicating suitability of the system for low feed water turbidity.

The UV reactor of the system performed efficiently to improve general bacteriological effluent quality. For HPC concentrations between 463 and 12,350/mL, the effluent HPC concentrations varied between 10 and 125/mL with the UV ON, and between 225 and 4,885/mL with the UV OFF. Depending on the feed concentrations, HPC removal efficiencies ranged from 95.3 to 99.2% with the UV ON, and between 42 and 84.3% without UV light.

Based on the data obtained from the different microbiological challenges, the system showed an adequate removal of PSL beads (as surrogate for *Cryptosporidium*) and *E. coli*, but did not perform adequately in removing *B. subtilis* and *MS2 bacteriophage*. The results demonstrate that the performance depends on the contaminant. The concentrations of PSL beads (2.83 μm) in the injected suspensions were $10^6$ per mL that generated a total beads count of approximately $10^9$ in the influent stream. The log removal of PSL beads varied between 2.3 and 2.5 that satisfied the Long-Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR) standard for *Cryptosporidium* removal (2.0 log) (U.S. EPA 2004). The performance of the system in removing PSL beads improved significantly with finer inner media. Unlike turbidity and natural particles, the performance of the system deteriorated at dirty filter condition suggesting either different attachment/detachment of PSL beads due to more rigidity or composition of the membrane. The log removal of *B. subtilis* varied between 1.6 and 2.0, with an average log removal of 1.75 for an influent cell concentration ranging between $10^4$ and $10^5$ cells per 100 mL. The log removal of *E. coli* varied between 2.97 and 3.66 with an average log removal of 3.35 for an influent cell concentration of approximately $10^5$ cells per 100 mL. The relatively higher log removal of *E. coli* compared to *B. subtilis* spore followed the trend of vegetative cells being more vulnerable to UV treatment. The log removal of *MS2 bacteriophage* varied between 1.0 and 1.2 with an average log removal of 1.1 for an influent cell concentration of approximately $10^5$ cells per 100 mL. The results of collimated beam tests indicated that a stronger UV light was necessary to enhance MS2 bacteriophage removal. The log removal values of *B. subtilis* were less than that of PSL beads, indicating that the aerobic spore was a conservative surrogate for *Cryptosporidium*.

Based on the data obtained from different chemical challenges, the system showed excellent removal of chlorine, THM and diazinon, and adequate removal of MTBE and HAA5. The results demonstrate a similar trend to that observed for microbiological challenges in that the treatment performance of the system depends on the contaminant. The system achieved an overall 96.2% removal of chlorine at influent concentrations ranging between 4.00 and 5.70 mg/L, 84% removal of THMs for influent concentrations ranging between 27.7 and 45.5 mg/L, 99.3% removal of diazinon for an influent concentration of approximately 64 μg/L, 49% removal of MTBE for influent concentration of approximately 1.2 mg/L, and 46% removal of HAA5 compounds for an influent concentrations of 6.53 to 15.6 μg/L. Although the effluent water quality did not deteriorate during challenges with relatively higher feed concentrations of THM (75.0–112.4 μg/L), the effluent water quality deteriorated during challenges with relatively higher feed concentrations of HAA5 (20.7–66.8 μg/L). No breakthrough occurred during challenges with chlorine, THMs and diazinon; however, a continuous increase of effluent concentration was observed suggesting either a slight desorption or channelization of these contaminants due to loading on the carbon media. No breakthrough occurred for HAA5 during challenges with concentrations as available in drinking water; however, breakthrough occurred after 11 hours of filter run during challenges with relatively higher feed concentration of HAA5. For MTBE, the performance of the system deteriorated rapidly with time during challenges with very high feed concentration; however, a very short-lived recovery of treatment capacity was observed following a rest period at the end of each test before breakthrough occurred after 8 hours of injection of MTBE.

The composite cartridge has demonstrated potential to improve quality and safety of an individual household and small community on a daily basis. The treatment capability

of the system depends on the target contaminants, hence it is important to identify the target contaminant to achieve the desired removal and to avoid problems associated with desorption/breakthrough of contaminant. The system will serve as an additional treatment barrier in circumstances where there is little or no treatment or where the quality of treated water may have deteriorated during distribution.

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