ABSTRACT

Amanda Kaufman: Efficacy of CrystalPur™ Household Water Filter
for Removal of Pathogenic Microorganisms: Lifespan Volume Test
(Under the direction of Professor Mark D. Sobsey)

Over 1.6 million people, most of whom are children, die each year from ingesting water contaminated with bacteria, viruses, and parasites. Treatment of drinking water at the point of use (POU) has demonstrated health benefits for people who have access only to microbially contaminated drinking water sources. The ceramic siphon household water filter is one option for POU treatment. In this work, the ceramic siphon filter was evaluated in the laboratory for its ability to reduce indicator microorganisms in test waters. During batch challenge tests, the ceramic siphon filter reduced *E. coli* in filtered water by 7 $\log_{10}$ (99.999987%). The filter was not effective for virus removal, with reductions of only 0.12 $\log_{10}$ (24.0%) observed for coliphage MS-2. In addition, a continuous flow dosing system allowing water to constantly run through the filters for extended periods of time daily allowed for determination of changes in microbial reductions over time. *E. coli B*, MS-2 and fluorescent microspheres (as a surrogate for *Cryptosporidium* oocysts) were seeded into test water and dosed to filters at 10%, 25%, and 50% of the filter's volume lifespan. One of the three replicate filters was only tested at 10% and 25% of the filter's volume lifespan because the filter broke prior to reaching its reported 50% volume lifespan. There was a decrease in microbial removal efficacy as the volume of water filtered increased and test filters did not achieve their target volume lifespan before physically failing. The ceramic siphon household water filter is effective in reducing *E. coli* and fluorescent microsphere surrogates for

Cryptosporidium in water, but filter modifications may be needed to achieve acceptable levels of virus removal and to reach the target 7000 liter volume lifespan of the filter.

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Unsafe drinking water affects millions of people worldwide, with those living in the most underserved regions in developing countries often being the most affected populations. Over 1.6 million people, most of whom are children, die each year from ingesting water contaminated with bacteria, viruses, and parasites. Although the ideal solution to this problem would be increased infrastructure providing universal access to safe, pathogen-free, and reliable piped water, this solution is not feasible for many developing countries due to high capital costs of water infrastructure construction and maintenance.

B. Point of Use Drinking Water Treatment Technologies

Treatment of drinking water at the point of use (POU) has demonstrated improvements in microbial as well as chemical and physical quality and health benefits for people who have access only to microbially contaminated drinking water sources. POU treatments may include chlorine disinfection, UV irradiation, boiling, or filtration using ceramic pots or other types of filters. Limitations of some of these treatment options have led to a search for alternative methods for POU treatment of drinking water.

C. Ceramic Siphon Filter

The ceramic siphon household water filter is one alternative to other water filtration technologies and to chemical disinfection. A candle element composed of diatomaceous earth and nanosilver particles reduces microbes in water, supposedly by both chemical inactivation and physical removal. The siphon design allows for faster flow rates than gravity-fed filters and the small size of the filter eliminates the need for integrating large plastic filtration containers into the device design.

Figure 1: Ceramic Siphon Filter

Little research has been conducted on the ceramic siphon filter to date. Only one laboratory test has been reported, in which the removal efficiency of *E. coli* in silver-impregnated ceramic siphon filters was tested over an expedited (compressed time) lifespan water volume filtered (7,000 liters). Results from this test show a decline in *E. coli* removal efficiency over time (WaterLaboratorium/NOORD, 2008) from an initial 5.3 log10 to about 1.9 log10.

It is important to test point of use treatment technologies using conditions that closely mimic the real world. This research highlights the results of testing a ceramic siphon filter over its lifespan water volume using feed water and test conditions similar to those experienced in developing countries. The use of primary effluent models fecally contaminated ground and surface water that is often the source for drinking water in developing countries. The declining head water surface level also mimics the usage characteristics of a real world user, in which a bucket would be filled with water and allowed to drain to near the bottom of the bucket. Periodic challenge tests at specified lifespan water volume points (10%, 25%, and 50%) are intended to test the $\log_{10}$ reductions of the key classes of waterborne microbes, specifically bacteria (*E. coli*), viruses (F+ coliphage MS2), and a protozoan parasite surrogate for *Cryptosporidium* oocysts, at different points in the volume lifespan of the ceramic siphon filter.

This research also highlights the importance of evaluating the effects of cleaning on flow rate and microbial reductions over the lifespan of the ceramic siphon filter. Regular cleaning of other POU ceramic filters has been shown to wear away at the filter element, but there have been no tests performed to determine the effects of such wear and tear on microbial removal efficacy.

D. Choice Microbial Indicators

E. coli B was chosen as a bacterial indicator because it is a nonpathogenic, well-characterized strain that is easy to produce and identify in laboratory tests. It is also similar in size and morphology to other pathogenic bacteria in water, such as pathogenic strains of *E. coli*, *Salmonella* spp, *Shigella* spp, *Camplobacter* spp, and *Vibrio* spp. Bacteriophage MS-2 was chosen as a viral indicator due to its nonpathogenic nature, its similarities to human enteric viruses (poliovirus and other enteroviruses, noroviruses, astroviruses and hepatitis A and E viruses), and its ease of production, recovery, and enumeration. Fluorescent microspheres (3µm, specific gravity 1.05) were used to mimic *Cryptosporidium parvum* oocysts due to their ease of testing and also to prevent lab staff exposure to the protozoan parasite. Previous filtration studies have shown that the use of microspheres to mimic *Cryptosporidium parvum* oocysts can provide a conservative estimate of oocyst removal in filters (Dai and Hozalski, 2003).

E. Objectives

i. To determine the $\log_{10}$ reductions of *E. coli* and F+ coliphage MS2 by a ceramic siphon drinking water filter.

ii. To measure changes in the $\log_{10}$ reductions of *E. coli*, F+ coliphage MS2, and the surrogate for *Cryptosporidium* oocysts at different points in the volume lifespan of the ceramic siphon filter (7000L).

iii. To determine the effect of physical cleaning of the filter on flow rate and microbial reductions over the lifespan of the ceramic siphon filter.

iv. To measure chemical and physical water quality parameters in filtered water, including turbidity, silver content, total organic carbon, and pH.

2. Literature Review

A. Waterborne Illnesses

About 1.1 billion people worldwide do not have access to improved drinking water supplies and use unsafe surface and ground- water supplies. Unsafe drinking water affects millions of people worldwide, with those living in the most underserved regions in developing countries often being the most affected populations. Over 1.6 million people, most of whom are children, die each year from ingesting water contaminated with bacteria, viruses, and parasites. Waterborne illnesses, such as diarrheal diseases, enteric fevers, and Hepatitis A, are transmitted through the ingestion of pathogens in drinking water. These diseases are largely preventable through interventions in water, sanitation, and hygiene (Pruss, 2002). Children under five are affected most severely from such illnesses.

B. Burden of Diarrheal Disease

Inadequate water and sanitation are associated with poorer child health and increased diarrheal illness (Checkley, 2004). For children under five in developing countries and areas, there are 3.2 diarrheal episodes per child-year, and 4.9 out of 1000 children die in the first five years due to diarrhea, equaling over 2.5 million deaths each year (Kosek, 2003). Furthermore, a meta-analysis and systematic review by Clasen *et al.* (2007) incorporated 33 trials on household-based interventions, including point-of-use chlorination, filtration, solar disinfection, combined flocculation and disinfection, and improved storage. Results indicate that these interventions reduce diarrheal disease in all age groups (longitudinal prevalence proportion ratio = 0.70, 95% CI 0.56 to 0.88, 9 trials) and in children under 5 years of age (longitudinal prevalence proportion ratio = 0.76, 95% CI 0.66 to 0.88, 9 trials).

C. Drinking Water Quality Improvements

The international commitment to alleviating the global burden associated with inadequate drinking water was furthered during the Millennium Development Goal (MDG) process. One of the goals directly addresses water supply and sanitation, aiming to: "Halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation" based on baseline data from 1990 (United Nations, 2002).

Zwane and Kremer (2007) suggest that providing piped water and sanitation structure are most likely to reduce child mortality, but often these interventions are not a realistic solution for poor rural populations. Household water treatments hold the potential to help alleviate the burden of diarrheal disease in areas where providing piped water is not a feasible solution in the near future. Diarrheal reduction impacts of household water treatment interventions have, in fact, previously been underestimated. Esrey et al. (1991) concluded that sanitation and hygiene education yielded greater reduction of diarrheal disease than water supply or water quality interventions. More recently a study by Fewtrell & Colford (2004) found that hygiene education and water quality improvements have a greater impact on the incidence of diarrheal disease (42% and 29% respectively), than sanitation and water supply (24% and 23% respectively). Table 1 summarizes diarrheal disease reductions by point of use (POU) technologies in controlled studies (Sobsey et al., 2008).

Technology	Diarrheal disease reduction estimate (95% CI)	Compliance (estimates of self-reported and/or measured % user compliance)
SODIS (solar UV radiation + thermal effects)	31% (26%-37%) [a]	78% compliance during study; however post-study compliance rates may drop as low as 9%
Free chlorine and safe storage	37% (25%-48%) 29% [b]	60-73% of households were self-reported users, but only approximately 30-40% of those who reported use had detectable free chlorine levels
Coagulation/chlorination	31% (18%-42%) 29%	Usage rates may drop to as low as 10% after intervention ends
Ceramic filtration through candle filters	63% (51%-72%)	High until filter breaks; in a trial in Bolivia, compliance was 88% over 6 months
Ceramic filtration through ceramic water purifiers	46% (29%-59%)	Dependent on filter breakage rates
Biosand filtration	47% (21%-64%)	>85% post-implementation

[a] Summary estimates stratified by type of intervention (from a meta-analysis of drinking water quality interventions and diarrheal disease reductions). [b] Summary estimate from meta-analysis on POU chlorination (includes both free chlorine disinfection and combined coagulation-disinfection).

Table 1: Diarrheal disease reduction based on several POU technologies (Sobsey et al., 2008)

D. Point of Use Water Treatment Technologies

POU systems refer to the range of water treatment methods, including filters, chemicals, and others, which treat water at the point of consumption rather than at the source. POU technologies can be physical, chemical, or a combination of physical/chemical methods. Physical methods include boiling, heating, filtering, settling, and ultraviolet (UV) radiation. Chemical methods include coagulation-flocculation, ion exchange, chemical disinfection, and adsorption (Brown, 2007a). Combinations of physical and chemical methods include coagulation combined with disinfection, media filtration followed by chemical disinfection, and media filtration followed by membrane filtration. Most current POU technologies are intended to reduce microbial pathogens, although some also reduce chemical and radiological contaminants. The Environmental Protection Agency set current United States standards for POU water treatment at a minimum 6 $\log_{10}$ (99.9999%) reduction in bacteria, 4 log_{10} (99.99%) reduction in viruses, and 3 log_{10} (99.9%) reduction in protozoan parasites (USEPA 1987; NSF 2003).

Table 2 shows estimates of the baseline and maximum effectiveness of POU household water treatment technologies against microbes in water.

Treatment process	Pathogen Group	Baseline LRV [a,b]	Maximum LRV [c]	Factors influencing performance efficacy
Porous ceramic filtration	Bacteria	2	6	Varies with pore size/structure, tortuosity, flow rate, filter medium composition, augmentation with silver or other chemical agents that enhance microbe inactivation or retention
	Viruses	0.5	4	
	Protozoa	4	6	
Biosand filtration (BSF)	Bacteria	1	3	Varies with filter maturity, dosing conditions, flow rate, pause time between doses, grain size, filter bed contact time, other design and operational factors; POUs may differ in microbial removal from conventional SSF
	Viruses	0.5	3	
	Protozoa	2	4	
SODIS	Bacteria	3	5.5+	Depends on water oxygenation, sunlight intensity, exposure time, temperature, turbidity, and size of vessel (depth of water)
	Viruses	2	4+	
	Protozoa	1	3+	
Free chlorine	Bacteria	3	6+	Turbidity and chlorine demand reduce efficacy; concentration × contact time predicts efficacy; [d]
	Viruses	3	6+	
	Protozoa[d]	3	5+	
Coagulation/chlorination	Bacteria	7	9	Possible physical removal of chlorine-resistant pathogens by coagulation-flocculation; turbidity may inhibit performance; reductions differ among viruses
	Viruses	2-4.5	6	
	Protozoa	3	5	

[a] LRV: Log_{10} reduction value = log_{10} (pretreatment concn) - log_{10} (post-treatment concn). [b] Baseline LRV: LRV typically expected in actual field practice when done by relatively unskilled persons who apply the treatment to waters of varying quality and where there are minimum facilities or supporting instruments to optimize treatment conditions and practices. [c] Maximum LRV: LRV possible when treatment is optimized by skilled operators who are supported with instrumentation and other tools to maintain the highest level of performance in waters of predictable and unchanging quality. [d] Minimally effective against *Cryptosporidium parvum* oocysts.

Table 2: Estimates of baseline and maximum effectiveness of POU water treatment technologies (Sobsey et al., 2008)

POU technologies are often tested to determine their ability to reduce turbidity in water. Turbidity particles reduce access to target microbes, thereby reducing the microbiocidal efficacy of chemical disinfectants, and they physically shield microbes from the UV radiation that could potentially inactivate the microbes (Sobsey, 2002). Turbidity of water seems to be a limiting factor in all POU technologies discussed. Additionally, pH adjustments and total organic carbon measurements are often observed in filtrate water versus filtered water. Colloidal silver is frequently incorporated into the design of ceramic filters, as can be seen in the Potters for Peace (PFP) ceramic pot filter and in the ceramic siphon filter. Silver has been used as a disinfectant in water for decades. The EPA (2002) considers silver to be safe for human consumption at levels less than the standard 0.1mg/L (100 parts per billion). Studies show that silver can be effective at reducing microbes both pre and post filtration (Silvestry-Rodriguez, 2008).

E. Water Quality Testing Parameters

Each POU technology listed in Table 2 has benefits and drawbacks related to key water quality testing parameters of turbidity, pH, and total organic carbon. The use of free chlorine (hypochlorite) is more effective at reducing microbes at low pH than at high pH values (Sobsey, 2002). Turbidity of water also reduces microbial removal efficacy of chlorine treatment. Combination of coagulant-flocculants and chlorine systems are often distributed as tablets or sachets of granular particles. Dissolved ions in this method regulate pH to optimal levels for drinking water. Turbidity of water may inhibit the performance of this system, although it has also been shown that this method reduces turbidity in samples to less than 1 NTU (mean 0.25NTU) (Souter et al, 2003).

The SODIS POU treatment technology uses transparent polyethylene terephthlate (PET or PETE) bottles that are filled with aerated water and exposed to solar UV and heat energy during the sunlight hours of the day (Sobsey et al., 2008). Studies report that SODIS had no significant effect on the physical characteristics of the sample water. Over a period of seven hours, pH, TDS, and turbidity were measured hourly, with little to no change in any of these parameters (Meyer, 2004).

The biosand filter is a slow sand filter that consists of a concrete or plastic chamber filled with sand. Water is pulled through the filter via gravity. Over time, a biolayer (or schmutzdecke) forms which retains microbes and improves performance (Elliott, 2008). Stauber (2006) reported that the BSF reduced pH from a mean of pH 7.4 before filtration to pH 8.0 after filtration. Mean turbidity decreased from 8.1 NTU to 1.3 NTU. Information on TOC in filtered versus non filtered water was not available. Later studies showed that turbidity removal improved as the BSF ripened. A decrease in mean filtered water turbidity was observed, from 1.45 NTU to 0.98 NTU (range 0.65–1.4 NTU) after more than 30 days of operation (Elliott, 2008).

F. Ceramic Pot Filters

Porous ceramic filtration options can be divided into the ceramic pot filter and the ceramic siphon filter. The Potters For Peace (PFP) ceramic pot filter consists of a colloidal silver-impregnated ceramic pot suspended inside a collection bucket. Numerous studies have been conducted to determine the microbial removal effectiveness of the ceramic pot filter. Table 2 outlines baseline and maximum log reduction values taken from a number of studies (Sobsey et al., 2008). It should be noted that these results were based on batch challenge tests, and not on tests conducted over the lifespan of the filters. A recent study found that the ceramic pot filter reduced E. coli by up to 99.9999% and MS2 by 90-99% (Brown, 2007a). Additionally, diarrheal diseases were reduced by approximately 40% in users versus nonusers in a randomized, control trial (ibid). Another study in Cambodia reported a fifty percent reduction in diarrheal diseases in users versus nonusers (Roberts, 2003). Lastly, a Guatemalan study reported a 53% reduction in diarrheal incidence in children under 5 and a 65% reduction when filters were used in conjunction with an educational program (AFA

Guatemala, 1995). Sobsey (2008) reported a diarrheal disease estimate based on several studies of 46% (range 29%-59%).

Typical flow rates for the PFP filter range from 1.0 to 3.0 L/hr (Brown, 2007a). The filter has been found to reduce turbidity by an average of 83 percent. One study found that pH increased by an average of 0.8 pH units post-filtration due to alkalinity dissolved from the clay-based ceramic (Lantagne, 2001). Additionally, colloidal silver painted on the filter was necessary to achieve 100 percent removal of indicators in laboratory tests. Small amounts of silver were detected in some filtrate samples, although the levels found did not exceed the EPA guideline standard of 0.1 mg/L (Lantagne, 2001).

G. Lifespan Testing

Filtration rate of the PFP ceramic filter decreased over time in use. Filters were cleaned periodically, effectively restoring filtration rates to near factory rates. During cleaning, filters were scrubbed with a brush, washed using boiled water, and reassembled for use (Brown, 2007a). Also stated in this study is that continued cleaning may limit the useful life of the filter by reducing the thickness of the filter element, causing reduced microbial removal and eventual filter breakage. A similar study in Cambodia found that cleaning the ceramic filters at the recommended rate of twice per week too often increased the chance of breakage, so recommendations were changed to suggest cleaning once per month or when the flow rate drops significantly (Roberts, 2003).

No studies investigating changes in flow rate over the lifespan volume of the PFP ceramic pot filters have been published to date. In fact, most testing protocols for POU water treatment technologies do not address the need to test the technology over the duration of the recommended lifespan. Furthermore, there is a large gap in the literature pertaining to studies that test the changes in microbial removal over the lifespan of specific POU technologies while using conditions that simulate real world settings. Therefore, research should be directed towards testing POU technologies using an amended protocol that includes microbial reduction testing at various points throughout the lifespan of the technology while using at least one type of sewage-amended feed water consistently over the lifespan of the technology. One study using the ceramic pot filter revealed a pattern of decreased microbial removal of *E. coli* after the first 100 liters of water flowed through the filters, but the study did not follow through to the projected volume lifespan of the filters. In fact, the study ended after 600 liters passed through each filter, and no statistically significant difference was found linking microbial removal reduction to volume of water filtered (Brown, 2007a). A longitudinal field study of filter effectiveness in Cambodia over a time period of 44 months found no difference in *E. coli* $\log_{10}$ reduction values in treated versus untreated water samples (Brown, 2007b).

H. Ceramic Siphon Filter

The ceramic siphon filter is a single element ceramic candle filter that operates in siphon mode to filter water at the POU level. The siphon filter is compact, consisting of a filter element, fleece pre-filter, plastic housing, plastic hose, and siphon valve. Filtrate water can be collected into existing water storage containers. The filter element is impregnated with silver with the goal of providing bacteriostatic or bactericidal activity. The filter was designed by Basic Water Needs Foundation, Netherlands; and it is marketed by Enterprise Works/VITA and other NGOs and companies. The chemical composition of the ceramic candle element has not been released in detail, but it is known to consist of diatomaceous earth materials.

There is little available literature on the ceramic siphon filter, and none has been published in the peer-reviewed scientific literature. To date, one study on the bacterial removal efficiency over the volume life span of the filter has been completed (WaterLaboratorium/Noord, 2008). Batch tests using *E. coli* were performed every thousand liters up to a lifespan volume of 8000 liters. Water was pumped through the filters at a rate of 50-liters per hour, except for during batch tests, where water was pumped at three and six liters per hour, depending on the filter being tested. Results indicated that filters that are impregnated with silver have a higher bacterial removal capacity at all points in the volume lifespan, especially after the 7000 liter point. Additionally, filters achieved between a 5-6 $\log_{10}$ reduction in *E. coli* from 0-50% of their volume lifespan. Log_{10} reductions decreased after 50%, eventually dropping to 1-3 $\log_{10}$ reductions at the 100% volume lifespan point.

EnterpriseWorks India reported users' perceptions and usage in "Consumer Evaluation of the CrystalPur Water Filter in India, Interim Report." This report shows findings after six weeks of usage. Out of the 57 households interviewed, 36 households used the filter for 3 to 5 hours per day, therefore acquiring about 15 to 20 liter of water per day. Thirteen households used it for 1 to 3 hours (10-12 liters per day), and 8 households used it more than 5 hours per day (more than 30 liters). It was also observed that 42 out of the 57 households expressed that the scrubber used for cleaning was easy to handle, but they worried that cleaning the candle would shorten the life of the candle. They also worried that the chemical coating of the candle element may dissolve and affect the purity of the water. Other suggestions for cleaning the filter included using soft fibers, cotton cloths, and coconut fibers. 54% of households cleaned their filter every three days (which could correspond to every 30 to 90+ liters filtered, depending on usage), 25% cleaned it once a week (70-210+ liters), and 21% cleaned it daily (every 10-30+ liters). Users reported an average flow rate of 4 to 5 liters per hour. Three households reported that the candle element broke after several weeks of continuous use. Additionally, 4 out of 21 candles inside stainless steel jars broke before the boxes were opened for use.

Reported benefits of the siphon filter include faster flow rates (4-6L/hr), compact size leading to ease of transport, and low cost (price $7-12, depending on the country). Potential drawbacks to this filter, contradictory to reports by the manufacturer, are that it does not effectively filter turbid water and the microbial reduction efficiency is decreased by routine cleaning.

There have been no studies to date investigating changes in flow rate over the lifespan water volume passed through the ceramic siphon filter. Similar to the ceramic pot filter, it is hypothesized that regular cleaning will decrease the lifespan of the filter due to the ceramic element being depleted slightly with each cleaning. Thus, research needs to be conducted to determine the effects of regular cleaning on the flow rate, lifespan, and other water quality parameters (such as silver leaching, turbidity removal, and total organic carbon).

I. Summary

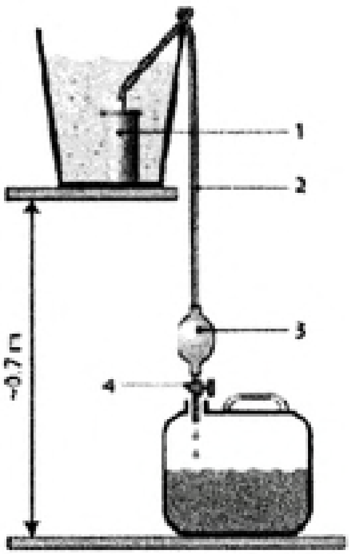
Based on the lack of literature on the ceramic siphon filter, its microbial removal efficacy in batch as well as lifespan challenge tests, and field studies, it is obvious that further studies need to be conducted to determine the usefulness of this POU water treatment filter.

The research highlighted in this study is an obvious and needed next step in evaluating the performance of this promising POU household water treatment technology.

3. Materials and Methods

A. Characteristics of siphon filter design and operation

The siphon filter consists of the candle filter element, plastic housing, plastic hose, siphon bulb, and siphon valve. The candle filter element is composed of diatomaceous earth materials and is impregnated with nanosilver particles. The filter is placed at the bottom of a bucket as seen in Figure 2. The siphon bulb is squeezed 2-3 times to create negative pressure to draw water through the filter and the filtrate is collected in a separate receptacle.



1 — Filter element and prefilter

2 — Siphon hose

3 — Rubber bulb

4 — one way valve and tap

Figure 2: Schematic layout for ceramic siphon filter

B. Batch tests

Batch tests were performed in triplicate to determine baseline log_{10} reductions of *E. coli B* and MS-2 coliphage. For *E. coli* batch tests, *E. coli B* was grown to log phase in tryptic soy broth. Culture volumes of 50 ml were pelleted by centrifugation (7277 rpm x g, 4°C, 10 minutes) and resuspended in 10 mL of phosphate buffered saline. The 10 mL suspension was added to 10 liters of laboratory reagent grade water treated by reverse osmosis and UV light (Dracor, Durham NC). Microbes were dispersed by continuous stirring for fifteen minutes. Influent samples were collected before filtration. The filter was placed in the bucket containing the feed water and siphon flow was initiated. Filtered water was collected in a sterile carboy. The time it took to filter all 10-liters (minus a minimal amount of feed water left in the bottom of the bucket) was recorded. *E. coli* titers in influent samples were analyzed using the spread plate method on MacConkey agar and titers in effluent samples were analyzed using membrane filtration of 10 mL and 100 mL volumes of effluent water on MacConkey agar plates.

For MS2 batch tests, bacteriophage MS2 was grown in tryptic soy broth containing host *E. coli* F_{amp}, purified by extraction with ½ volume of chloroform followed by centrifugation (7277 rpm x g, 4°C, 10 minutes), and storage at -80°C. The titer of the stock was 2.23×10^{11} plaque-forming units (PFU)/ml. One milliliter aliquots of the stock were dosed into feed water. MS2 concentrations in influent and effluent water were plaque assayed using the double agar layer method (EPA Method 1601) on host *E. coli* F_{amp}. (US EPA, 2001)

C. Initial Flow Rate experiments

Initial flow rates were measured by passing deionized water through the filter at a constant head water level. A filter was placed at the bottom of a large plastic bucket and the bucket was filled with water to a level of 25-centimeters ± 2-centimeters. Flow was initiated and a timer was started. Changes in time and volume were noted at regular intervals to determine flow rate over a total of three hours.

D. Continuous flow setup

An automated water feed system continuously delivered water through three new parallel filters running simultaneously with a declining head water level mode. Water level sensors in buckets containing the filters triggered water to flow and refill the bucket when the water level reached a low level sensor. Feed water stopped flowing into the bucket when water reached a top level sensor. To ensure that primary effluent was properly mixed in line with feed water, there was a 15- second flow of water to waste (to a drain) before an outflow valve closed and the feed water mixture was routed to filter buckets. Flow meters at water outlet collection points measured flow rate, and data were transferred to a laptop computer for later analysis. The overall system was controlled by a Programmable Logic Controller unit (Model Click C0-00DR-D, Automation Direct, Inc., Atlanta, GA). About 70-120 liters of water flowed through each filter daily. Feed water contained 1% (V/V) pre-filtered (5 micrometer mesh) primary sewage effluent from the local wastewater treatment plant (Orange County Water and Sewage Authority (OWASA), Chapel Hill, NC) which was mixed in-line with dechlorinated, activated carbon-filtered municipal tap water. To address health and safety risks in the lab, filtered water containing primary effluent was passed through two 5-gallon buckets containing a chlorination agent, before flowing into a floor drain to a sewer line.

For microbial challenges with test water containing seeded test microbes, a separate container of 10L of microbe-seeded test water was prepared. The microbial, chemical and physical quality of this microbe-seeded feed water was determined from sub-samples of it taken prior to delivery of this water to the filters. Following the addition of challenge microbes, influent samples were collected and turbidity and pH were measured immediately. Silver concentration and total organic carbon (TOC) were measured at later times. *E. coli* and MS2 coliphage were analyzed by standard culture/infectivity assay procedures as described in section 2G. The feed water was poured into the previously emptied bucket containing the filter and water flow was initiated. Flow rate was monitored throughout challenge tests. Challenge water filtrate was collected for analysis of added test microbes as well as key chemical and physical parameters. Effluent samples were collected and turbidity and pH were measured immediately. Silver concentration and TOC were measured at later times. *E. coli* and MS2 coliphage were analyzed by standard culture/infectivity assay procedures and fluorescent microspheres were counted using fluorescent microscopy. The differences in $\log_{10}$ concentrations of test microbes in the seeded challenge water and the filtrate provided the $\log_{10}$ reduction performance of the filters.

E. Design of microbial challenge studies

Projected filter lifespan was suggested by the manufacturer to be approximately 7,000 liters. Microbial challenge tests were scheduled to occur at the following points in the volume lifespan: 10%, 25%, 50%, 75% and 100%. None of the filters made it to the reported lifespan end. Therefore, we collected data from 10% and 25% volume life span for Filter 1, and 10%, 25%, and 50% volume life span for Filters 2 and 3. Filter 1 broke during routine cleaning at 42.2% of its volume lifespan. Filter 2 broke immediately after the 50% challenge test while the bulb was being squeezed to re-initiate flow in the filter. Filter 3 broke during cleaning at 64.6% of its volume life span.

Periodic microbial challenges used *E. coli B*, coliphage MS2, and fluorescent microspheres (as surrogate for *Cryptosporidium* oocysts) in test water at concentrations that allowed determination of up to 5 to 7 $\log_{10}$ reductions of these test microbes. Fluorescent microspheres were 3-micrometer diameter, specific gravity of 1.05. Effluent from the siphon filters was collected and stored in plastic Nalgene bottles at 4°C.

F. *E. coli*, MS2, and fluorescent microspheres

A frozen stock of *E. coli* strain B (ATCC No. 11303) was thawed and a culture was grown to log phase in tryptic soy broth, enumerated by spread plating on MacConkey Agar, and stored at -80°C. For the 10% and 25% challenge points, *E. coli B* was grown to log phase growth in tryptic soy broth. Culture volumes of 50 ml were centrifuged at 7277 rpm x g at 4°C for 10 minutes (RC-3B Refrigerated Centrifuge, Sorvall Instruments). Pellets were resuspended in 10 ml phosphate buffered saline, of which the entire volume was added to the 10 liters of challenge water per filter. Due to low initial *E. coli* concentrations achieved in feed water, an alternate method was used at the 50% challenge point. *E. coli B* was grown in 400-milliliters of tryptic soy broth overnight (16-24hr) and then centrifuged using the conditions described above. Following centrifugation, the *E. coli B* was resuspended in 10-milliliters of phosphate buffered saline, of which the entire volume was added to the 10 liters of challenge test feed water for each filter. Bacteriophage MS2 was spiked into feed water using the same method as previous batch tests.

Carboxylate fluorescent microspheres (Catalog # 17147-5, Polysciences Inc., Warrington, PA) with a 3-micrometer diameter and specific gravity of 1.05 were used as a surrogate for *Cryptosporidium* oocysts. The feed water contained 10^7 microspheres in 10 liters to allow for detection of up to 5 $\log_{10}$ reduction in filtered effluent. For microsphere analysis in the continuous flow test, samples from microbial challenges were taken and stored at 4°C until analysis. Samples were shaken vigorously by hand or on a shaker to resuspend microspheres that may have settled while in storage. Water sample volumes of 100 mL were filtered through a 2.0μm pore size Nucleopore Track- Etch Membrane (Whatman, Banbury Oxon, UK). The membrane was then mounted on a 3" x 1" clean glass microscope slide, a 13-14 microliter drop of mounting medium composed of 1,4-Diazabicyclo(2.2.2)octane (*DABCO*) with glycerol and PBS was applied to the center of the filter, and a clean 25-millimeter square glass cover slip was placed on top.

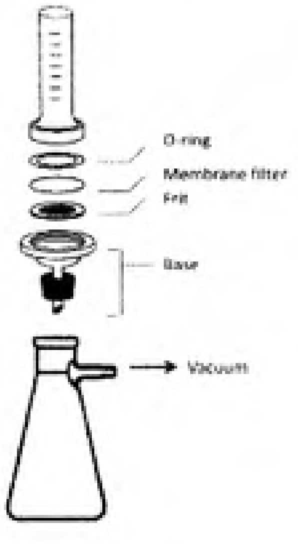


Figure 3: Schematic representation of filtration apparatus. (Source: Patti Chuang undergraduate thesis)

Microspheres were enumerated using an epifluorescent microscope. The surface areas of the membranes were scanned by the following procedure: the topmost point of the surface was located under 100X magnification, and then the user scanned the membrane using a right to left motion, followed by lowering the viewing plane to the next unviewed portion of the membrane and scanning across the membrane from left to right. Microspheres were counted as they were viewed through the lens using a hand counter. This process continued until the bottommost point of the membrane was reached.

G. Microbial analyses

For the 10% challenge point, initial *E. coli* concentrations in influent water were quantified by the spreadplate method using BBL™ MacConkey Agar (Catalog # 211387, Becton Dickinson and Company, Sparks, MD) plates. For the 25% and 50% challenge points, initial *E. coli* concentrations in influent water were quantified by the spreadplate method using BioRad RAPID *E. coli* 2 Agar (Catalog # 356-4024, Bio-Rad Laboratories Inc., Hercules, CA), in which the *E. coli* colonies will appear purple in color and other coliform colonies will appear blue-green.

At the 10% challenge point, final *E. coli* concentrations in effluent water were quantified by membrane filtration on BioRad RAPID *E. coli* 2 Agar using USEPA Method 1604 (USEPA, 2002). At the 25% and 50% challenge points, final *E. coli* concentrations in effluent water were quantified by spreadplating an entire milliliter of sample onto BioRad RAPID *E. coli* 2 Agar using a dilution series to allow for a count of up to 6 $\log_{10}$ *E. coli* in one milliliter of water.

MS2 concentrations were assayed for plaques forming units (PFU) using the double agar layer method (EPA Method 1601) on host *E. coli* F_{amp}. Bottom agar plates and top agar tubes contained antibiotics streptomycin and ampicillin according to EPA Method 1601 (US EPA, 2001).

H. Cleaning of Filters

Filters were cleaned daily according to directions in the instruction manual. Daily cleaning was necessary due to the flow rate decline by 75-80% (<1 liter per hour) over a period of 24 hours. The fleece pre-filters were removed from the candle elements on day 5 of the continuous flow experiment, because they further slowed the flow rates of the filters. The daily flow 70-120 liters per filter corresponds approximately to the amount of water that a household might filter per week, if daily household use was between 10-17 liters. Filters were removed from the water, the outer container was removed and the tap was closed. Circular scrubber pads were used to gently clean the ceramic filter element, using a circular back and forth motion, then rinsing with clean water. Once a week, filters were back washed by removing the filter from the water, removing the outer container, closing the tap and gently squeezing the rubber bulb 2-3 times. During this process, cloudy water flowed out of the filter element, removing the particles clogging the filter. This process was supposed to increase the life of the filter element. The diameter of the candle element was measured weekly with calipers to determine the effects of routine cleaning on the diameter size.

I. Key Water Quality Parameters

i. Total Organic Carbon Measurements

Total organic carbon was measured on a Shimadzu TOC 5000 Analyzer fitted with an ASI 5000 autosampler (Shimadzu Corporation, Atlanta, GA). The instrument measured non-purgeable organic carbon according to the High Temperature Combustion Method (American Public Health Association, Standard Methods 5310 B, 1998).

A stock solution of TOC was prepared by dissolving 2.125 g of American Chemical Society grade potassium hydrogen phthalate (Fisher Scientific, Fair Lawn, NJ) into 1 L of de-ionized organic-free water (DOFW); this solution was made fresh every two months. A working solution was prepared weekly by diluting the stock solution 1:10 in DOFW. Calibration standards were prepared on the day of analysis by diluting appropriate quantities of working solution in 100 mL volumetric flasks using DOFW. All solutions were stored at 4 °C.

Samples and calibration standards were placed in 20 mL glass vials and acidified with 2N hydrochloric acid to pH 2-3. During the instrument run, each sample was sparged for five minutes with zero grade air (National Welders Supply Co., Durham, NC) to remove inorganic carbon before being analyzed for organic carbon. Check standards and DOFW blanks were placed between every six samples to verify the consistency of the instrument response.

ii. pH Measurements

Following the addition of challenge microbes, influent samples were collected and pH was measured immediately. Upon completion of challenge tests, effluent samples were collected and pH was measured immediately. pH was measured using a pH meter (Model 215, Denver Instruments, Denver, CO).

iii. Turbidity Measurements

Following the addition of challenge microbes, influent samples were collected and turbidity was measured immediately. Upon completion of challenge tests, effluent samples were collected and turbidity was measured immediately. Turbidity was measured using a turbidimeter (Model 2100N, Hach, Loveland, CO).

iv. Measuring Silver Concentrations

Silver concentration in filtered water samples was measured using the RapidSilver™ Test Kit (Hach Company, Loveland, CO).

J. Flow meters

Water flow rates were measured using DigiFlow flow meters (Model DFS-2W, DigiFlow Systems, Mansfield, OH). Flow meters were connected to a USB data acquisition system (Model OMB-DAQ-56, Omega, Stamford, CT) which relayed information to a laptop computer. Flow data were collected using the Omega Personal DaqView program (Omega, Stamford, CT), and readings were taken every 32 seconds. Data were saved periodically and transferred to Microsoft Excel (Microsoft Corporation, Redmond, WA) for analysis.

4. Results

A. Batch tests

Removal of *E. coli* and MS2 was first examined in batch experiments. Initial batch challenge experiments showed a mean reduction of 7.02 $\log_{10}$ (99.999987%) for *E. coli*. There was almost no reduction of MS2 by the filter; mean $\log_{10}$ reduction was 0.12 $\log_{10}$ (24.0%). Table 3 shows results from three trials for each organism. The three trials were performed using the same filter each time, and separate filters were used for *E. coli* and MS2 challenges.

	E.coli		MS2	
	% reduction	Log $_{10}$ Reduction	% reduction	Log $_{10}$ Reduction
1	99.999978	6.65	21.4	0.10
2	99.999987	6.87	19.3	0.09
3	99.999997	7.55	31.3	0.16
Average	99.999987	7.02	24.0	0.12

Table 3: Reductions of *E.coli* and MS2 from seeded test water during batch challenge tests.

B. Lifespan Volume Challenge Tests

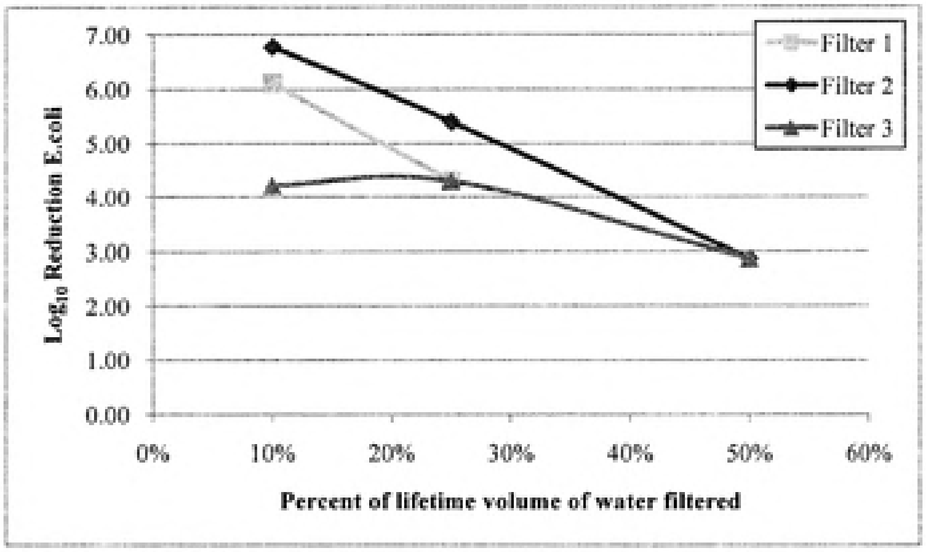
Challenge tests conducted during the continuous flow experiment occurred at 10%, 25% and 50% (except for Filter 1) of the projected volume lifespan of the filters (7000 L). Table 4 shows % reductions and $\log_{10}$ reductions of each challenge organism at the different volume points. At all points tested, the $\log_{10}$ reductions were lower than those observed in batch tests. At the 10% volume lifespan, filters 1, 2, and 3 achieved 6.11, 6.78, and 4.22 $\log_{10}$ reductions of *E. coli*, respectively. When they reached the 25% volume lifespan, $\log_{10}$ *E. coli* reductions decreased in all but filter 3, with reductions of 4.30, 5.40, and 4.30 $\log_{10}$. Lastly, filters 2 and 3 showed decreased reductions at 50% volume lifespan, with reductions of 2.86 $\log_{10}$ for both filters (Fig. 4A). MS2 reductions were low throughout the lifespan of the filters, with results similar to those observed in batch testing. There still appeared to be a slightly negative trend as volume filtered increased (Fig. 4B). Reductions of fluorescent microspheres were relatively consistent throughout testing, with $\log_{10}$ reduction values ranging from 3.74-5.00 $\log_{10}$ (Fig 4C). Results for later volume time points in the lifespan cannot be presented due to breakage of all three filters before the manufacturer's projected maximum volume lifespan of 7000 L. Filter 1 broke at the earliest time point, 42.2% of volume lifespan, during routine cleaning. Filter 2 broke at 49.2% volume lifespan, immediately following the 50% challenge test while the bulb was being squeezed to re-initiate water flow. Filter 3 lasted the longest, at 64.6% of its volume lifespan, when it broke during routine cleaning.

Filter	Time Point	$\log_{10}$ Reduction *E. coli*	% Reduction *E. coli*	$\log_{10}$ Reduction MS2	% Reduction MS2	$\log_{10}$ Reduction microspheres	% Reduction microspheres
1	10%	6.11	99.99992	0.26	44.9	4.37	99.995
1	25%	4.30	99.995	0.05	11.5	4.22	99.994
1	50%	N/A	N/A	N/A	N/A	N/A	N/A
2	10%	6.78	99.99998	0.13	25.8	3.89	99.987
2	25%	5.40	99.9996	0.04	8.6	5.00	99.999
2	50%	2.86	99.86	-0.06	-15.0	4.35	99.995
3	10%	4.22	99.994	0.29	48.9	4.40	99.996
3	25%	4.30	99.995	0.03	7.3	4.22	99.99
3	50%	2.86	99.86	0.04	8.6	3.74	99.98

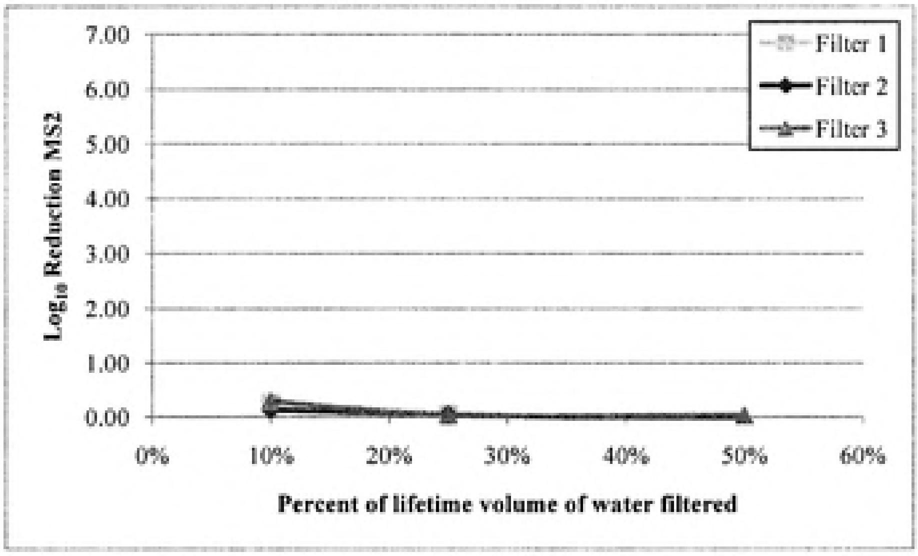
Table 4: % reductions and $\log_{10}$ reductions of *E. coli*, MS2, and fluorescent microspheres at 10%, 25%, and 50% of volume lifespan.

Figure 4: Log_{10} reductions in microbes during challenge tests: *E. coli* (A), MS2 (B), and fluorescent microspheres (C).

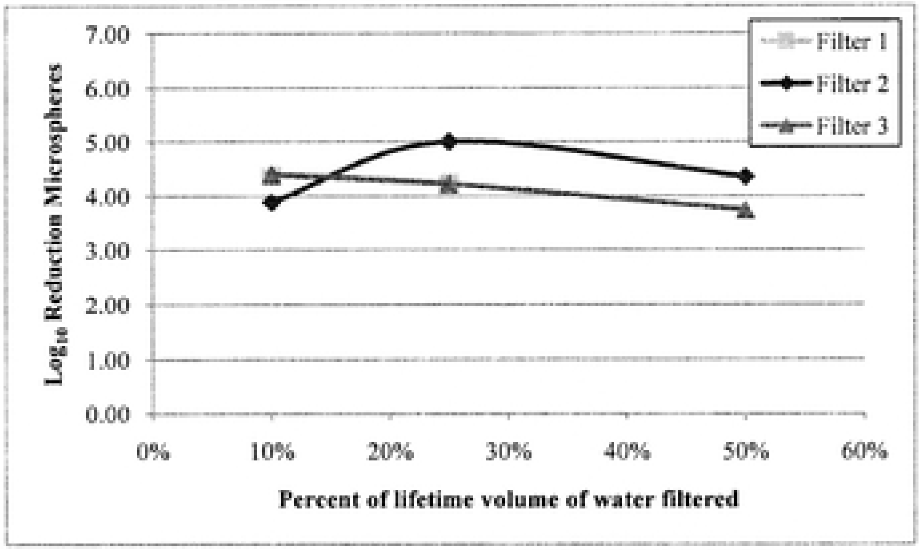
A



B



C



Filter 1
Filter 2
Filter 3
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Log10 Reduction Microspheres
0%
10%
20%
30%
40%
50%
60%
Percent of lifetime volume of water filtered

C. Effect of Cleaning on Filter Diameter and Longevity

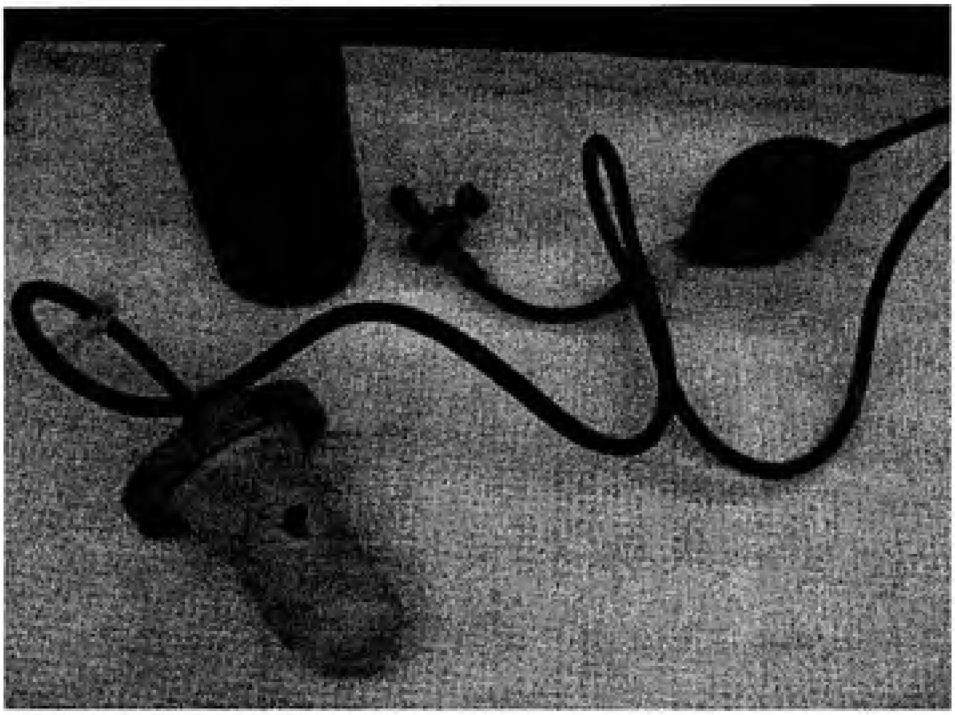
Filter diameter measurements are shown in Table 5. Although the diameters of the top portion of the filter elements did not change much, there were considerable decreases in the diameters of the middle and bottom portions of the filter elements over time and periodic cleaning. Baseline filter diameters for these specific filters were not measured, but three filters from the same batch were measured to estimate the initial filter diameters. The average diameters for the three untested filters are as follows: top – 56.82mm, middle – 56.88mm, and bottom – 55.83mm. These numbers were used to determine the corresponding loss of filter diameter by subtracting from the estimate of the initial filter diameters.

		Diameter Loss (mm)		
Filter	**Time Point**	**Top**	**Middle**	**Bottom**
1	29.5%	8.47	7.68	9.64
1	42.2%	13.99	N/A	N/A
2	16.4%	2.95	3.57	4.75
2	30.6%	5.06	5.24	8.89
2	41.4%	5.31	7.21	9.13
2	49.2%	6.34	13.29	11.05
3	29.1%	4.11	4.42	6.21
3	42.0%	8.42	8.68	10.09
3	54.9%	8.63	10.98	11.77
3	64.6%	8.73	13.86	13.50

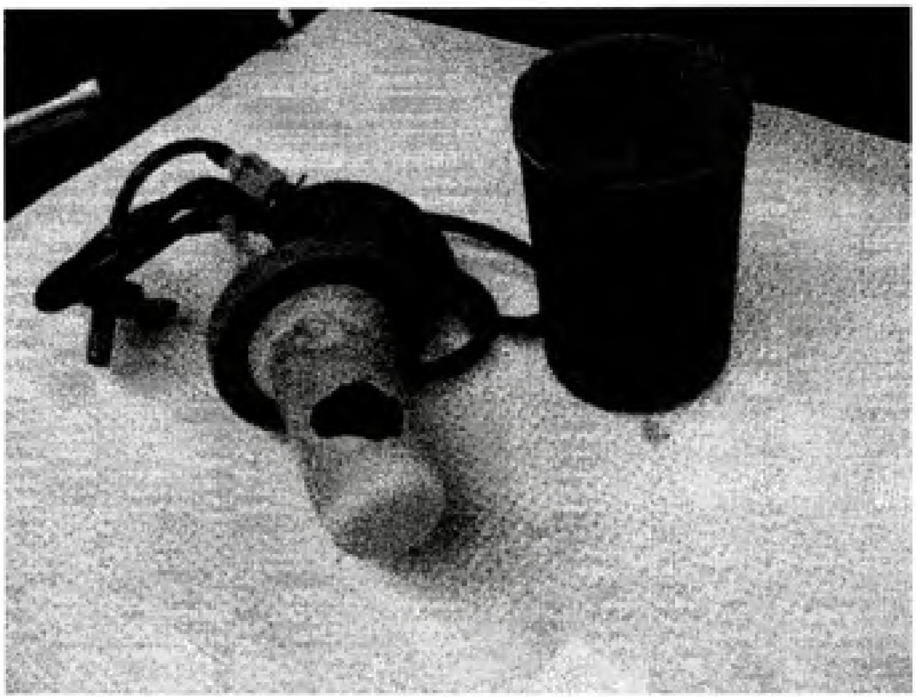
Table 5: Filter diameter loss compared to estimated baseline measurements.

Figure 5: Photographs of broken filters following continuous flow test.

A. Filter 1 following breakage



B. Filter 2 following breakage



C. Filter 3 following breakage

As can be seen in the pictures of the broken filters, the candle elements were all very thin by the time the filters broke. Composition of the three filters was very different. Filter 1 was the least compact, and it was observed that more of the ceramic element was removed during cleaning as compared to filters 2 and 3. Filter 2 was more compact than both filters 1 and 3. It also was much darker in color after about one week of testing with water continuously running through it. Filter 3 was closer in characteristics to filter 1, although it appeared to be a slightly more compact.

D. Water quality parameters

Turbidity measurements showed a decrease in turbidity of water following filtration (Table 6). Feed turbidity ranged from 1.20 to 13.1NTU with a mean of 3.88 NTU. Turbidity decreased through the siphon filter, producing filtered water turbidities that ranged from 0.291 to 0.752 NTU and with a mean of 0.47 NTU. It is possible that the high turbidity readings at the 50% points for filters 2 and 3 may have been caused by the methodological change of adding larger amounts of *E. coli* in influent challenge water following low initial *E. coli* counts at previous time points. Turbidity removal improved as the volume of water filtered increased, as can be seen from percent reductions in Table 6. Additionally, it should be noted that even when influent turbidity was high, the filtered effluent waters had relatively similar low turbidity levels.

		Turbidity		
Filter	**Time Point**	**Influent**	**Effluent**	**% reduction**
1	10%	1.20	0.291	75.75
1	25%	1.71	0.466	72.75
1	50%	N/A	N/A	N/A
2	10%	1.33	0.554	58.35
2	25%	2.15	0.273	87.30
2	50%	13.1	0.517	96.05
3	10%	1.36	0.752	44.71
3	25%	1.78	0.350	80.34
3	50%	8.43	0.525	93.77

Table 6: Turbidity measurements before and after challenge tests.

pH levels also decreased as challenge feed water was passed through the filters, as can be seen in Table 7. The average pH level for all influent waters was pH 8.49 and after filtration the average dropped to pH 8.03.

		pH	
Filter	Time Point	Influent	Effluent
1	10%	7.75	7.49
1	25%	8.66	8.62
1	50%	N/A	N/A
2	10%	8.48	7.59
2	25%	9.08	8.75
2	50%	7.93	7.57
3	10%	8.42	7.87
3	25%	8.86	8.73
3	50%	8.72	7.61

Table 7: pH levels before and after challenge tests.

Silver concentration in filter effluent appeared to decrease as more water flowed through the filters. As seen in Table 8, at 10% of the volume lifespan, all three filters' effluent contained 25 parts per billion (ppb) of silver. At the 25% and 50% lifespan points, effluent from filter 1 showed no trace of silver and effluent from filters 2 and 3 showed 5 ppb.

		Silver Concentration
Filter	Time Point	Effluent (ppb)
1	10%	25
1	25%	0
1	50%	N/A
2	10%	25
2	25%	5
2	50%	5
3	10%	25
3	25%	5
3	50%	5

Table 8: Silver concentration in filtered water.

Total organic carbon measurements did not show a clear trend. Influent samples ranged from 10.24 mg/L to 107.9 mg/L and effluent samples ranged from 10.24 mg/L to 123.6 mg/L (Table 9). Some samples increased post filtration, and some samples decreased post filtration. Therefore, no patterns of TOC changes are evidenced in the data.

10%	Sample	Result	Dil fctr	Con. (mg/L)
	1i	1.079	100	107.9
	1e	0.2338	100	23.38
	2i	0.6372	100	63.72
	2e	1.236	100	123.6
	3i	0.7129	100	71.29
	3e	0.7597	100	75.97

25%	Sample	Result	Dil fctr	Con. (mg/L)
	1i	0.3274	50	16.37
	1e	0.06733	25	1.68325
	2i	0.5652	50	28.26
	2e	0.5837	50	29.185
	3i	0.2197	50	10.985
	3e	0.6203	50	31.015

50%	Sample	Result	Dil fctr	Con. (mg/L)
	1i	N/A	N/A	N/A
	1e	N/A	N/A	N/A
	2i	0.0548	50	2.74
	2e	0.05063	50	2.5315
	3i	0.4971	50	24.855
	3e	0.05063	50	2.5315

Table 9: Total Organic Carbon content for influent and effluent samples at 10%, 25%, and 50% volume points.

E. Flow Rates

Initial flow rate experiments using constant head water level gave flow rates between 6.2-6.4 L/hr after initial fluctuations due to changes in spout distance from bottom of filter. Distance of spout from bottom of filter changed flow rate. Figure 3 shows flow rates over a three hour time period.

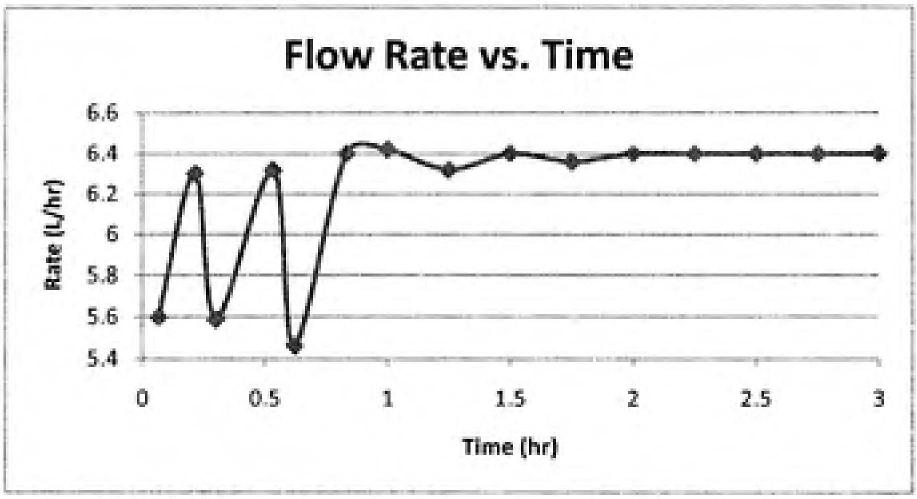
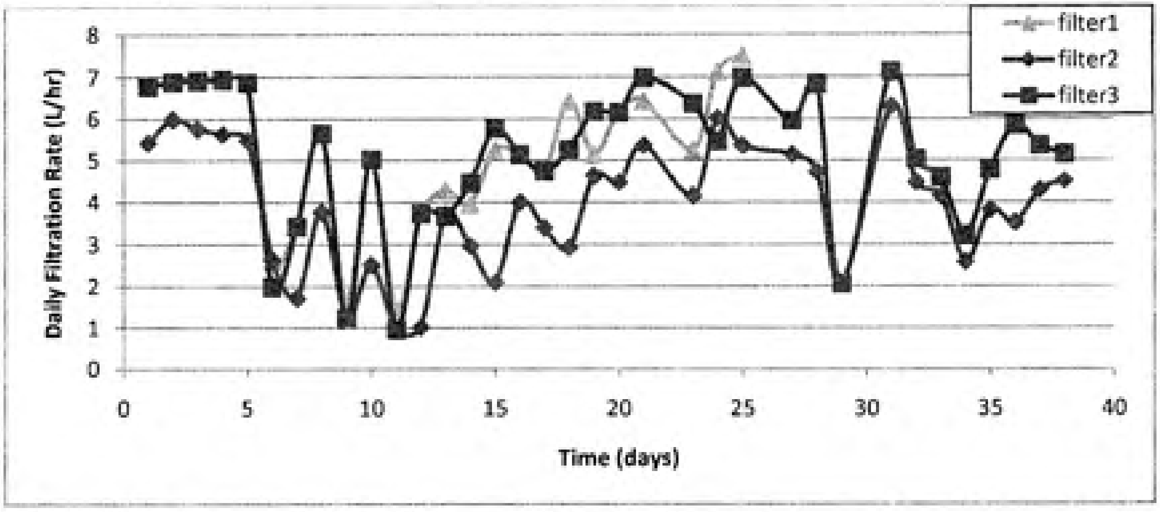


Figure 6: Initial flow rates using deionized water.

Declines in the flow rate as depicted in Figure 6 occur when the distance from the bottom of the filter to the spout decreases from 66-centimeters to 60-centimeters. This change occurred due to switching collection containers from a 500-milliliter graduated cylinder (which prevented the bulb from hanging freely) to a large basin which allowed the tubing to hang freely.

Water flow rates varied during the continuous flow experiment. Figure 7 shows the flow rates of all three filters over the duration of the experiment. Reasons for these variations can be explained by several factors. Below Figure 7 is a timeline describing possible reasons for variations in flow rates at specific time points. As can be seen by examining the time line in Figure 7, many technical difficulties were faced throughout the course of the experiment. Therefore, no clear trend in flow rate is evident. In comparison to initial flow rate experiments, flow rates were similar for the first five days of testing, and then they dropped to levels far below initial flow rate test values of 6.2- 6.2 liters/hour. No clear changes are seen over time or volume of water filtered.

Figure 7: Daily flow rates of filters 1, 2, and 3 during continuous flow experiment.



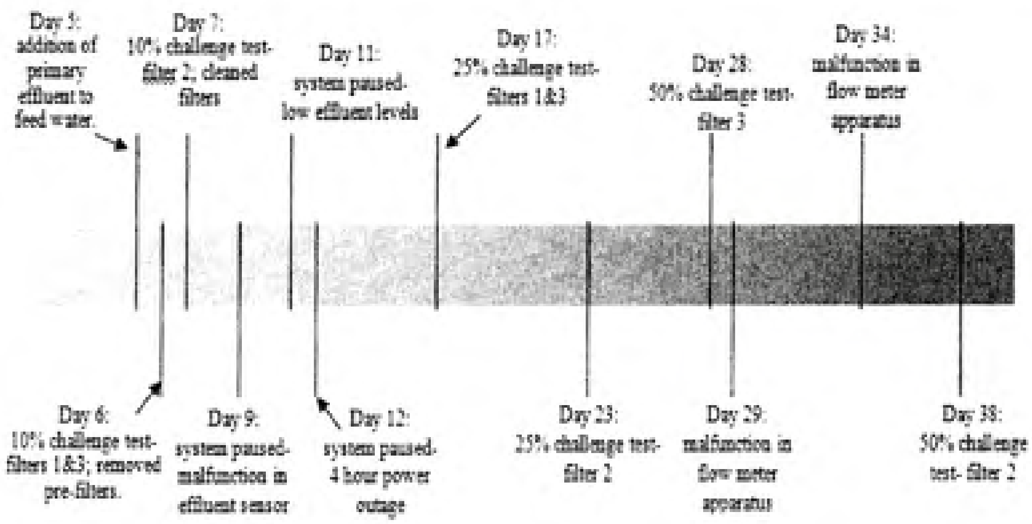


Figure 8 shows flow rates during the 2nd and 3rd days of continuous water flowing through the filters. It should be noted that no primary effluent was running through the system at this point due to a malfunction in the feed system. Flow rates decline in all three filters as the water head level drops. Bucket refills can be tracked by assessing peaks on the graph. According to Figure 8, filter 2 filtered water consistently slower than filters 1 and 3. The flow meter for filter 1 malfunctioned after day 5, so no data on this filter is available following addition of primary effluent.

Flow rates for later on in the experiment are depicted in Figure 9. Flow rates are highest after cleaning. As more water passes through the filters, the peak flow rates and subsequent flow rates decline. It is important to note the relationship between flow rate and cleaning. As can be seen in Figure 9, before cleaning the flow rates are slower compared to the rates from earlier in the day. As time progresses and more water is passed through the filters, they eventually clog, typically reducing the flow rates by about 80%. Following cleaning, flow rates once again are high, and then over time and water volume filtered they gradually decrease again. This trend can be seen throughout the lifespan of the filters.

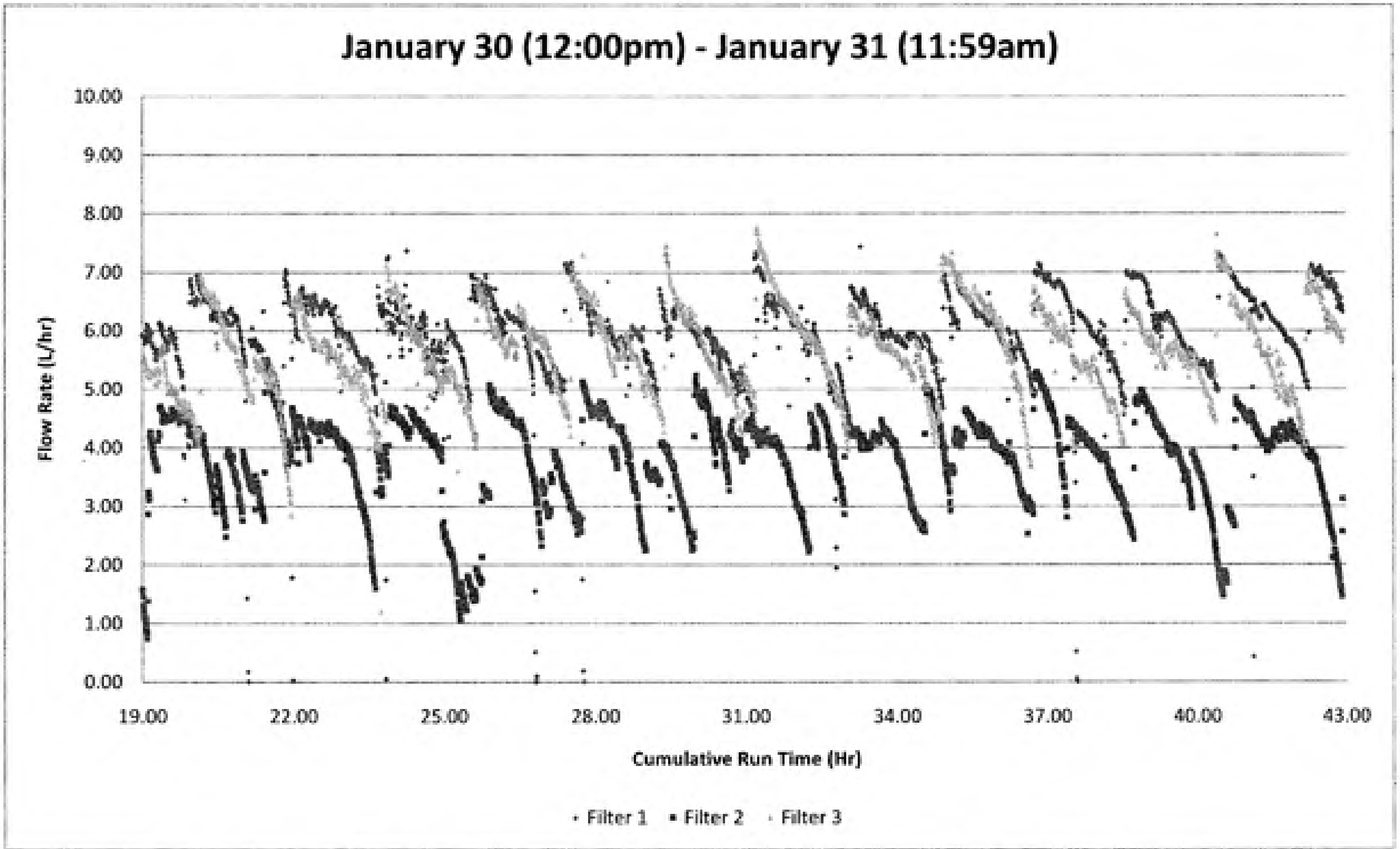


Figure 8: Flow rates over 24-hr period without primary effluent in feed water.

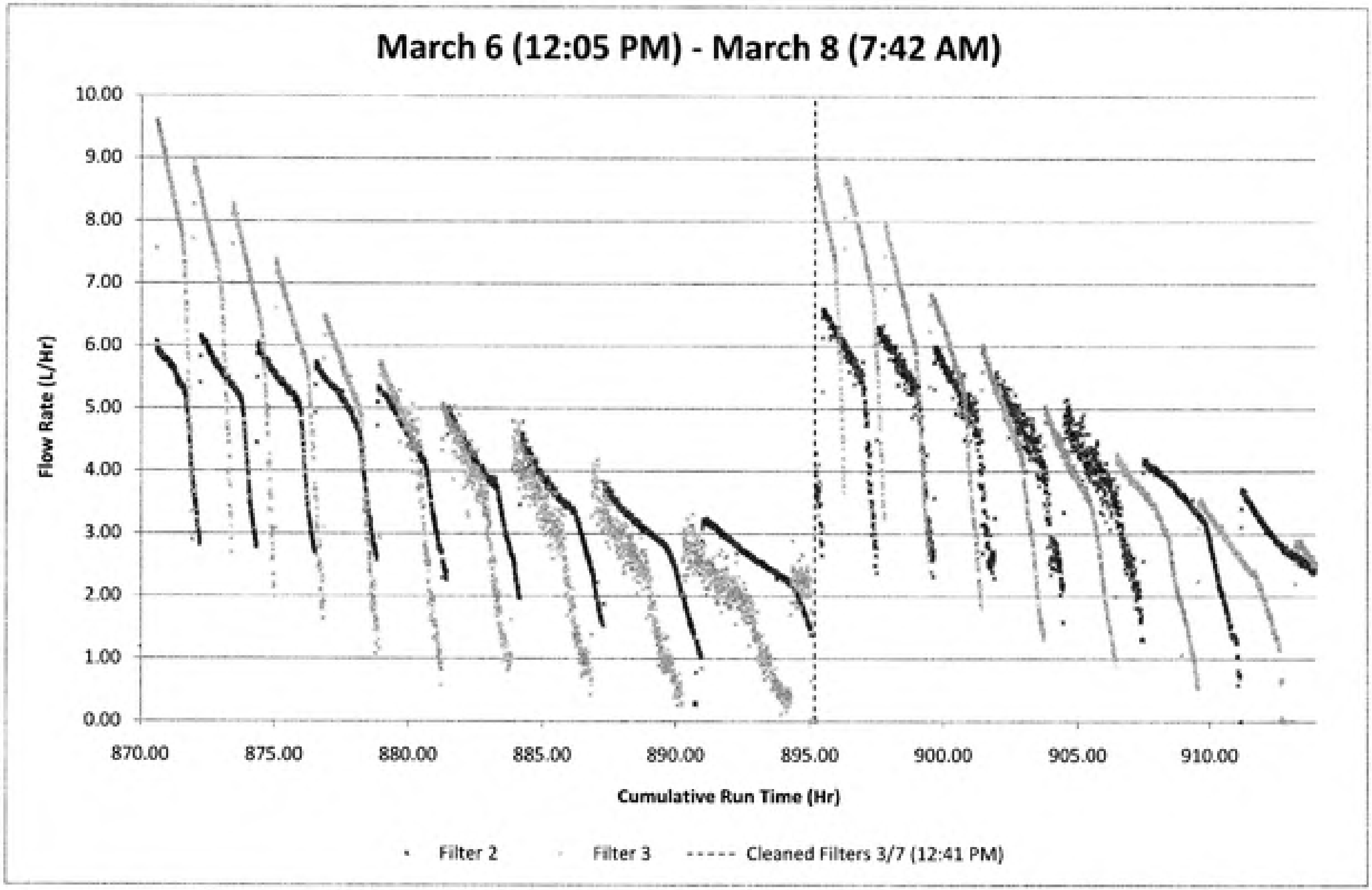


Figure 9: Flow rates over 2-day period with cleaning.

5. Discussion

This is the first effort to evaluate reductions of bacteria, viruses and protozoa by a ceramic siphon filter over its projected lifespan using test water designed to simulate fecally contaminated drinking water sources in developing countries. This study shows that reductions of *E. coli*, MS2, and fluorescent microsphere surrogates for protozoa decrease over the volume lifespan of the filter. Additionally, the use of sewage-amended water as feed to the filter leads to the need for routine cleaning, which reduces the lifespan of the filter by thinning the ceramic element. The results from this study should inform and influence future POU technology testing protocols as well as decisions about the acceptability of the ceramic siphon filter.

A. Log_{10} reductions of *E. coli* and F+ coliphage MS2

As can be seen by the variations in microbial reduction during the initial batch challenge tests using the same filter, there are differences in the filter's ability to reduce *E. coli* and MS2 between trials using the same filter. *E. coli* reduction in batch testing was higher than previously reported by other investigators for the siphon filter, with a mean reduction of 7 log_{10} (WaterLaboratorium/NOORD reported 6 log_{10}). Other types of ceramic filters, such as the ceramic pot filter show a maximum of 6 log_{10} reduction of *E. coli*, and an even lower reduction of 2 log_{10} *E. coli* when testing is done in the field by unskilled persons using waters of varying quality (Sobsey et al., 2008). Laboratory studies of viral reduction by ceramic filters show a maximum of 4 log_{10} removal, with field tests resulting in reductions closer to 0.5 $\log_{10}$ (ibid). Consistent with reported results of ceramic filter challenge studies, the siphon produced little to no reduction of F+ coliphage MS2, a surrogate for human enteric viruses. Porous ceramic media filter microbes from drinking water by size exclusion (Sobsey et al., 2008). Pore size for the ceramic pot filter can be made as small as 0.2µm, which can effectively trap bacteria and protozoa, but viruses are smaller, and thus capable of passing through the filter (Brown, 2007b). Therefore, the low reductions of MS2 by the ceramic siphon filter is possibly due to the pore size not being effectively small enough to trap viruses during filtration. Efforts to increase virus retention in porous ceramic filters by incorporating positively charged media such as iron oxides into the ceramic material have been reported, but such amendment of the ceramic material has not been reported for the ceramic siphon filter (Brown and Sobsey, 2010).

B. $\log_{10}$ reductions of *E. coli*, F+ coliphage MS2, and fluorescent microspheres at different points in the volume lifespan of the filter

In this study it was shown that $\log_{10}$ reductions of *E. coli*, MS2, and fluorescent microspheres decrease over time and as the volume of water filtered increases. Decreases in filter performance over time may lead to degradation of microbial water quality and increased risks of waterborne disease. Examining the trends in microbial reductions over time, the batch and continuous flow test results suggest that using batch test data alone will give misleading results and lead to overestimation of filter efficacy. Batch testing assumes that reductions do not fluctuate throughout the lifespan of the filter; however the results of this study suggest this assumption is faulty. Therefore, challenge tests at various points in the lifespan of the filter should be conducted when testing filter performance for microbial reduction. It may be advisable to alter filter instructions to recommend using a second treatment option, such as chlorination, at a certain time point or after a certain volume has been filtered, as the microbial removal efficacy of the filter decreases. It may also be necessary to lower the projected volume lifespan of the ceramic siphon filter; based on these results it needs to be replaced more often than currently recommended.

The differences between batch and continuous flow testing are also important for benchmarking point of use technologies of this type against performance standards. The Environmental Protection Agency (EPA) sets current United States standards for POU water treatment at a minimum 6 $\log_{10}$ (99.9999%) reduction in bacteria, 4 $\log_{10}$ (99.99%) reduction in viruses, and 3 $\log_{10}$ (99.9%) reduction in protozoan parasites (USEPA 1987; NSF 2003). Only two out of the three filters tested in this study met the EPA standard for 6 $\log_{10}$ reduction of *E. coli* at the 10% volume lifespan point. At future volume lifespan points, all three filters failed to meet the EPA standards for *E. coli*. In addition, none of the filters met the EPA standards for MS2 reductions at any of the volume lifespan points. Results indicate that protozoan parasites (as represented by fluorescent microspheres) met the EPA standards of at least 3 $\log_{10}$ reductions at every challenge point throughout the lifespan of the filters. There is a need for a standard protocol to be developed to test POU water treatment technologies for use in the developing world, perhaps with similar or modified standards to the EPA POU standards. This will be discussed in more detail below.

This study also suggests that the lifespan performance of siphon filters differs from that of traditional ceramic pot filters. This study differs from a field study of ceramic pot filters in Cambodia, in that differences in $\log_{10}$ reduction were found as volume of water filtered increased over time. In contrast, no such differences in $\log_{10}$ reduction were found over time in the Cambodia study (Brown, 2007b). The Cambodia study indicates that the expiration time of 1-2 years for ceramic pot filters should be reconsidered, since no differences were found in the $\log_{10}$ reduction values, indicating that the lifespan of pot filters may be longer than currently thought. The results of this current study suggest that the situation is different for ceramic siphon filters, with shorter filter lifespans than currently projected.

The siphon filter can also be compared to other types of POU filtration technologies. Stauber (2006) performed a study measuring the *E. coli* reductions over time in a biosand filter, but experiments were only done for 17 days and for 43 days, respectively. This does not represent the lifespan of the filter. Daily dosing feed water contained raw sewage and *E. coli* at concentrations of either 10^5 CFU/mL or 10^3 CFU/mL. Observed results were that maximum *E. coli* reduction occurred towards the end of the longitudinal filter dosing experiments. Minimum *E. coli* reductions occurred at day 4 and day 3, with reductions of 1.2 $\log_{10}$ and 0.43 $\log_{10}$, respectively. In contrast, the lowest log reduction observed from the siphon filter (at the 50% volume lifespan point) was 2.86 $\log_{10}$. Maximum *E. coli* reductions for the biosand filter were 2.0 $\log_{10}$ on day 17 and 1.9 $\log_{10}$ on day 42, respectively. Once again, these reductions are much lower than those found during the ceramic siphon filter study. Unlike the siphon filter, however, levels of *E. coli* reduction in the biosand filter increase over time, as a result of the filter design. The biosand filter undergoes a process called ripening or maturation, where a biological layer forms inside the filter, making the filter microbially active against pathogens and slowing water flow which contribute to increasing microbial removal (Stauber, 2006). Thus, the differences between filter performances may be attributed to these differences in properties.

Since there have been no studies to date on reduction of diarrheal diseases with the ceramic siphon filter, the potential for diarrheal disease reduction can only be estimated from existing studies of ceramic pot filters. With similar $\log_{10}$ reduction values for microbes, it is possible that similar diarrheal disease reductions might be achieved. An independent post-implementation assessment comparing filter and non-filter households in Cambodia found a 46% reduction in diarrheal disease in ceramic pot filter users versus non-user households (Brown, 2007b). Similar results were reported in Cambodia for a randomized controlled trial of newly introduced filters (Brown et al., 2008). Thus, it is possible that similar results might be achieved by the ceramic siphon filter, but studies are necessary to measure diarrheal disease changes, which are also dependent on behavioral factors.

C. Effects of cleaning on flow rate and microbial reductions over the lifespan of the filter.

Initial flow tests indicate the importance of having a constant distance from the bottom of the filter to the hose spout outflow. Differences in this distance changed the flow rate. Therefore, the distance needs to be constant in order to ensure consistent flow rates. The instruction manual recommends a distance from the bottom of the filter to the ground of 0.7 meters, but nothing is said about the height of the bucket, even though that will alter distance of bottom of filter to hose spout. This is important for testing in order to control or account for flow rate variables over the filter lifespan.

The results of this study also show that regular cleaning of the siphon filter decreased the lifespan when fecally contaminated test water with organic matter was used. Cleaning was done daily because the filter flow rates dropped by about 80% within twenty four hours after each cleaning. The filters were cleaned after every 70-120L of water passed through, which corresponded to about once every twenty four hours. Based on the interim report on filter use in India by EnterpriseWorks India, cleaning every 70-120 L is consistent with actual cleaning cycles that occur in use settings. Because of the additional reduction of flow rates caused by the fleece pre-filters, the pre-filters were removed on day five of the experiment. Users in the field may or may not be removing the pre-filters when they experience clogging, so it is unclear whether similar patterns of clogging following cleaning occur in the field. Cleaning is done by scrubbing with a scouring pad, and each consecutive cleaning causes small amounts of the ceramic candle element to wear away. As a result, the effective life of the filter was reduced because it eventually becomes so thin that it is extremely vulnerable to breakage during routine use. The decreasing microbial reductions over the lifespan of the filters and the increased flow rates immediately following cleaning could be a result of a decrease in the amount of pores in which the water must flow through. In addition, the pore size may increase over time because the water flowing through them would be greater as the number of pores is decreased by routine cleaning.

When using deionized water during initial flow rate testing, flow rates were high, ranging from 6.2 to 6.4 liters per hour. Addition of the primary effluent to the test water reduced flow rates. Reduced flow rates were potentially caused by the feed water particles clogging the pores of the filter. Another explanation could be that the clogging is biologically-mediated as microbes accumulate and possibly proliferate on the filter surface as a biofilm. The results of this current study suggest that previous claims that the filter is capable of filtering turbid water may not be entirely accurate.

This is the first study of its kind, in which the lifespan of the siphon filter is tested using water containing sewage effluent (sewage effluent-amended test water) that is continuously flowing through the filters. The use of primary effluent models fecally contaminated surface water in developing countries. The effluent is filtered before addition to the feed water flow, to better model ground water and surface water in which larger particles are either filtered out in the soil or can settle out, such as in reservoirs, lakes and ponds. The only other study that investigated microbial reductions over the volume lifespan of the filter used only deionized water, with no fecal or other organic matter. This previous study is also quite different in that test water was pulled through the filters by suction at a rate of 100 liters per hour (WaterLadoratorium/NOORD, 2008). These conditions are not representative of real world use conditions. Also, the physical manipulation of the filters to pull water through at a rate over ten times the normal rate achieved by siphon action could alter the properties of filtration.

With this new information, it may be necessary to redesign the siphon filter in order to address problems encountered when filtering water with turbidity and organic content. It may also be necessary to redesign filter efficacy testing protocols to better reflect the actual performance of these types of filters over their lifespan. New POU performance evaluation guidelines to be released by the WHO suggest using higher concentrations of effluent in feed water than was used in this study. This would most likely cause more difficulty with clogging. Thus, filter design may need to be further altered to accommodate this type of water. Additionally, a redesigned pre-filter may be beneficial for reducing clogging in filters. Perhaps a pre-filter that was thinner in diameter might reduce clogging while still decreasing the need for frequent cleanings. The manufacturer of the ceramic siphon filter does not provide any information regarding average, nominal, or absolute pore size rating for this filter. This information is vital for determining its potential effectiveness.

Studies with ceramic pot filters also suggest other potential issues with use of the siphon filter. A ceramic pot filter study in Cambodia found that ceramic pot filters broke at a rate of 2% per month (Brown, 2007b). Additionally, odds of finding a filter still in use in intervention homes decreased at a rate of 44% every six months. Of those households where the filters were no longer in use, 65% of them reported that the filter (element, tap, or container) was broken. Ceramic pot filters are said to have a useful life of 5+ years, although some manufacturers recommend replacement of the filter element every 1 to 2 years. This current study suggests that the useful lifespan may be even shorter for siphon filters.

The Cambodia study also found that there was a potential for recontamination of the filter during cleaning due to the use of contaminated rags and other cleaning tools. This should be a concern for siphon filters as well, since it is recommended that users utilize the same scrubber throughout the lifespan of the filter. If the scrubber is not properly cleaned between filter cleanings, then the potential for recontamination can be high.

A study of the biosand filter over two different time periods (17 days and 43 days) found that in both cases there was more than a 25% decline in flow rate compared to initial flow rates (Stauber, 2006). Decline in flow rates in this type of filter is thought to be the result of a biological layer forming inside the filter (ibid). Due to the differences in filter design, it is not likely that the observed long-term decreased flow rate in the ceramic siphon is due to this phenomenon.

D. Water quality parameters

Similar to the biosand filter and the ceramic pot filter, the ceramic siphon filter is capable of removing turbidity (Stauber, 2006; Lantagne, 2001). In addition, the percent reductions in turbidity increased as volume of water and time increased. This result is consistent with biosand filter turbidity tests over time (Stauber, 2006). While turbid water can be a drawback for many POU treatment technologies, the biosand and ceramic filters (as well as coagulation/flocculation) are most capable of reducing turbidity in water (Sobsey et al., 2008). This present study further supports this claim as turbidity was consistently reduced by the ceramic siphon filter to below 1 NTU.

pH levels of water decreased following filtration by the ceramic siphon filter. This is different from the results reported for both the biosand and ceramic pot filter that showed a mean increase in pH following filtration (Stauber, 2006; Lantagne, 2001). Silver concentration in filtered water was highest at the 10% volume point, and then it dropped to lower concentrations in later volume points. At the 10% volume point, the silver concentration of 25 ppb was far below the US EPA (2002) standard of 100 ppb. Thus, silver leaching at concentrations affecting human health does not appear to be a concern for this filter. The role of the silver in the candle element of the ceramic siphon filter is still somewhat unknown. It may have an effect on microbial reduction, which might account for the higher reductions that were seen at earlier challenge testing points in this experiment. There are many factors that are not known about the silver in the ceramic siphon filter, such as the total amount of silver in each filter and what form the silver is in within the candle element. This is an area that requires further investigation.

E. Study flaws

As with any study, there are some sources of error or flaws in the design of the study. One such flaw could be the use of continuous water flow through the system, whereas in the real world, volumes of around 15-20L would be filtered periodically throughout the day and there would be an overnight rest period. The removal of the fleece pre-filter may have altered results of this study, as well. In addition, a silver concentration reading close to the zero percent water volume point (in the very beginning of the filter lifespan) would have been useful to see if silver leaching is higher at this point. Also, for the first five days of the experiment, there was a malfunction in the pump that delivered effluent into the feed water, so the actual water going through the filters was almost entirely free of contaminants such as particles and dissolved organic matter. Furthermore, diameters of individual filters were measured weekly, which was problematic for direct comparisons among the three filters because they were at different points in their volume lifespan. Measuring of filter diameters did not begin until later in the experiment, so baseline measurements of filter diameter are not available. Lastly, differences seen in $\log_{10}$ reductions at different volume time points could be due to the fact that the 10% and 25% points *E. coli* reductions were measured by membrane filtration methods, whereas the 50% point *E. coli* reductions were measured by the spreadplate method.

F. Need for further and more rigorous research

There is a need for standardized protocols for POU technology testing in developing countries. Although there are protocols in use for developed countries, like the United States (USEPA, 1987), these protocols are often not applicable for use in developing countries due to resource limitations and other constraints. As can be seen from the differences in the batch challenge tests versus the challenge tests over the lifespan of the filter, changes in the microbial reduction occur over time and with increasing volume of water filtered. Other types of water should also be tested during lifespan studies so that the testing encompasses a wide and representative range of water types found in the developing world. Additionally, testing should be done using alternative microbial indicators to ensure removal is consistent and generalizable amongst different microbes in the same family. Side by side comparisons of POU technologies using identical conditions is also necessary to determine which technology would be the best choice for specific conditions. Furthermore, studies that link interventions to health outcomes using rigorous epidemiological methods are necessary. Lastly, there is a need for evaluations that examine past interventions to determine successes, failures, and challenges so lessons can be learned and improvements made to improve the effectiveness of future efforts.

G. Summary

The ceramic siphon filter has the potential to be successful in producing acceptable drinking water at POU. It reduces *E. coli* and fluorescent microspheres (representing protozoan parasites) to levels that meet US EPA drinking water standards (2006). However, it performs poorly in reducing viruses, with $<1 \log_{10}$ ($<90\%$) reduction. It has a faster flow rate (almost 3X) than that of the ceramic pot filter, and it performs similarly in reducing turbidity. It is also more compact than the ceramic pot filter, making it a better solution for places where transportation and delivery might be an issue. Like the ceramic pot filter, continued cleaning causes wear and tear, which decreases the effective lifespan of the filter. Both filters are priced similarly, ranging from $7-12, depending on the country.

Following filtration, it is important that safe storage of water occurs in order to prevent recontamination. Implementers need to stress hygienic handling of the filter, filter hose, spout and receiving receptacle of the filtered water to avoid recontamination. Furthermore, it might be necessary to alter the method of cleaning to reduce the effects of cleaning on the filter diameter. It is recommended that changes in the filter composition be explored to reduce the amount of material that sloughs off during cleaning.

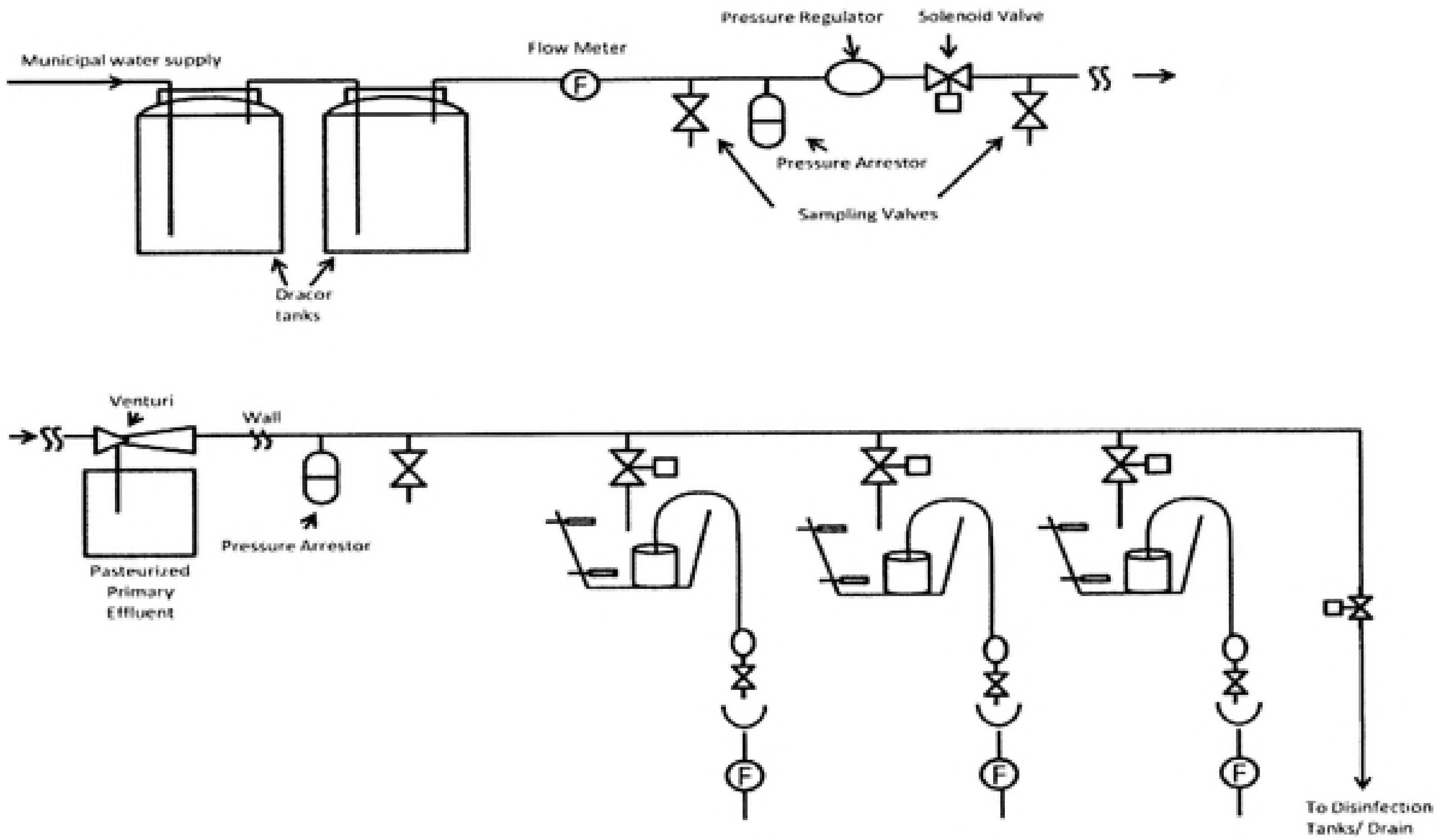
Perhaps the most promising method to improve performance would be the use of two successive POU treatments in order to ensure safe water. Future research directions could include the use of chemical treatments to enhance the removal of turbidity and viruses in influent water, such as chemical coagulants like chitosan or adsorbents like goethite. Chemical disinfection of the filtered water would also further improve reduction of viruses and other microbes and provide residual disinfectant as a barrier against recontamination.

6. Conclusions

- In batch challenge tests there were relatively high *E. coli* reductions of about 2.9 to 6 log_{10}, which were higher than previously reported *E. coli* reductions by the biosand and ceramic pot filters. Reductions of MS2 coliphage, an indicator virus, were low at consistently less than 1 log_{10}.
- Microbial challenge tests over the volume lifespan of the filter resulted in log_{10} reductions of 2.9 to 6 for *E. coli*, <1 log_{10} for MS-2 and 3.8 to 5.0 for protozoan parasites, with decreased reductions with increasing volume of water filtered and time. Regular cleaning of the ceramic siphon filter is necessary to restore flow rates when using sewage amended water, but consequently reduces effective lifespan of the filter. Filters failed at 42, 49 and 65% of the lifetime volume of 7000 liters.
- Differences in results from batch tests versus challenge tests throughout the lifespan, with decreased performance in the lifespan studies, indicate the need for POU testing to be done throughout the lifespan of the technology. Additionally, use of sewage amended feed water to simulate real world conditions should be incorporated into protocols for testing POU technologies.
- There is a need for standard POU testing protocols to evaluate devices for use in developing countries.

Appendix:

Continuous flow design schematic:



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