Spring 2017

The use of ceramic water filters under pressure in an in-line water pumping system

Travis Dean Gardner

THE USE OF CERAMIC WATER FILTERS UNDER PRESSURE IN AN IN-LINE WATER PUMPING SYSTEM

by

TRAVIS DEAN GARDNER

A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN GEOLOGICAL ENGINEERING

2017

Approved by

Joe D. Guggenberger, Advisor
A. Curt Elmore
Mary Reidmeyer

PUBLICATION THESIS OPTION

This thesis includes an article prepared for submission to the journal Water Science and Technology: Water Supply. The content of pages 19-37 will be submitted for publication in the journal mentioned above. Note that sections of this document contain additional information supplemental to that journal paper.

ABSTRACT

Ceramic pot filters (CPFs) have proven an effective point of use (POU) filter due to their relative low cost, ease to manufacture, and effectiveness at treating contaminated water. These filters are used by individual homes, and sometimes multiple filters are needed for each home in order to produce enough water for the family's household. If these filters could be used in-line with a pumping system or elevated storage tank, water could be filtered and used on demand for a community in an economically feasible way. However, CPFs are too fragile to use under pressure due to the weak points where the side wall and the bottom of the filter meet and the difficulty of keeping CPFs tightly sealed to an apparatus

To use ceramic filters in a system under pressure, ceramic disks were manufactured and housed in a special apparatus designed from polyvinyl chloride (PVC), a rubber coupling, and hose clamps. Ceramic disks were made with varying thicknesses and clay to sawdust ratios. Filters were tested under pressures of 5 and 10 psi to determine flowrate and microbiological efficacy, based on total and fecal coliforms, at these pressures. Filters with log reduction values (LRV) of 2 or greater were considered effective, based on standards presented by the World Health Organization (WHO).

Initial results show that ceramic disk filters could be an effective way of filtering water in a closed system under pressures of 10 psi. From testing, it was determined that filters with thicknesses of 1.25 inches were the most effective at meeting the WHO removal requirements with the highest flowrate. Porosity of the filters did not contribute to the removal effectiveness. Filters with clay to sawdust ratios of 6 to 1 by mass proved the most effective during testing.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Joe Guggenberger, for sharing his extensive experiences and abounding knowledge to assist my research endeavors. His guidance has been imperative throughout my experience at Missouri S&T.

I would also like to thank my committee members, Dr. Mary Reidmeyer and Dr. Curt Elmore, for their interest in this project and for their assistance. I would like to especially thank Dr. Reidmeyer for her extensive help and guidance in the production of appropriate experimental filters and disk for the study, and Dr. Elmore for sharing his knowledge of ceramic water filters and for his help in apparatus design.

I would also like to thank the CPF factory near Antigua, Guatemala for the opportunity to observe their process and learn about the filters, and for the inspiration to investigate the possibility of putting CWFs under pressure.

I would also like to thank my office mate and a previous instructor, Carlo Salvinelli, for his extensive knowledge on ceramic water filters and the process of making them as well. I appreciate the constant support I received and constant help in the lab whenever he was busy himself. I would like to thank my other office mates Zane Helwig and Rachel Utrecht for their encouragement and help in my research.

I also want to thank my family for their continued support throughout my education and Erica Wellen for her assistance in research and continued support and encouragement during all stressful times.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

NOMENCLATURE

CPF	Ceramic Pot Filter
CV	Coefficient of Variation
°C	Degrees Celsius
ft	Feet
hp	Horsepower
in.	Inches
in-lb	Inch-pounds
kg	Kilogram
L	Liters
L/hr	Liters/hour
LRV	Logarithmic Reduction Value
mm	Millimeter
MPN	Most Probable Number
psi	Pounds per Square Inch
POU	Point Of Use
WHO	World Health Organization

1. INTRODUCTION

1.1 DRINKING WATER FILTRATION IN DEVELOPING COUNTRIES

Access to clean drinking water in developing nations continues to be an important concern for human health. An estimated 748 million people (about 11% of the world's population) lack access to improved water supplies (WHO/UNICEF, 2014). Clasen and Bastable (2003) estimate that hundreds of millions more of that population drink water contaminated during collection, transport, and storage. Diarrhea, a health consequence of drinking contaminated water, accounts for approximately 1.87 million, or 19%, of childhood deaths each year (Boschi-Pinto et al., 2008). It can therefore be seen that a water filtration system that is cost-effective and easy to make in-country would greatly improve the overall health of a developing nation's community. Ceramic pot filters (CPFs) have shown to be effective at producing potable water and a good alternative for household water treatment (Hunter, 2009). CPFs are porous ceramic filters with a flower pot shape design. Colloidal silver is added to the outside of the pot and acts as a disinfectant. Figure 1.1 shows a typical in-home setup of the filter system. Water is poured into the pot-shaped filter reservoir and flows by gravity through the CPF and into a plastic bucket to be dispensed from a spigot for drinking.

1.2 CPFS EFFECTIVENESS AND LIMITATIONS

1.2.1. Microbiological Removal. Ceramic pot filters have proven to effectively remove microbiological contamination by multiple sources, including van Halem et al. (2007), Brown and Sobsey (2010), Kallman et al. (2011), Soppe et al. (2015), and others. Van Halem et al. (2007) showed that filters that are gravity fed are capable of at least a logarithmic reduction value (LRV) of 2 and up to 7 depending on where the CPF was manufactured. This means filters have been shown to remove 99% to 99.99999% of E.coli. The World Health Organization (2011) states that filtration systems that can have a minimum LRV of 2 of bacteria are protective of human health. Therefore, it appears that CPFs are an effective technology to remove harmful bacteria from drinking water.

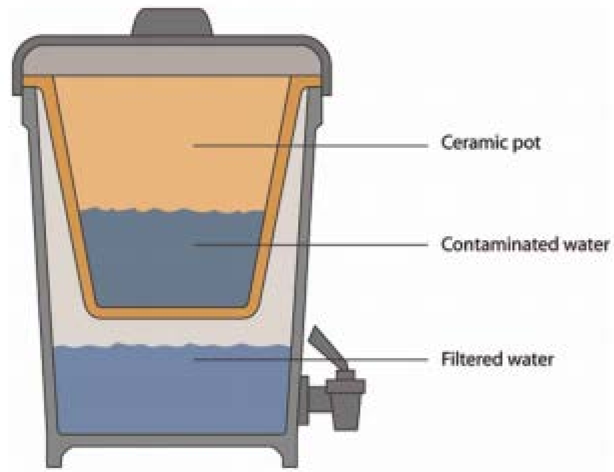


Figure 1.1: Typical CPF setup (Soppe et al. 2015)

1.2.2. Flowrate as a Limitation. CPFs also have a filtration rate that users can find too slow for their use or not produce enough the water for the user. For quality control standards, a filter must have a flowrate of one to two liter/hour (L/hr) (Lantagne et al., 2010). At the filter factory near Antigua, Guatemala, filters with flowrates higher or lower than this range of values are discarded and not sold to any users. Flowrates that are too high tend to not filter water effectively while flowrates that are too low will not produce enough water for daily use. Ceramics Manufacturing Group (2011) found that there was a two percent per month disuse rate and that five percent of those who stopped using the filter did so because the filtration rate was too slow. In larger households, multiple filters may be needed which would be more expensive to families.

1.2.3. Filter Limitation for Use in the Field. A field study conducted by Roberts (2004) surveyed 35 households who had previously been using the CPFs but had stopped for one reason or another. Reportedly, 71% of the users stopped using the filter due to the tap breaking on the filtering element and 20% stopped using the filter due to the filter breaking and no longer filtering water effectively. Individual homes need to own a CPF, possibly even multiple filters, in order to filter enough water for daily use. Purchasing filters, especially multiple per household, can be too expensive for some users to afford. These limitations can cause families to stop using the filters.

1.3 MOTIVATION

A typical CPF system filters water using only gravity. No research on putting ceramic pot filters under pressures greater than one foot of water head was found during a literature review. CPFs prove effective in an area where there is no centralized water distribution system since the user can filter water at their home. The problem with using the standard CPF is that the user must carry water to the filter and then wait until filtration is complete before drinking or using water. Not having water on demand and having to coordinate your day around the use of drinking water can be a great inconvenience to the user. Areas where there is a centralized water distribution system (such as a groundwater pumping well or elevated storage tanks) still typically need a disinfection system to prevent bacteria from contaminating drinking water. Using an inexpensive, reliable filter at the end of a water distribution system would allow for users to have water on demand and relieve the need of constantly filling a water filter to produce clean water. Cleaned water could also be pumped into storage units and users could access the water whenever they would need throughout the day. Using a centralized filter would also be less expensive for communities. Instead of every household purchasing a filter for their home, a community would only need one filter to produce clean water for the community on demand. Using a filter in an in-line system could also help to prevent typical complaints users have of the filter being too fragile. Once the filter is in place in the system, there would be no added risk of breaking the filter from refilling or cleaning as with the standard CPF.

2. OBJECTIVES

2.1 PROBLEM STATEMENT

Ceramic pot filters can be problematic in terms of water production and practicality. The use of ceramic pot filters could be greatly improved by being used in-line with a pumping system to have an on demand, clean water system for developing communities rather than separate filters for induvial families

2.2 STUDY OBJECTIVES

The objectives of this research were to:

- Produce filters to withstand pressure of a typical pumping system
- Develop an apparatus to house the filter and keep the filter under pressure under typical pumping conditions
- Determine if disk filters are suitable to treat contaminated water by measuring log reduction value (LRV)
- Analyze the relationship between flowrate and sawdust to clay ratio with filter under pressure
- Analyze relationship between flowrate and thickness with filter under pressure
- Analyze relationship between LRV and sawdust to clay ratio with filter under pressure

- Analyze relationship between LRV and thickness with filter under pressure
- Determine the optimum thickness and clay to sawdust ratio to effectively treat contaminated water at the best flowrate

3. METHODS

3.1 USE OF CERAMIC POT FILTERS UNDER PRESSURE

All filters used in this study were manufactured on campus at the Missouri University of Science and Technology using a synthetic clay body that was made to as closely mimic the clay used at the filter factory near Antigua, Guatemala. The clay body used in this study was developed in an earlier process by Hubbel et al. (2015). The sawdust used in this study was collected from a local sawmill and was sieved through a U.S. No. 10 sieve (2 millimeter [2mm]). The sawdust was combined with the clay in a 5:1, 6:1, and 7:1 clay to sawdust ratio by mass. Deionized water was mixed with the clay mixture to achieve a desired consistency for spinning the clay in a mold.

3.1.1. CPF Manufactured in Bucket Stacked with Ceramic Disks. Ceramic pot filters with disks stacked in them were first used as the filter element in this study. The pot filters were made in plastic buckets that would eventually house the filters. The buckets were lined in a thick paper to help absorb moisture. The clay mixture was placed in the bucket and the bucket was put on the pottery wheel and spun. A jolly was used to mold the clay into the shape of the ceramic pot filter. This method proved unsuccessful as there was no easy way to separate the filter from the plastic bucket, the filters tended to have cracks or creases from where the paper in the bucket came into contact with the filter causing the filter to be fragile, and the clay dried unevenly causing cracking in the filter.

3.1.2. CPFs Manufactured in Plaster Mold with Ceramic Disks. Following the above method, a plaster mold was made of the bucket in order for the filter to dry evenly and so that the clay would release from the mold. Figure 3.1 shows the plaster mold used for making the CPF. This mold was then placed on the pottery wheel and spun using the same jolly as before to create filters. These pots were allowed to dry for three days before being pulled out of the mold and placed in a soil oven for at least 24 hours at approximately 100 degrees Celsius (°C) to dry. Disk were made to have as close an outer diameter as the inner diameter of the pot. Three different diameter disks were made to fit inside the filter. Disks were made by pressing a clay mixture into wooden molds with holes cut in them. The holes in the wooden molds were made bigger than the disk needed to be to try and best account for shrinkage from drying of the clay mixture and from firing. These filter disks did not fit well into the CPF created and manufacturing disks to the correct size proved to be very difficult.

Figure 3.1: Plaster mold used to make CPFs

The filter and disk were fired in an electric kiln following the same firing schedule (temperatures and times) for all clay mixtures. The firing schedule slowly increased the temperature of the kiln to 993°C over the course of approximately 14 hours and then cooled back to room temperature. The kiln was propped open to allow for smoke from the sawdust burning out to escape and to allow for air flow to allow for as complete combustion as possible. Figure 3.2 shows the fired CPF used for testing. The filters were then placed in the plastic buckets and caulk and plumbers putty were used to try and seal the filter to the bucket. The lid was then screwed onto the bucket to tightly seal the entire filter. Testing was conducted using a tank raised approximately 10 feet (ft) from the filter element and water in the tank raised to a level that allowed for approximately 12 ft of head to be put onto the filter element. The lid eventually had to be clamped down between two pieces of plywood to prevent the lid from popping off when put under pressure. Figure 3.3 shows the apparatus without having the lid clamped down.

Figure 3.2: Fired CPF used for testing

Figure 3.3: Apparatus used to test CPFs without clamps

The problem found with using ceramic pot filters was the fragility of the filter element and the ability to establish a tight seal between the filter and the bucket and the disks to the filter. When put under pressure, the filters continuously cracked wherever there was a joint connecting the side to the bottom of the CPF. It also appeared that plumbers putty and caulk were not ideal for establishing a tight seal with the filter element to the plastic bucket. From this testing, it was determined that the use of a ceramic disk as the filter element would be the better option to study for this method of filtration due to its ability to withstand higher pressure since there are no joints on a ceramic disk filter.

3.2 USE OF CERAMIC DISK FILTERS UNDER PRESSURE

Ceramic disks were manufactured using the same clay mixture and sawdust ratios as the ceramic pot filters were. The mixture was made to be drier than the mixture used to make the ceramic pot filters to allow for better compaction. The authors felt that compaction was very important to allow for the filters to be strong enough to withstand the pressure that a pump would put on them. Originally, the filters were pressed in a 9 inch (in). by 9 in. wooden box. The clay mixture was compacted by placing the clay mixture in a 9 in. by 9 in. piece of plywood on top and pressing down by hand with approximately 200 pounds of force (lb) for one minute. The wooden mold was removed after approximately an hour. These mixtures were dried and placed in the electric kiln using the same times and firing schedule as the previously fired ceramic pot filters. The fired filter square was then placed in the drill press and a 6.63 in hole saw with the pilot bit removed was used to drill a circular disk filter.

An apparatus was also constructed in order to effectively house the ceramic disk filter and to keep it contained and under pressure. A piece of 6 in Schedule 40 PVC pipe was cut into two pieces approximately 9.75 in. in length. A cap was threaded to allow for a valve to be placed on the top PVC pipe section and a threaded pipe into the bottom cap. The caps were then glued onto one end of each section of PVC pipe. A rubber coupling was used to house the filter and to connect the two sections of pipe. A pressure gauge was put into the top and bottom section of the pipe of the apparatus to measure influent pressure and effluent pressure if present. House clamps were used to tighten the coupling to each section of pipe and to tighten the disk filter to the rubber coupling. The apparatus can be seen in Figure 3.4 and the filter installed in the apparatus can be seen in Figure 3.5.

Figure 3.4: Apparatus used for testing

Figure 3.5: Filter in apparatus

The filters were put under relatively low pressure (approximately 5 pounds per square inch [psi]) to determine if the apparatus was suitable for keeping a tight seal to the filter and to determine if the filters were able to remove microbiological contamination under low pressure conditions. The apparatus was connected to the same tank elevated approximately 10 ft to provide approximately 10 ft of hydraulic head to the filter in the Subsurface Hydrology Lab at Missouri S&T. The findings showed that these filters were able to remove microbes and produce a higher flowrate than the typical 1-2 L/hr of a ceramic pot filter. During testing though, filters seemed to be more fragile than expected. When tightening the filter to the rubber coupling, the disk would tend to chip around the sides. Testing moved forward to testing filters under a higher pressure. A large tank supplied water to a 1 horsepower (hp) pump and was connected to the apparatus. Flowrate testing continued on the disk filters manufactured. After a few tests, two problems arose with the filters and apparatus. First, the top section of pipe would pop out of the rubber coupling under around 10 psi. To combat this problem, more hose clamps were added to the apparatus as well as the top section of the apparatus being glued to the rubber coupling. This approach appears to be a good solution to the problem. The second and bigger problem was the disk filters continuously breaking under pressures varying between 10-15 psi, while some disks failed at pressures as low as 5 psi. It was concluded that this problem was due to the filters not being pressed enough during manufacturing.

To press the filters in a more effective and consistent way and to allow for more pressure to be put on the mixture during manufacturing, a 12-ton press was purchased for use. The press was retrofitted to be able to press an 8 in. by 8 in. square clay mixture at 375 psi. This process was accomplished by screwing an 8 in. by 8 in. steel plate with a thickness of 0.5 in. into the press and by making a steel table to press the filter mixture on to. The press setup can be seen in Figure 3.6. Hollow steel tubes were also welded together to make a square mold slightly larger than the steel pressing plate to effectively press the clay mixture. Figure 3.7 shows the molds used to make the clay mixture squares with a pressed clay mixture in it. The square tube molds had heights of 1.00, 1.25 and 1.50 in. The molds were clamped to the bottom plate and the clay mixture with a piece of wax paper placed between the bottom plate and the clay as well as between the top of the clay and the top plate. The mixture was then pressed for one minute. The finished pressed filter block can be found in Figure 3.7. These filters were again dried and fired the same as the previous filters were.

Figure 3.6: Hydraulic press used to make filter disk

Figure 3.7: Pressed filter block before firing

After the filter block was fired, a hole saw was used to cut the block into 6.63 in. diameter disks. These pressed filters seemed to be more abrasive on the hole saw and the hole saw bit dulled very quickly and would no longer effectively cut the filter block into disks. To remedy this problem, the water jet at Missouri University of Science and Technology Rock Mechanics Laboratory was used to cut the filter blocks to the correct diameter to fit into the apparatus. Figure 3.8 shows the filter block being cut by the water jet.

Using the water jet proved to be a very effective way to cut the filter blocks into disks. This process allowed the filters to be cut to within 1 mm of the exact size that was required. The water jet also left the filter block a very smooth edge cut, allowing the disk to fit very tightly in the apparatus. Figure 3.9 shows the cut filter.

Figure 3.8: Water jetting filter block

Figure 3.9: Finished filter disk

3.3 FLOWRATE AND MICROBIOLOGICAL TESTING

Filters were placed in the apparatus constructed and tightened using hose clamps. A torque wrench was used first to tighten a solid wooden disk to determine the amount of torque needed to create a tight seal between the rubber coupling and the filter disk. The amount of torque needed was determined to be 25 inch-pounds (in-lbs). This amount of torque was applied to all the filter disks during testing. Before testing, filters were dechlorinated and water filtered through was tested with a Hach Total Chlorine field kit (CN-66T) to make sure no chlorine was left in the filters. If residual chlorine was present in the filters, filters were again dechlorinated with sodium thiosulfate capsules until there was no residual chlorine detected by the Hach Chlorine Test. A presence/absence test was performed using Colilert before microbiological testing was performed to ensure no contaminants were present before testing.

Flowrate and microbiological tests were performed in hour long tests. Colilert and Quani-Tray 2000 was used for testing microbiological effectiveness. Log reduction values (LRV) were determined for each filter for each test. LRV was calculated by taking the difference in the log10 of the influent bacteria concentration (most probable number [MPN]/100mL) and the log10 of the effluent bacteria concentration from the filter (MPN/100mL). To determine flowrate, water was allowed to filter through the filter in one hour test increments and was collected in a 5-gallon bucket. Water was measured in a graduated cylinder to determine flowrate in L/hr. Tests were conducted at pressures of 5 psi first. Filters that showed a good log reduction value (greater than 2) were tested at 10 psi using the same procedure as the filters tested at 5 psi.

3.4 PORE ANALYSIS AND INCOMPLETE BURNOUT ANALYSIS

Incomplete burnout was observed in some disks, especially those with thickness of 1.5 inches. It was speculated that this layer of incomplete burnout could be contributing to inconsistencies seen in the data, specifically low LRV in filters with the greatest thickness. To get a better picture of this in the filter element, the Leica S8APO digital stereoscope was used. Filter elements were cut into thin strips to better analyze the different layers observed. Analysis was performed to determine the amount of pores per area of a section that was completely fired compared to a section that showed incomplete combustion of a filter with the same clay to sawdust ratio.

PAPER

Use of Ceramic Pot Filter (CPF) Technology Under Pressure in an In-Line Pumping System

Travis D. Gardner, E.I.[1] and Joe D. Guggenberger, Ph.D., P.E.[2]

[1]Graduate Student of Geological Engineering: Missouri University of Science and Technology; 129 McNutt Hall, 1400 N Bishop Ave, Rolla, MO 65409; email: tdgtzc@mst.edu

[2]Assistant Professor of Geological Engineering; Missouri University of Science and Technology; 129 McNutt Hall, 1400 N Bishop Ave, Rolla, MO 65409

ABSTRACT

Ceramic pot filters (CPFs) have been proven to be an effective point of use water treatment device in developing nations due to its relatively low cost and effectiveness. CPFs are gravity fed and used in homes to filter water in batches. Water production is a major limiting factor to a CPF's lifetime and acceptability. Directly connecting a CPF to an in-line pumping system or a system with an elevated storage tank would allow filters to be used for constant water treatment at increased pressures, significantly increasing the quantity of treated water. Due to the fragility of typical ceramic filters, ceramic disks were manufactured for testing in a specially designed housing apparatus, and filters of varying thicknesses and porosities were manufactured to an appropriate diameter to fit tightly. Flowrate and microbiological removal efficacy were determined for each filter over the testing period at various pressures. These filters proved effective at removing total and fecal coliforms at pressures less than 10 pounds per square inch. The optimum

filter disk design proved to have a thickness of 1.25 inches and clay to sawdust ratio of 6:1 by mass. Filters proved to not be effective if flowrates were above 5 liters/hour.

Keywords: ceramic disk filter, ceramic filter under pressure, water filtration

INTRODUCTION

Access to clean drinking water in developing nations continues to be an important concern for human health. An estimated 748 million people lack access to improved water supplies (WHO and UNICEF 2014). It is estimated that hundreds of millions of that population drinks water contaminated during collection, transport, and storage (Clasen and Bastable 2003). The United Nations Children Fund (UNICEF) (2008) states that many improved water sources in developing nations do not provide safe water due to microbiological contamination from water sources with inadequate fecal contamination protection. A drinking water source can be improved by the use of a centralized community system or by a point of use (POU) system. POU systems are designed to provide adequate water for one household and can be effective for rural communities with no centralized improved water source. A very effective household water treatment device is the ceramic pot filter (CPF) (Hunter 2009). CPFs are a flower-pot shaped filter made from mixing clay, water, and sawdust and pressed to shape typically using a hydraulic press and mold. The pots are typically coated in colloidal silver that acts as a disinfectant. These pots are fired in a kiln, removing most of the sawdust and leaving pores through which water can flow. The filter is housed in a 3.8 liter (L) bucket with a lid and filtered water collects in the bottom of the bucket. It can then be poured out using a spigot at the bottom of the bucket when needed. The main bacterial removal mechanisms for CPFs, as identified by Van Halem et al. (2007), are exclusion by pore size, exclusion by effective pore size (tortuosity), and deactivation of bacteria by contact with silver.

For communities with a centralized water source, this may be an inconvenient way to filter water and some households may not be able to afford a CPF. CPFs typically have a flowrate of 1-2 liters per hour (L/hr) for quality control standards when manufactured (Lantagne et al. 2010). CPFs in households also filter water in batches and must be filled multiple times per day, depending on the number of people in a household, to produce enough water for the household. A more effective method of producing enough clean water for a household would be to put the filter in-line with a pumping system or elevated storage tank so that the user would have access to safe drinking water on demand and allow an entire community to have clean drinking water. This would help communities to afford using ceramic filters and help prevent filters from being broken during filling and cleaning since the filter will stay contained in an apparatus. CPFs are a good candidate for this type of process in developing countries due to their low cost, material availability, and relatively simple manufacturing requirements. CPFs also have been proven to effectively remove harmful bacteria in water, such as total and fecal coliforms, as documented by van Halem et al. (2007), Brown and Sobsey (2010), Kallman et al. (2011), and others.

In order to use the CPF in a pumping system, some significant problems need to be addressed. These problems include keeping a tight seal between the ceramic filter and the housing apparatus to prevent bypass, as well as the observed problem of the fragility of the filters. Putting a standard filter under pressure not only makes the seal more difficult to maintain, it also makes the filter element easier to break since the edges of the filter are weak points and therefore more prone to failure. Due to this, a ceramic disk was developed as the filter element for this testing.

This paper describes a study of the use of ceramic disk filters in an in-line pumping system to test their applicability in a field setting. The primary purpose of the study was to determine the effectiveness of ceramic disk filters at removing microbiological contamination and providing effective flowrates at different pressures. This testing was performed on disks with varying porosities and thicknesses to determine the optimal ceramic disk filter design.

METHODS

All filters used in this study were manufactured on campus at the Missouri University of Science and Technology using a synthetic clay body that was designed to closely mimic the clay used for CPF manufacturing at a factory near Antigua, Guatemala. The clay body used in this study was developed in an earlier process by Hubbel et al. (2015). The sawdust used in this study was collected from a local sawmill and sieved to remove particles that did not pass through a U.S. No. 10 sieve (2 millimeters [mm] slot size). The sawdust was combined with the clay in a 5:1, 6:1, and 7:1 clay to sawdust mass ratio, and then mixed with deionized water in a 1.8 kilograms (kg) to 1 L clay to water ratio with a mixer attached to a power drill. A total of 27 filters were constructed and tested during experimentation. This consisted of three filters of the same thickness and clay to sawdust ratio by mass to have triplicates for testing. Filters were constructed in an 8 inch (in.) by 8 in. block with thickness of 1.00 in., 1.25 in. and 1.50 in., and clay to sawdust ratio of

5:1, 6:1, and 7:1 by mass, respectively. The clay was pressed to the above thicknesses using a 12-ton press that allowed for pressure of 375 pounds per square inch (psi) for one minute to mimic the procedure developed by Oyandel-Craver and Smith (2007) and Ren and Smith (2013) at a slightly lower pressure. Before the pressed clay was fired, the clay mixture was allowed to dry for a minimum of 48 hours, and then was inserted in a soils oven set at 35 degrees Celsius (°C). The oven's temperature was gradually increased until the temperature reached 100 °C. The filters were allowed to stay at this temperature for a 24 hour period to allow for the filter block to completely dry. The filters in this study had no colloidal silver applied to them in an effort to simplify the focus of this study. Oyandel-Carver and Smith (2007) and Clark and Elmore (2011) have both found that the filters are effective at removing bacteria even with no silver present.

The clay mixture was fired in an electric kiln with the same firing schedule (temperatures and times) which slowly increased the temperature of the kiln to 993°C over the course of approximately 14 hours and then cooled back to room temperature. The kiln was propped open to allow for smoke from the sawdust burning out to escape and to allow for airflow through the kiln to maximize as much complete combustion as possible. After the clay mixture was fired, the resulting filter block was cut into a cylindrical disk with a diameter of approximately 6.63 in. using a high-pressure water jet at Missouri University of Science and Technology's Rock Mechanics laboratory to allow a consistent diameter and clean cut on the filter disk. The porosity of each disk was also determined using a modified Archimedes method by using the American Society for testing and Materials (ASTM) standard C373-88 (ASTM 2006). Prior to testing, filters were submerged in tap water for at least 24 hours to allow complete saturation. Tap water was then filtered through the filters and effluent water was tested for total chlorine with a Hach Total Chlorine field kit (CN-66T) to make sure that all chlorine was removed from the filter to not allow residual chlorine to affect microbiological removal efficacy. If a test showed presence of chlorine, a solution of thiosulfate was passed through the filters to remove any excess chlorine until chlorine was at levels not detectable by testing, approximately 0.02 milligram/liter (mg/L) of free chlorine. In addition, a presence/absence Colilert test analyzed effluent from the filters to show that no coliforms were present at the beginning of testing.

The design of the in-line testing apparatus is presented as Figure 1. This apparatus was constructed using a six in. inner diameter Schedule 40 polyvinyl chloride (PVC) pipe. Two separate pipe sections were cut to lengths of 9.75 in. and capped. The caps were threaded to allow for the apparatus to be connected to a pumping system. A rubber coupling was used to connect the two separate pipe sections together and the disk filter was placed in the middle of the rubber coupling and between the two PVC pipe pieces.

In order to make sure that filters were tightly sealed to the rubber coupling of the apparatus, a wooden disk of the same diameter of the filters was placed in the apparatus and tightened with hose clamps until no water flowed out of the filter. The hose clamps were tightened using a torque wrench to measure the required torque to prevent bypass. From this testing, it was determined that the required torque to prevent bypass was approximately 25 in-lb. All filters tested were tightened to this torque using the same torque wrench. The top pipe was glued to the rubber coupling to allow it to stay in place when under higher pressures. A pressure gauge was attached to the upper pipe to measure pressure coming into the disk filter. The arrows indicate the direction of flow of the system. A recycle line was attached to regulate pressure entering the system.

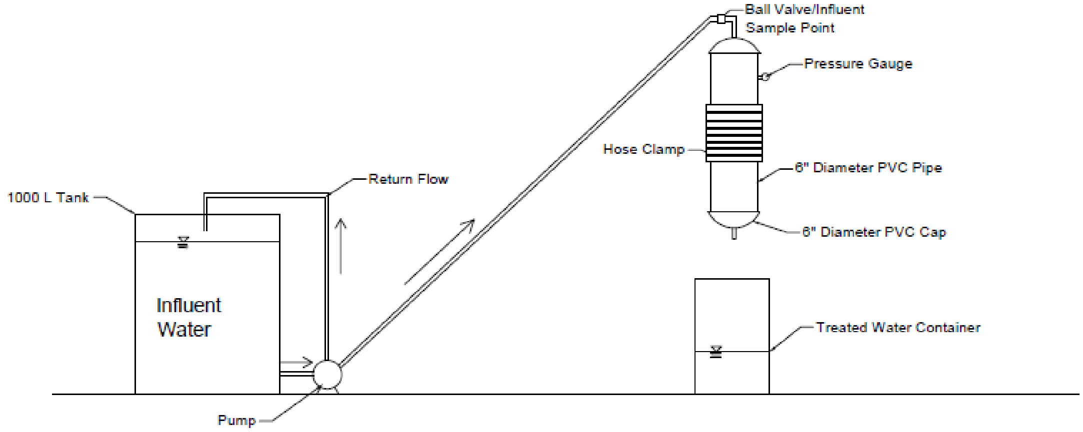


Figure 1: Laboratory setup

Tests were conducted using a 1 horsepower (hp) pump. The pump was connected to the filter apparatus using 1 in. diameter Schedule 40 PVC pipe. Flowrate tests were conducted at 60 minute increments. A ball valve was connected at the top of the pipe system to remove any air that would be in the system while testing and also to take influent samples from the apparatus.

Microbiological testing was conducted during one hour long tests at 5 psi first. Filters that proved to effectively remove bacteria under this pressure were tested at 10 psi on a different date during a different test. Challenge water was created using an approximately 3% mixture of raw influent wastewater from the local wastewater treatment plant and tap water to try and cause failure in the filters. By causing failure in the filters, a logarithmic reduction value (LRV) can be calculated for each filter. LRV is a typically used value to measure bacterial removal efficacy in point of use (POU) water treatment systems (Van Halem et al. 2007; Clark and Elmore 2011). Filters were allowed to filter water for an hour prior to testing. Microbiological testing was conducted using Colilert and the Colilert Quani-Tray 2000 to determine the presence of total coliforms and fecal coliforms in the filter effluent.

The non-parametric two-sample Wilcoxon rank sum test, also known as the Mann-Whitney test, was used to evaluate the relationships between flowrate, porosity, thickness, and clay to sawdust ratio to LRV. The Mann-Whitney test was performed since none of the data fit a normal distribution based on using Minitab's distribution analysis. A p-value that is less than one minus the confidence interval results in rejecting the null hypothesis. The confidence interval used for this testing was 95%, meaning a p-value of greater than 0.05 indicates a relationship between the two variables tested.

RESULTS AND DISCUSSION

The flowrate and LRV from each test for each individual filter were determined and a summary of these values for each filter based on thickness and clay to sawdust ratio by mass can be found in Table 1. LRV was calculated by taking the $\log_{10}$ of the influent bacteria concentration (most probable number [MPN]/100mL) divided by the $\log_{10}$ of the effluent bacteria concentration from the filter (MPN/100mL). According to WHO (2011), the performance target for a household water treatment system for bacteria must be an LRV of at least 2. Therefore, filters with LRV of 2 or greater were considered effective at removing bacteria. Filters with thicknesses of 1.25 in. appear to be the most effective at removing bacteria from influent water, especially in the filters with a 5:1 and 6:1 clay to sawdust ratio. Based on this statistical summary, more analysis was performed on the tested filters based on the different characteristics of the filters.

Table 1: Statistics of Filters Grouped by Thickness and Clay to Sawdust Ratio by Mass

	Mean		Standard Deviation		Coefficient of Variation	
	Q (L/hr)	LRV	Q (L/hr)	LRV	Q (L/hr)	LRV
5:1 1 in.	3.80	1.3	2.09	0.50	0.550	0.39
6:1 1 in.	2.44	2.1	1.27	0.48	0.521	0.23
7:1 1 in.	3.18	2.0	1.49	0.97	0.469	0.49
5:1 1.25 in.	4.06	2.0	2.50	0.98	0.615	0.48
6:1 1.25 in.	2.17	2.1	1.48	0.66	0.682	0.31
7:1 1.25 in.	7.59	1.3	9.13	0.44	1.20	0.34
5:1 1.5 in.	9.04	1.1	11.9	0.66	1.31	0.61
6:1 1.5 in.	2.85	1.4	0.82	0.56	0.287	0.42
7:1 1.5 in.	7.55	1.1	2.77	0.24	0.366	0.22

LRV as a Function of Porosity

A comparison was performed on the filters tested, comparing the effect that flowrate, porosity, and thickness have on the calculated LRV values. Figure 2 shows LRV plotted against the measured porosity for each filter for each filter thickness. From this graph, no correlation between bacterial removal and porosity was observed for any filter thickness. This phenomenon has been seen in other research conducted on CPFs by Soppe et al.

(2015) and White et al. (2015), both of which showed little correlation between porosity and LRV. Soppe et al. (2015) concluded that bacterial removal will only be compromised by the size of the burnout material, not necessarily the amount.

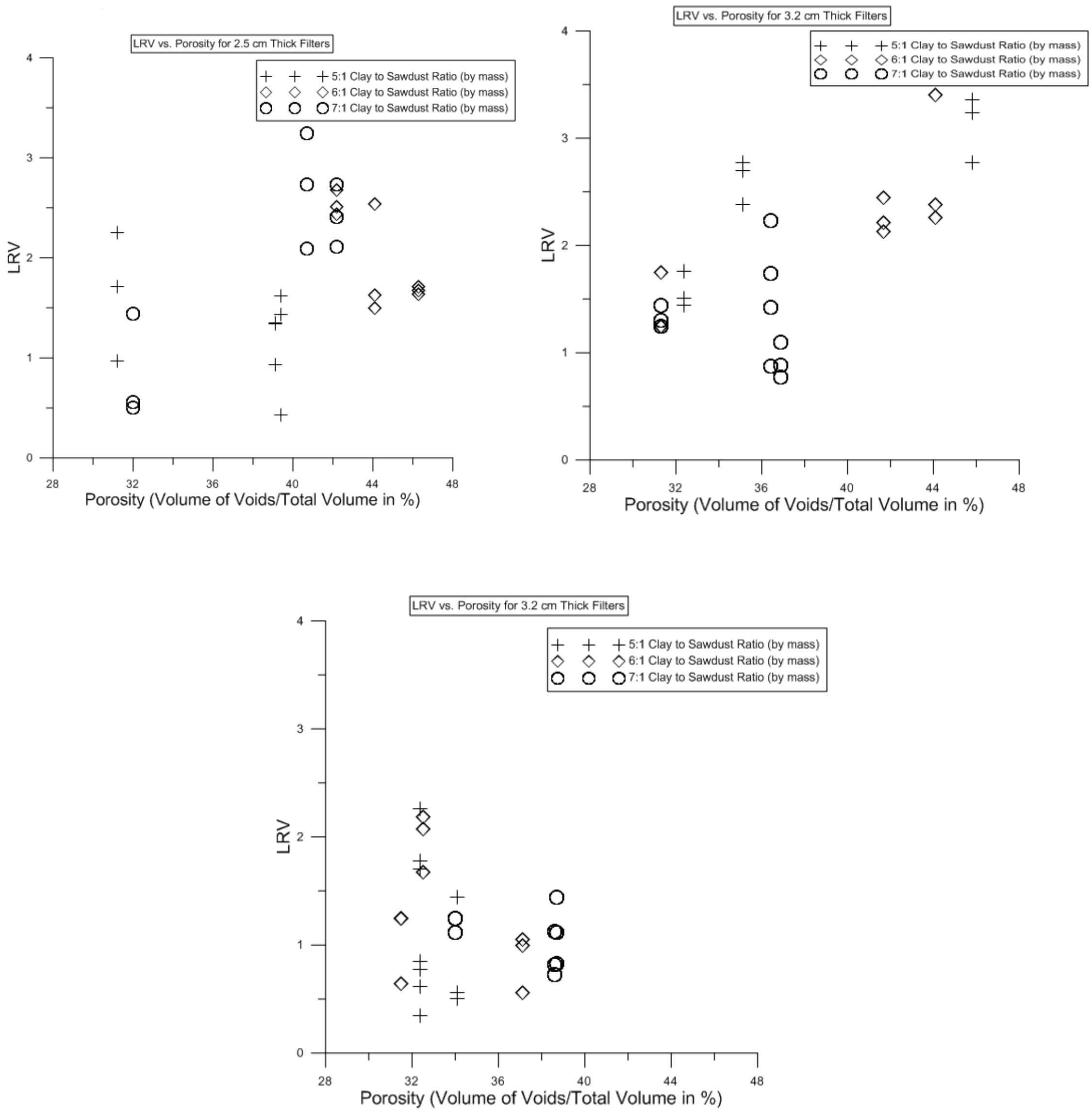


Figure 2: LRV vs. measured porosity for each thickness group

The Mann-Whitney test was performed to test if LRV was related to porosity, with the null hypothesis being that there was a relationship between the two variables.

The results from these tests showed a p-value of 0.000, meaning the null hypothesis is rejected and that there is no relationship between LRV and porosity for this testing.

LRV as a Function of Thickness

Figure 3 shows the relationship between LRV and thickness of the filter. From this graph it can be observed that the 1.25 in. thick filters performed the best in regards to LRV. The mean LRV of the filters with 1.25. thickness was the greatest of all filters tested, followed closely by the 1in. thick filters. From this figure, it can be seen that the range of logarithmic reduction values is quite large, with most ranges being 2 LRV or greater. It also shows that the 1.5 in. thick filters were the most ineffective filters used. This does not follow the hypothesis that the thicker the filters, the more effective the filters will be when put under pressure. This could be due to the higher flowrates that were seen in the filters with thicknesses of 1.5 in. Filters with 1.5 in. thicknesses also appeared to not fire completely through the filter. This caused filters to be more fragile and chip around the edges of the filter, reducing the effective thickness of the filters.

The Mann-Whitney test was performed on all filters used during testing, with the null hypothesis being that LRV were related to thickness. The p-value for the LRV to thickness test was 0.0031, rejecting the null hypothesis. This suggests that thickness of the filter is not related to LRV. This analysis may have been affected by the 1.50 in. filters since these filters showed higher flowrate and consistently low LRV.

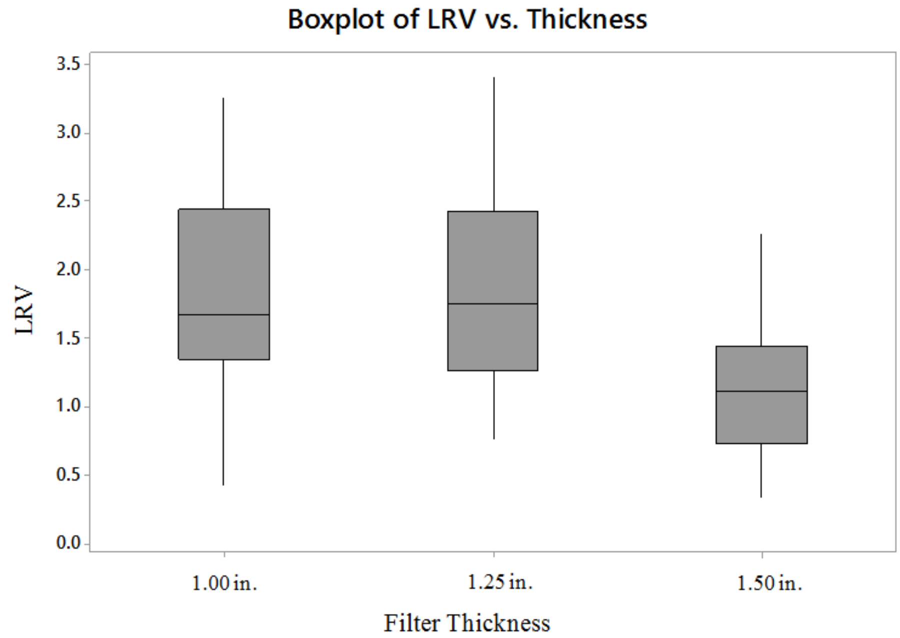


Figure 3: Boxplot of LRV vs. thickness based on clay to sawdust ratio by mass

LRV as a Function of Flowrate

Flowrate is a commonly used parameter for quality control in CPF factories to determine the effectiveness of filters to remove bacteria (Ceramics Manufacturing Group 2011). This would indicate that there would typically be a relationship between flowrate and LRV (namely, that filters with a higher flowrate would allow more bacteria to pass through the filter and vice versa), as shown by White et al. (2015). A scatter plot of the data in these tests did not show a direct relationship between flowrate and LRV, especially in the filters that were 1.00 in. thick. The data did show that any flowrate above 5 L/hr would unlikely give an LRV value of 2 or greater.

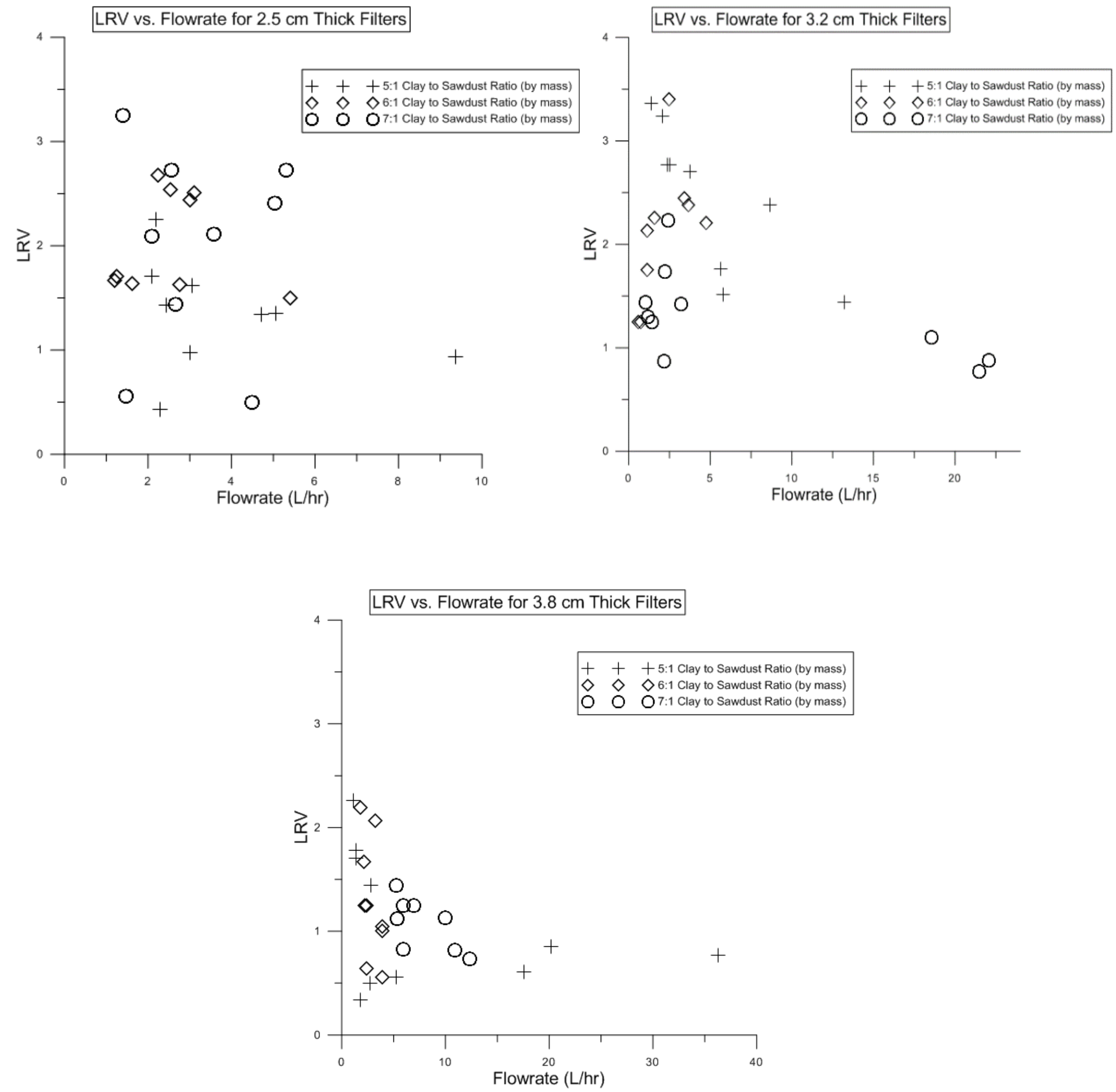


Figure 4: Flowrate vs. LRV based on filter thickness

The Mann-Whitney test was performed on each clay to sawdust ratio groups based on thicknesses, testing to see if flowrate and LRV were related. The null hypothesis was that flowrate and LRV were related. The results from this testing can be seen in Table 2. From this statistical test, it can be seen that the filters that showed a relationship between flowrate and LRV were the 5:1 1.25 in., 6:1 1 in., 6:1 1.25 in., and 7:1 1 in. These filters are filters that had a mean LRV value greater than or equal to 2. The other five filter groups did not show relationships between flowrate and LRV and also had mean LRV values of less than 2. Analysis of these five filter groups indicated the reasons why these filters did not show a relationship between LRV and flowrate included having filters with higher flowrates than the necessary 5 L/hr and that filters in these groups experienced more chipping than filters in the groups that did show a relationship. The 1.5 in. filters were especially ineffective due to most of the filters not completing firing in the kiln. This caused filters to be more fragile and this group had higher flowrates than most filter groups.

Table 2: Mann-Whitney Test Results for Flowrate and LRV for Each Filter Group

	p-value
5:1 1 in.	0.001
5:1 1.25 in.	0.204
5:1 1.5 in.	0.004
6:1 1 in.	0.453
6:1 1.25 in.	0.791
6:1 1.5 in.	0.001
7:1 1 in.	0.158
7:1 1.25 in.	0.014
7:1 1.5 in.	0.000

The Mann-Whitney test was also performed testing the relationship between LRV and porosity, thickness, and flowrate while taking out the 1.5 in. filters. From this testing, there was still no relationship found between LRV and porosity, thickness, and clay to sawdust ratio. There was no relationship found from literature review between these relationships as it does not appear to have been tested yet.

Testing Conducted at 10 psi

Table 2 shows data collected during testing at 10 psi. The letter designates the filter name used during testing. Not all filters that did not have a 2 LRV at 5 psi were tested at 10 psi since it was shown that if filters were not effective at 5 psi they would not be effective at 10 psi, as evident by filters 5:1 1 in. C, 6:1 1 in. C, and 7:1 1.25 in. B. Results indicate that the LRV is typically lower than at lower pressures, but acceptable LRVs can be obtained.

Table 3: Results of Tests Conducted at 70 kPa

	LRV 1	Q 1 (L/hr)	LRV 2	Q 2 (L/hr)
5:1 1 in. C	0.78	20.2		
5:1 1.25 in. B	1.9	6.74	2.7	4.98
5:1 1.25 in. C	1.9	4.25	2.6	3.61
6:1 1 in. A	1.9	8.98	1.4	7.63
6:1 1 in. C	1.01	7.88		
6:1 1.25 in. A	1.7	3.76	1.0	4.75
6:1 1.25 in. C	1.9	3.32	1.4	5.57
7:1 1 in. B	2.1	2.12	1.7	3.56
7:1 1 in. C	2.2	4.55	1.7	5.94
7:1 1.25 in. B	0.761	18.2		

CONCLUSIONS

The use of ceramic filter disks under pressure has a potential to be an efficient and economical way to filter water, especially in a pressurized system. The filters that showed the most consistent removal were filters with a thickness of 1.25 in. The porosity of the filter doesn't seem to be a primary factor in the LRV of filters. This indicates that porosity of the filters can be a value that can be as high as the manufacturer wants as long as it does not affect the strength of the filter. The maximum porosity of a filter that did not break that was completely fired during our testing was 46.5%. More testing would need to be done to determine the strength of the filter based on porosity.

One limiting factor during testing was the fragility of the filters when under pressure. When the filters are put into the apparatus, the hose clamps are tightened and the filter is compressed within the rubber coupling. During testing, filters were taken in and out of the apparatus multiple times. This led to filters chipping and breaking. If filters were left in place during operation, the filters should have less chipping then the filters tested during this study. This compression caused some of the filters to chip around the sides of the disk, making it much more difficult to keep the filter tightly sealed to the rubber coupling. Some of the filters also cracked when pressure was induced on them. Most filters remained working under 5 psi conditions although some cracked down the middle of the filter, making them ineffective. This phenomena was increased for filters that were put under a pressure of 10 psi. Filters should be completely fired and have complete combustion to increase strength in the filters.

Tests indicate that the filter disks were unable to effectively remove bacteria when flowrate through the filter was above 5 L/hr. Therefore, if a filter has a flowrate above 5 L/hr the filter will not effectively remove bacteria under pressures equal to or greater than 5 psi. This is greater than the recommended 1-2 L/hr, but Soppe et al. (2015) has stated that gravity fed filters could be effective at flowrates of up to 10 L/hr. Testing also indicated that LRV and flowrate are related, according from the results of the Mann-Whitney testing. Porosity and thickness do not seem to have a relationship to LRV from this testing. Further analysis should be performed to determine a better correlation between flowrate and LRV.

A long-term study on the use of filter disks under pressure would allow better characterization of the lifetime of the ceramic disk filter and the ability of the filter to consistently remove bacteria at acceptable flowrates. More tests also need to be performed to improve the filters ability to stay consistently tight to the rubber coupling. Thicker filter disks seemed to have a higher chance of being ineffective. This seems counter intuitive since the thicker filters should remove more bacteria than a thinner filter but our testing did not show this result. A complete firing of the filter also appears to be important in removal when filters are put under pressure. Filters with a zone that did not completely fired never reached LRVs of 2 during testing. A dye test could be performed on the filters to test if bypass was occurring. This would help validate if a filter was performing as intended and a more ideal filter design could be implemented for use in the field.

REFERENCES

Brown, J., Sobsey, M.D. (2010). "Microbiological effectiveness of locally produced ceramic filters for drinking water treatment in Cambodia." *J. Water Health,* **8**(1), 1-10.

Ceramics Manufacturing Working Group (2011). *Best Practice Recommendations for Local Manufacturing of Ceramic Pot Filters for Household Water Treatment* 1st edn, Center for Disease Control and Prevention, Atlanta, GA, USA.

Clark, K.N. and Elmore, A.C. (2011). "Bacteria removal effectiveness of ceramic pot filters not applied with colloidal silver." *Water Science and Technology: Water Supply*, **11**(6), 765- 772.

Clasen, T.F., Bastable, A. (2003). "Fecal contamination of drinking water during collection and household storage; the need to extend protection to the point of use." *J. Water Health*, **1**(3), 109-115.

Hunter, P.R. (2009). "Household water treatment in developing countries: comparing different intervention types using meta-regression." *Environmental Science and Technology*, **43**(23), 8991-8997.

Kalman, E.N., Oyanedel-Craver, V.A., and Smith, J.A. (2011). "Ceramic filters impregnated with silver nanoparticles for point-of-use water treatment in rural Guatemala." *Journal of Environmental Engineering,* **137**(6), 407-415.

Lantagne, D., Klarman, M., Mayer, A., Preston, K., Napotnik, J., and Jellison, K. (2010). "Effect of production variables on microbiological removal in locally-produced ceramic filters for household water treatment." *International Journal of Environmental Health Research*, **20**(3), 171-187.

Oyandel-Craver, V.A. and Smith, J.A. (2007). "Sustainable colloidal-silver-impregnated ceramic filter for point-of-use water treatment." *Environmental Science and Technology*, 42, 927-9330

Ren, D. and Smith, J.A. (2013). "Retention and transport of silver nanoparticles in a ceramic porous medium used for point-of-use water treatment." *Environmental Science and Technology*, 47, 3825-3832.

Soppe, A.I.A., Heijman, S.G.J., Gensburger, I., Shantz, A., van Halem, D., Kroesbergen, J., Wubbles, G.H., and Smeets, P.W.M.H. (2015). "Critical parameters in the production of ceramic pot filters for household water treatment in developing nations." *Journal of Water and Health*, **13**(2), 587-599.

American Society for Testing and Materials (ASTM). *Standard Test Method for Water Adsorption, Bulk Density, Apparent Porosity, and Apparent Specific Gravity of Fired Whiteware Products* 2006, C373-88,, West Conshohocken, PA, USA.

United Nations Children's Fund. (2008). *UNICEF Handbook on Water Quality*, UNICEF, New York, NY, USA

van Halem, D., Heijman, S.G.J., Soppe, A.I.A., van Dijk, J.C. and Amy, G.L. (2007) Ceramic silver-impregnated pot filters for household drinking water treatment in developing countries: material characterization and performance study. *Water Science and Technology: Water Supply*, **7**(5-6), 9-17.

White, E. P., Langenfeld, J. K., Bradford, E. L., Haywood, H. G., Salvinelli, C., and Elmore, A. C. (2015). "Assessment of Flow Rate as a Quality Control Test for Ceramic Pot Filters." *World Environmental and Water Resources Congress 2015*, 1378–1387.

World Health Organization. (2011). "Evaluating household water treatment options: health-based targets and microbiological performance specifications." *World Health Organization Water Sanitation Health*.

World Health Organization and United Nations Children's Fund. (2014). *Progress on sanitation and drinking-water – 2014 update*. *Joint Monitoring Programme for Water Supply and Sanitation*, WHO, Geneva, Switzerland.

SECTION

4. DISCUSSION

4.1 LABORATORY FINDINGS

Appendix A shows pictures of all filters used in this testing and the associated flowrate and LRV with each test performed and shows why a filter failed if it did break during testing. Plots comparing flowrates, LRV, thicknesses, and porosity were constructed to perform an analysis on the filter disks produced. Raw data used in these plots collected during testing can be found in Appendices at the end of this document. Appendix B shows LRV vs. porosity grouped by thicknesses of 1, 1.25, and 1.5 in. Appendix C shows LRV vs. thickness grouped by clay to sawdust ratio by mass and Appendix D shows LRV vs. flowrate grouped by filter thickness. Using all of these plots, there appeared to be very little correlation between porosity and LRV based on the thicknesses of the filters and very little correlation between clay to sawdust ratio and LRV based on thickness. The best correlation appeared to be between flowrate and LRV, particularly in filters with thicknesses of 1.25 in. and 1.5 in. There appears to be a general trend of the lower the flowrate, the more effective at removing bacteria the filter is. This was not true for all filters though and could be caused by ineffective sealing in the filter. Filters with a flowrate higher than 5 L/hr will be ineffective at removing bacteria under conditions were the filter is put under pressure.

Filters that were effective at 5 psi were tested at 10 psi. Three filters (5:1 1 in. C, 6:1 1 in. C, and 7:1 1.25 in. B) were ineffective at 5 psi and also at 10 psi. Some of the filters tested did break when subjected to 10 psi of pressure. Filters seemed to be inconsistent when tested at this pressure as well. More testing would need to be conducted at both 5 and 10 psi to develop a better relationship between the variables, although filters with a 1.25 in. thickness and sawdust to clay ratio of 6:1 appears to be the most effective for removing bacteria under pressure in an in-line pumping system.

4.2 EFFECT OF INCOMPLETE BURNOUT ON FILTER EFFECTIVENESS

Thicker filters, especially those with a thickness of 1.5 in., had a noticeable layer of material near the middle of the disk that did not appear to effectively fire in the kiln do to incomplete oxidation. To better understand the effect this layer could have on bacterial effectiveness, disks with this layer were cut using a wet diamond saws into thin slices. These thin slices were then placed under a Leica S8APO digital stereoscope. Images were taken of the zone that was completely fired and the zone that did not completely fire. These pictures can be seen in Figure 4.1. Due to the way the filters were cut, it could be hard to differentiate between pores and grain pull out from the saw used to cut. The section in between the two black lines is the unfired zone and the sections above the top black line and below the black bottom line are completely fired zones. Black zones were considered pores in the filter. It is noticeable that filters that completely fired (top images) have more void areas than those that did not fire completely (bottom image)The images were processed and the area of the voids in each zone where measured and compared to the total area of the zone. Table 4.1 shows results of the processed images. These results showed that the zone that completely fired had an average of 19.5% more area of voids compared to total area than the zone that did not completely fire. This change in porosity could contribute to some flow bypassing the filter and water not going through the entire filter. This zone also seemed to cause the filters to be more fragile when tested. Filters with a zone that did not completely fire tended to break along the plane where the unfired zone met the fired zone.

Table 4.1: Comparison of Filters with Complete and Incomplete Firing

	Area of Voids/Total Area (%)		
	Complete Fire	Incomplete Fire	Difference (%)
Filter Section 1	3.24	2.84	12.3%
Filter Section 2	1.39	1.02	26.6%
		Average	19.5%

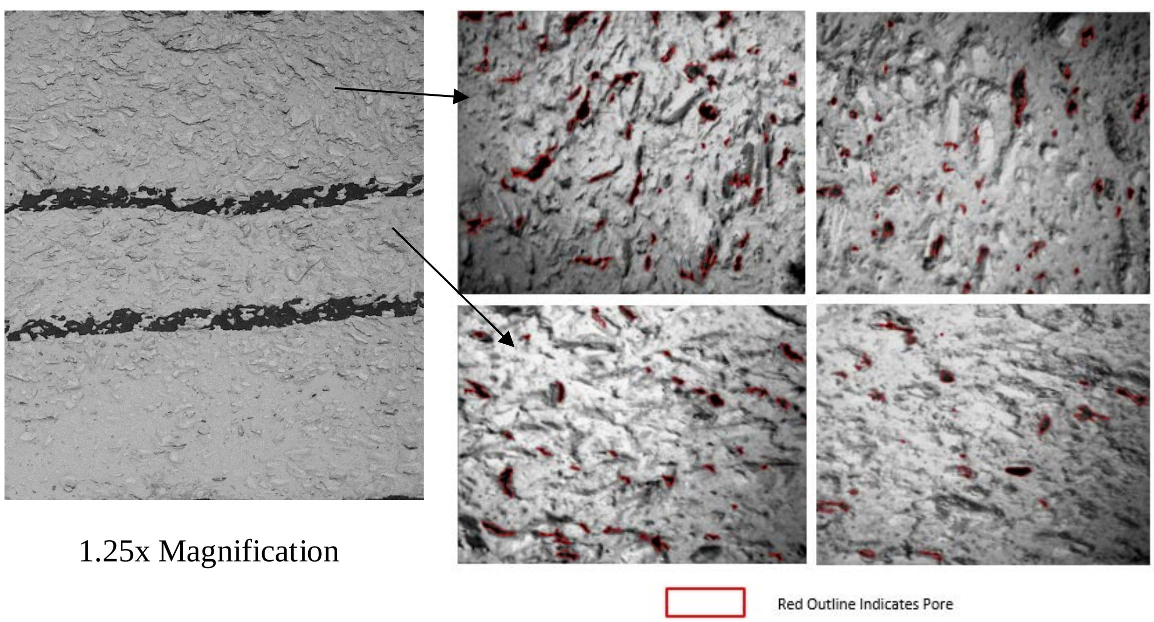


Figure 4.1: Complete fired section (top left and right) compared to incomplete fired section (bottom left and right)

For filters to be most effective in a pressurized system, the disk need to be completely fired. For this to occur, especially in thicker filters, the firing schedule of the kiln would need to be adjusted. The filters with thicknesses of 3.8 cm seem to not be reaching a high enough temperature to completely fire and burnout all material. Therefore, the firing schedule should be adjusted to hold temperatures longer between 300-600 °C to give the filter disk a better opportunity to completely fire in the middle.

5 CONCLUSIONS

5.1 CONSLUSIONS OF LABORATORY TESTING

The use of filter disk in a pumping or elevated tank system could be an effective and economical way to treat microbiological contamination in a water supply. Our results have shown that ceramic disk filters can treat water to the WHO recommended level for water treatment at 5 psi and possibly 10 psi. The system studied here would be more representative of a system that uses an elevated tank and a gravity fed water distribution system as the pressure put on the filter was a constant. Filters with a thickness of 1.25 in. appear to be the most effective. Porosity in the filter does not seem to affect the removal efficiency but can greatly affect the strength of the filter. This study showed that filters with a 6:1 clay to sawdust ratio by mass were the most effective when put under pressure as well. One of the greatest limiting factors of using these filters under pressure continues to be the strength of the filter and keeping a tight seal between the filter and the housing apparatus. This study also showed the importance of completely firing a filter for it to be effective when testing under pressure. Any filters that showed incomplete firing were not effective at removing total and fecal coliform.

5.2 FUTURE WORK

More laboratory studies need to be implemented before field test could be performed on these filters. One study to help determine if bypass is occurring in the filters would be the use of a dye test. Dye testing on these filter disks would help to determine if there is any bypass in the filter. Another study could be conducted to try and improve the strength of the filter. One of the biggest limitations in this study was the chipping or breaking of the filter during testing under pressure. These filters when compressed with the hose clamps caused the filters to chip or break, especially when filters were taken in and out of the apparatus. Filters that were allowed to stay in the apparatus to filter water should not chip or break as easily. Also, if something could be added to the filter mixture to improve the strength of the filter, it would be very helpful when putting filters under pressure. Lastly, filters need to be tested under conditions that are conductive of a hand pump. Hand pumps are typically found in developing countries to pump water out of wells. These hand pumps will send pulses of water through the filter, instead of a constant pressure the filters were subjected to during this testing. A study into determining how this changes the filters effectiveness and flowrate should be conducted since hand pumps are very prevalent

APPENDIX A.

IMAGES OF FILTERS USED WITH RESULTS OF TESTING

Filter 5A 1 in.

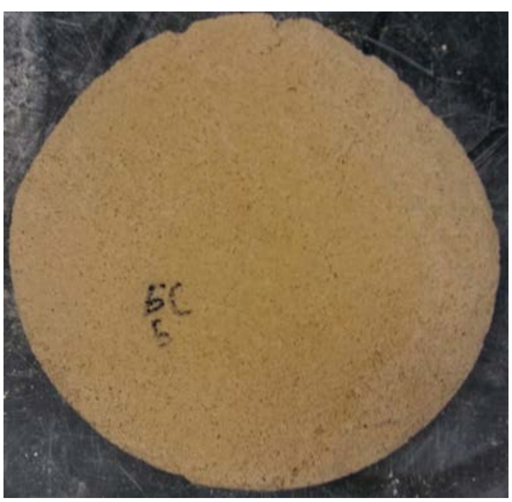
Test	Flowrate (L/hr)	LRV
1	3.06	1.62
2	2.44	1.43
3	2.30	0.43

Filter 5B 1 in.

Test	Flowrate (L/hr)	LRV
1	3.00	0.97
2	2.09	1.71
3	2.18	2.25

Broken during 10 psi testing

Filter 5C 1 in.



Test	Flowrate (L/hr)	LRV
1	9.38	0.93
2	4.72	1.34
3	5.05	1.35

Filter 5A 1.25 in.

Test	Flowrate (L/hr)	LRV
1	8.68	2.38
2	3.75	2.70
3	2.38	2.77

Filter 5B 1.25 in.

Test	Flowrate (L/hr)	LRV
1	13.21	1.44
2	5.63	1.76
3	5.81	1.51

Broken when extracting from apparatus during 3rd test

Filter 5C 1.25 in.

Test	Flowrate (L/hr)	LRV
1	2.51	2.77
2	2.10	3.24
3	1.39	3.36

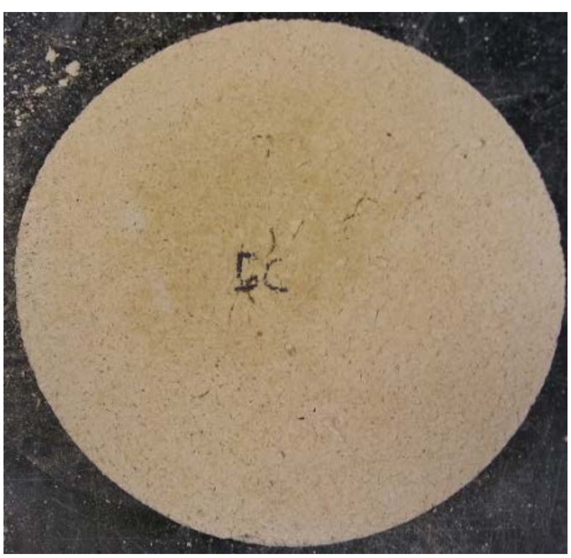
Filter 5A 1.5 in.

Test	Flowrate (L/hr)	LRV
1	1.38	1.78
2	1.10	2.26
3	1.80	0.34
4	1.37	1.70

Broken during 4th test, not completely fired

Filter 5B 1.5 in.

Test	Flowrate (L/hr)	LRV
1	36.3	0.77
2	20.2	0.85
3	17.56	0.61



Filter 5C 1.5 in.

Test	Flowrate (L/hr)	LRV
1	2.79	1.44
2	2.70	0.50
3	5.25	0.56

Filter 6A 1 in.

Test	Flowrate (L/hr)	LRV
1	2.23	2.68
2	3.10	2.51
3	3.01	2.44

Filter 6B 1 in.

Test	Flowrate (L/hr)	LRV
1	1.20	1.67
2	1.63	1.64
3	1.25	1.71

Broken when going to 10 psi

Filter 6C 1 in.

Test	Flowrate (L/hr)	LRV
1	2.75	1.63
2	5.40	1.50
3	2.53	2.54

Filter 6A 1.25 in.

Test	Flowrate (L/hr)	LRV
1	3.41	2.45
2	4.75	2.21
3	1.13	2.13

Broken while testing at 10 psi

Filter 6B 1.25 in.

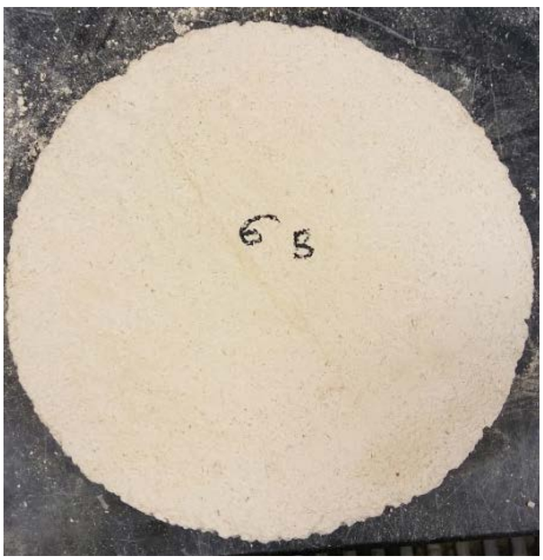
Test	Flowrate (L/hr)	LRV
1	0.76	1.25
2	0.61	1.25
3	1.12	1.75

Filter 6C 1.25 in.

Test	Flowrate (L/hr)	LRV
1	2.48	3.40
2	3.67	2.38
3	1.57	2.26

Filter 6A 1.5 in.

Test	Flowrate (L/hr)	LRV
1	3.24	2.07
2	1.80	2.19
3	2.15	1.67



Filter 6B 1.5 in.

Test	Flowrate (L/hr)	LRV
1	2.20	1.25
2	2.40	1.25
3	2.38	0.64

Filter 6C 1.5 in.

Test	Flowrate (L/hr)	LRV
1	3.94	0.56
2	3.90	1.00
3	3.88	1.05

Filter 7A 1 in.

Test	Flowrate (L/hr)	LRV
1	2.65	1.44
2	4.50	0.50
3	1.48	0.56

Filter 7B 1 in.

Test	Flowrate (L/hr)	LRV
1	2.55	2.73
2	2.10	2.09
3	1.39	3.25

Filter 7C 1 in.

Test	Flowrate (L/hr)	LRV
1	5.32	2.73
2	5.03	2.41
3	3.58	2.11

Filter 7A 1.25 in.

Test	Flowrate (L/hr)	LRV
1	1.45	1.25
2	1.05	1.44
3	1.21	1.30

Filter 7B 1.25 in.

Test	Flowrate (L/hr)	LRV
1	2.20	0.87
2	3.22	1.42
3	2.41	2.23
4	2.21	1.74

Filter 7C 1.25 in.

Test	Flowrate (L/hr)	LRV
1	22.10	0.88
2	21.50	0.77
3	18.56	1.1

Filter 7A 1.5 in.

Test	Flowrate (L/hr)	LRV
1	10.00	1.13
2	12.34	0.73
3	10.92	0.82

7B 1.5 in.

Test	Flowrate (L/hr)	LRV
1	5.25	1.44
2	5.94	0.83
3	5.32	1.12

Sheared during third test

7C 1.5 in.

Test	Flowrate (L/hr)	LRV
1	6.95	1.25
2	5.91	1.25
3	5.32	1.12

APPENDIX B.

LRV VS. POROSITY OF FILTERS BASED ON THICKNESS

LRV vs. Porosity of Filters Based Grouped by Thicknesses (in inches)

LRV 1.0	Porosity 1.0	LRV 1.25	Porosity 1.25	LRV 1.5	Porosity 1.5
1.15	39.4%	1.15	42.0%	1.78	32.4%
0.97	31.2%	0.97	45.8%	1.44	34.1%
0.93	39.1%	0.93	36.3%	2.07	32.5%
2.68	42.2%	2.45	41.7%	1.25	31.5%
1.67	46.3%	1.25	31.3%	0.56	37.1%
1.63	44.1%	3.40	35.1%	1.13	38.6%
1.44	32.0%	1.25	32.4%	1.44	38.7%
2.73	40.7%	0.87	36.4%	1.25	34.0%
2.73	42.2%	0.88	36.9%	2.26	32.4%
1.43	39.4%	1.76	42.0%	0.85	46.5%
1.71	31.2%	2.70	45.8%	0.50	34.1%
1.34	39.1%	3.24	36.3%	2.19	32.5%
2.51	42.2%	2.21	41.7%	1.25	31.5%
1.64	46.3%	1.25	31.3%	1.00	37.1%
1.50	44.1%	2.38	35.1%	0.73	38.6%
0.50	32.0%	1.44	32.4%	0.83	38.7%
2.09	40.7%	1.42	36.4%	1.25	34.0%
2.41	42.2%	0.77	36.9%	0.34	32.4%
0.49	39.4%	1.51	42.0%	0.61	46.5%
2.25	31.2%	2.77	45.8%	0.56	34.1%
1.35	39.1%	3.36	36.3%	1.67	32.5%
2.44	42.2%	2.13	41.7%	0.64	31.5%
1.71	46.3%	1.75	31.3%	1.05	37.1%
2.54	44.1%	2.26	35.1%	0.82	38.6%
0.56	32.0%	1.30	32.4%	1.12	38.7%
3.25	40.7%	2.23	36.4%	1.12	34.0%
2.11	42.2%	1.1	36.9%	1.7	32.4%
2.5	46.3%	1.74	36.4%	1.77	31.5%

APPENDIX C.

LRV VS. THICKNESS RAW DATA

LRV vs. Thickness (in inches) Raw Data

	LRV 1 5:1	T1 5:1	LRV 1 6:1	T1 6:1	LRV 1 7:1	T1 7:1	LRV 1.25 5:1	T1.25 5:1	LRV 1.25 6:1	T1.25 6:1	LRV 1.25 7:1	T1.25 7:1	LRV 1.5 5:1	T1.5 5:1	LRV 1.5 6:1	T1.5 6:1	LRV 1.5 7:1	T1.5 7:1
	1.15	1.00	2.68	1.00	1.44	1.00	1.15	1.25	2.45	1.25	1.25	1.25	1.78	1.50	2.07	1.50	1.13	1.50
	0.97	1.00	1.67	1.00	2.73	1.00	0.97	1.25	1.25	1.25	0.87	1.25	0.77	1.50	1.25	1.50	1.44	1.50
	0.93	1.00	1.63	1.00	2.73	1.00	0.93	1.25	3.40	1.25	0.88	1.25	1.44	1.50	0.56	1.50	1.25	1.50
	1.43	1.00	2.51	1.00	0.50	1.00	1.76	1.25	2.21	1.25	1.44	1.25	2.26	1.50	2.19	1.50	0.73	1.50
	1.71	1.00	1.64	1.00	2.09	1.00	2.70	1.25	1.25	1.25	1.42	1.25	0.85	1.50	1.25	1.50	0.83	1.50
	1.34	1.00	1.50	1.00	2.41	1.00	3.24	1.25	2.38	1.25	0.77	1.25	0.50	1.50	1.00	1.50	1.25	1.50
	0.49	1.00	2.44	1.00	0.56	1.00	1.51	1.25	2.13	1.25	1.30	1.25	0.34	1.50	1.67	1.50	0.82	1.50
	2.25	1.00	1.71	1.00	3.25	1.00	2.77	1.25	1.75	1.25	2.23	1.25	0.61	1.50	0.64	1.50	1.12	1.50
	1.35	1.00	2.54	1.00	2.11	1.00	3.36	1.25	2.26	1.25	1.1	1.25	0.56	1.50	1.05	1.50	1.12	1.50
			2.5	1.00							1.74	1.25	1.7	1.50	1.77	1.50		
Average	1.29	1.00	2.03	1.00	1.98	1.00	2.04	1.25	2.12	1.25	1.25	1.25	1.01	1.50	1.30	1.50	1.08	1.50

APPENDIX D.

LRV VS. FLOWRATE RAW DATA BASED ON THICKNESS

LRV vs. Flowrate Data Grouped by Thickness (in inches)

LRV 1.0	Q 1.0	LRV 1.25	Q 1.25	LRV 1.5	Q 1.5
1.15	3.06	1.15	3.06	1.78	1.38
0.97	3.00	0.97	3.00	1.44	2.79
0.93	9.38	0.93	9.38	2.07	3.24
2.68	2.23	2.45	3.41	1.25	2.20
1.67	1.20	1.25	0.76	0.56	3.94
1.63	2.75	3.40	2.48	1.13	10.00
1.44	2.65	1.25	1.45	1.44	5.25
2.73	2.55	0.87	2.20	1.25	6.95
2.73	5.32	0.88	22.10	2.26	1.10
1.43	2.44	1.76	5.63	0.85	20.20
1.71	2.09	2.70	3.75	0.50	2.70
1.34	4.72	3.24	2.10	2.19	1.80
2.51	3.10	2.21	4.75	1.25	2.40
1.64	1.63	1.25	0.61	1.00	3.90
1.50	5.40	2.38	3.67	0.73	12.34
0.50	4.50	1.44	1.05	0.83	5.94
2.09	2.10	1.42	3.22	1.25	5.91
2.41	5.03	0.77	21.50	0.34	1.8
0.49	2.3	1.51	5.81	0.61	17.56
2.25	2.18	2.77	2.38	0.56	5.25
1.35	5.05	3.36	1.39	1.67	2.15
2.44	3.01	2.13	1.13	0.64	2.38
1.71	1.25	1.75	1.12	1.05	3.88
2.54	2.53	2.26	1.57	0.82	10.92
0.56	1.48	1.30	1.21	1.12	5.32
3.25	1.39	2.23	2.41	1.12	5.32
2.11	3.58	1.1	18.56	1.7	1.37
2.5	1.32	1.74	2.21	1.77	2.6

APPENDIX E.

STATISTICAL ANALYSIS USING MINITAB RESULTS

Mann-Whitney Test and CI: Q 5:1 1, LRV 5:1 1

	N	Median
Q 5:1 1	9	3.000
LRV 5:1 1	9	1.350

Point estimate for η1 - η2 is 1.650
95.8 Percent CI for η1 - η2 is (0.820,3.620)
W = 124.0
Test of η1 = η2 vs η1 ≠ η2 is significant at 0.0008

Mann-Whitney Test and CI: Q 5:1 1.25, LRV 5:1 1.25

	N	Median
Q 5:1 1.25	9	3.750
LRV 5:1 1.25	9	2.700

Point estimate for η1 - η2 is 1.070
95.8 Percent CI for η1 - η2 is (-0.368,5.320)
W = 100.5
Test of η1 = η2 vs η1 ≠ η2 is significant at 0.2004
The test is significant at 0.1999 (adjusted for ties)

Mann-Whitney Test and CI: Q 5:1 1.5, LRV 5:1 1.5

	N	Median
Q 5:1 1.5	9	2.79
LRV 5:1 1.5	9	0.77

Point estimate for η1 - η2 is 2.20
95.8 Percent CI for η1 - η2 is (0.61,17.94)
W = 119.0
Test of η1 = η2 vs η1 ≠ η2 is significant at 0.0036

Mann-Whitney Test and CI: Q 6:1 1, LRV 6:1 1

	N	Median
Q 6:1 1	9	2.530
LRV 6:1 1	9	1.710

Point estimate for η1 - η2 is 0.420
95.8 Percent CI for η1 - η2 is (-0.430,1.340)
W = 94.5
Test of η1 = η2 vs η1 ≠ η2 is significant at 0.4529
The test is significant at 0.4527 (adjusted for ties)

Mann-Whitney Test and CI: Q 6:1 1.25, LRV 6:1 1.25

	N	Median

```
Q 6:1 1.25    9   1.570
LRV 6:1 1.25  9   2.210


Point estimate for η1 - η2 is -0.130
95.8 Percent CI for η1 - η2 is (-1.261,1.350)
W = 82.0
Test of η1 = η2 vs η1 ≠ η2 is significant at 0.7911
The test is significant at 0.7910 (adjusted for ties)
```

Mann-Whitney Test and CI: Q 6:1 1.5, LRV 6:1 1.5

```
             N  Median
Q 6:1 1.5    9   2.400
LRV 6:1 1.5  9   1.250


Point estimate for η1 - η2 is 1.560
95.8 Percent CI for η1 - η2 is (0.750,2.630)
W = 123.0
Test of η1 = η2 vs η1 ≠ η2 is significant at 0.0011
The test is significant at 0.0011 (adjusted for ties)
```

Mann-Whitney Test and CI: Q 7:1 1, LRV 7:1 1

```
           N  Median
Q 7:1 1    9   2.650
LRV 7:1 1  9   2.110


Point estimate for η1 - η2 is 1.110
95.8 Percent CI for η1 - η2 is (-0.310,2.589)
W = 102.0
Test of η1 = η2 vs η1 ≠ η2 is significant at 0.1577
The test is significant at 0.1575 (adjusted for ties)
```

Mann-Whitney Test and CI: Q 7:1 1.25, LRV 7:1 1.25

```
               N  Median
Q 7:1 1.25    10    2.31
LRV 7:1 1.25  10    1.27


Point estimate for η1 - η2 is 1.14
95.5 Percent CI for η1 - η2 is (0.18,17.46)
W = 138.0
Test of η1 = η2 vs η1 ≠ η2 is significant at 0.0140
```

Mann-Whitney Test and CI: Q 7:1 1.5, LRV 7:1 1.5

```
             N  Median
Q 7:1 1.5    9   5.940
LRV 7:1 1.5  9   1.120
```

```
Point estimate for η1 - η2 is 5.090
95.8 Percent CI for η1 - η2 is (4.201,9.479)
W = 126.0
Test of η1 = η2 vs η1 ≠ η2 is significant at 0.0004
The test is significant at 0.0004 (adjusted for ties)
```

Mann-Whitney Test and CI: LRV, t

```
      N  Median
LRV  82  1.4400
t    82  1.2500


Point estimate for η1 - η2 is 0.2500
95.0 Percent CI for η1 - η2 is (0.1201,0.4399)
W = 7655.0
Test of η1 = η2 vs η1 ≠ η2 is significant at 0.0034
The test is significant at 0.0031 (adjusted for ties)
```

Mann-Whitney Test and CI: LRV, Ratio

```
        N  Median
LRV    82  1.4400
Ratio  82  6.0000


Point estimate for η1 - η2 is -4.4400
95.0 Percent CI for η1 - η2 is (-4.6500,-4.2300)
W = 3403.0
Test of η1 = η2 vs η1 ≠ η2 is significant at 0.0000
The test is significant at 0.0000 (adjusted for ties)
```

Mann-Whitney Test and CI: LRV, Porosity

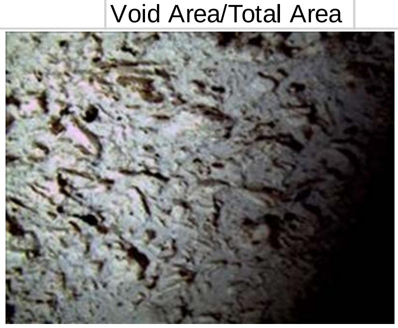
```
           N  Median
LRV       82   1.440
Porosity  82  36.900


Point estimate for η1 - η2 is -35.200
95.0 Percent CI for η1 - η2 is (-36.589,-33.671)
W = 3403.0
Test of η1 = η2 vs η1 ≠ η2 is significant at 0.0000
The test is significant at 0.0000 (adjusted for ties)
```

APPENDIX F.

FILTERS WITH COMPLETE AND INCOMPLETE BURNOUT MEASUREMENTS

Filter Section with Complete Burnout 1

Measurement #	Width (μm)	Height (μm)	Area (μm²)	Perimeter (μm)
Void 1	480.	524.8	129372.105	2291.021
Void 2	864.	390.4	151818.143	2318.146
Void 3	774.4	1139.2	283013.218	3876.924
Void 4	915.2	371.199	92037.068	2291.642
Void 5	435.2	230.4	57958.425	1240.566
Void 6	614.4	780.8	200355.962	3268.967
Void 7	275.2	710.4	127344.575	2315.587
Void 8	563.2	416.	89641.005	2050.863
Void 9	300.799	217.6	34918.392	941.031
Void 10	582.4	1132.8	141517.001	4875.831
Void 11	275.2	633.6	42434.539	1603.079
Void 12	428.8	787.2	100597.727	2423.546
Void 13	236.8	217.6	30617.677	888.753
Void 14	460.801	275.2	35041.326	1215.572
Void 15	454.4	294.4	46202.914	1585.927
Void 16	249.6	166.4	23510.992	730.051
Void 17	486.4	313.6	48291.833	1412.965
Void 18	256.	249.6	28160.015	811.762
Void 19	217.6	172.8	19230.713	717.724
Void 20	339.2	300.8	40959.987	1063.803
Void 21	364.8	704.	98959.362	2228.235
Void 22	416.	198.401	49254.433	1038.859
Void 23	300.799	128.	22118.436	764.315
Void 24	480.	300.8	33505.276	2040.898
Void 25	684.8	480.	181022.721	2799.582
Void 26	607.999	505.6	142745.612	2129.114
Void 27	121.6	83.2	5181.438	330.141
Void 28	121.6	64.	5201.947	352.967
Void 29	217.6	96.	14110.69	573.923
Void 30	428.8	140.8	34406.414	1081.047
Void 31	1644.8	627.201	118681.574	6966.997
Void 32	556.8	492.8	44728.311	3418.434
Void 33	473.6	550.4	124211.109	2220.784
Void 34	352.	268.8	39895.014	1179.249
Void 35	288.	268.8	31334.414	961.238
Void 36	345.6	236.8	28671.929	1039.425
Total Area	8520.814	9779.376	83328241.288	36600.379
		Void Area/Total Area	3.24%	

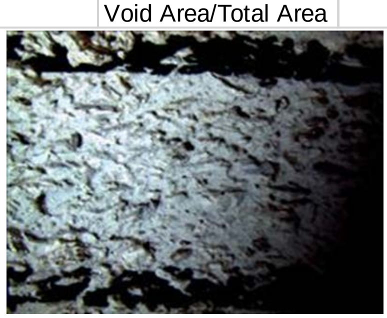


Filter Section with Complete Burnout 2

Measurement #	Width (μm)	Height (μm)	Area (μm²)	Perimeter (μm)
Void 1	435.2	281.6	68505.686	2285.73
Void 2	377.6	736.	134062.02	2856.023
Void 3	204.8	140.8	20193.234	594.981
Void 4	204.801	243.2	26705.989	1141.56
Void 5	300.8	467.2	27914.271	1871.46
Void 6	339.199	358.399	65679.355	1497.341
Void 7	294.4	172.8	31539.197	810.191
Void 8	371.2	288.	45834.251	1299.222
Void 9	377.6	281.6	60088.32	1299.133
Void 10	185.6	185.6	19435.512	603.028
Void 11	185.6	121.6	6860.767	718.488
Void 12	147.2	179.2	12308.476	551.581
Void 13	140.8	76.8	6717.469	362.53
Void 14	902.4	595.2	132239.356	3325.885
Void 15	665.6	326.4	88657.86	2017.355
Void 16	371.2	275.2	32460.818	1196.851
Void 17	384.	179.2	32194.564	973.864
Void 18	96.	44.8	1556.462	252.74
Void 19	51.2	147.2	4628.505	347.804
Void 20	256.	121.6	15421.412	653.193
Void 21	172.8	179.2	16076.808	608.862
Void 22	230.4	89.6	9175.029	578.496
Void 23	147.2	121.6	11960.293	479.08
Void 24	102.4	83.2	5468.147	298.786
Void 25	281.599	159.999	21934.106	776.154
Void 26	204.801	140.8	18432.045	586.394
Void 27	288.	364.8	40673.234	1606.237
Void 28	128.	377.6	12410.867	1082.258
Void 29	57.6	224.	5693.431	541.553
Void 30	249.6	211.2	26234.9	852.059
Void 31	710.4	448.001	127447.23	2725.631
Void 32	185.599	172.8	17674.218	570.508
Void 33	211.2	134.4	9011.239	722.693
Total Area	8758.92	9456.232	82826375.602	36430.303
		Void Area/Total Area	1.39%	

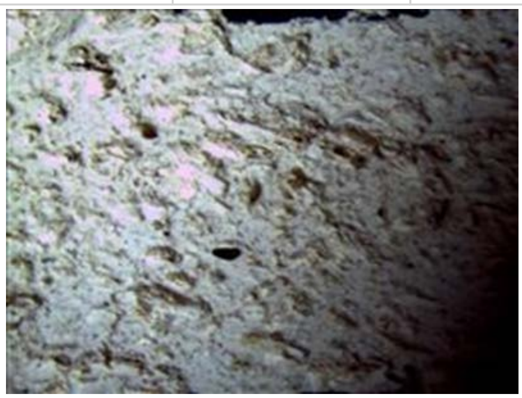
Filter Section with Incomplete Burnout

Measurement #	Width (µm)	Height (µm)	Area (µm²)	Perimeter (µm)
Void 1	352.001	268.8	20582.447	1873.014
Void 2	819.201	550.4	62013.425	5075.163
Void 3	505.6	364.8	91095.086	1706.676
Void 4	300.8	704.	89067.451	2199.616
Void 5	326.4	217.6	24309.678	1322.013
Void 6	128.	435.2	30658.663	1092.064
Void 7	409.6	390.4	42393.631	1420.852
Void 8	1075.2	556.8	74158.096	2878.633
Void 9	550.4	448.	90398.774	1890.022
Void 10	352.	300.8	65966.036	1117.015
Void 11	281.6	128.	19619.805	763.423
Void 12	243.199	134.4	16261.146	721.705
Void 13	473.6	390.4	67256.287	1702.203
Void 14	364.8	198.4	26521.566	982.777
Void 15	281.601	256.	32501.785	954.969
Void 16	121.6	140.8	9420.799	439.753
Void 17	288.	275.2	32870.426	1230.049
Void 18	243.2	147.2	19066.863	639.79
Void 19	556.8	217.6	45219.849	1812.802
Void 20	531.2	595.2	97361.826	3063.485
Void 21	665.6	755.2	170045.454	3797.303
Void 22	364.799	332.799	54968.364	1742.498
Void 23	704.	576.	233553.807	3109.163
Void 24	287.999	140.8	14888.925	734.861
Void 25	563.2	224.	74383.204	1842.028
Void 26	198.4	179.2	10956.806	682.239
Void 27	172.8	134.4	9891.815	520.471
Void 28	441.6	211.2	33198.096	1430.727
Void 29	166.4	153.6	12902.371	572.739
Void 30	166.401	147.2	11898.87	508.51
Void 31	159.999	204.8	13004.776	685.876
Void 32	217.6	134.4	16998.417	651.447
Void 33	153.6	160.	13762.537	598.985
Void 34	51.2	115.2	1904.639	279.867
Void 35	230.4	217.599	13434.879	689.669
Void 36	774.4	326.4	77639.638	2105.301
Void 37	460.8	217.601	36741.166	1345.998
Void 38	121.6	115.2	7802.849	391.841
Void 39	300.8	256.	31027.259	970.497
Void 40	166.4	204.8	18268.14	597.754
Void 41	140.8	115.2	7884.803	424.976
Total Area	9490.248	6769.03	64239771.164	32518.556
		Void Area/Total Area	2.84%	



Filter Section with Incomplete Burnout 2

Measurement #	Width (μm)	Height (μm)	Area (μm²)	Perimeter (μm)
Void 1	339.2	364.8	79319.134	1340.009
Void 2	198.4	268.8	24104.951	817.618
Void 3	268.8	192.	25907.188	802.085
Void 4	339.2	288.	43007.961	1337.526
Void 5	435.2	166.4	26050.548	1066.496
Void 6	243.2	147.2	18370.557	763.678
Void 7	339.2	268.8	52183.053	1222.569
Void 8	710.401	300.8	150548.543	1799.458
Void 9	499.2	268.8	53207.035	1417.77
Void 10	64.	70.4	3071.999	235.317
Void 11	256.001	147.2	20951.012	741.114
Void 12	422.401	307.2	47104.026	1477.898
Void 13	281.6	531.2	75980.632	1586.489
Void 14	121.6	89.6	7311.394	379.689
Void 15	384.	403.2	55766.98	1843.992
Void 16	435.2	230.4	33750.905	1365.133
Void 17	217.6	384.	33198.122	1161.11
Void 18	640.	345.6	52756.454	1986.844
Void 19	192.	166.4	18636.781	645.358
Void 20	281.599	64.	8314.857	684.913
Void 21	44.8	70.4	1249.313	189.077
Total Area	8809.943	9218.125	81211158.48	36056.137
		Void Area/Total Area	1.02%	



BIBLIOGRAPHY

Brown, J., Sobsey, M.D. (2010). “Microbiological effectiveness of locally produced ceramic filters for drinking water treatment in Cambodia.” *J. Water Health,* **8**(1), 1-10.

Boschi-Pinto, C., Velebit, L., and Shibuya, K. (2008). “Estimating child mortality due to diarrhea in developing countries.” *Bull World Health Organization* **86**(9), 710-717.

Ceramics Manufacturing Working Group (2011). *Best practice recommendations for local manufacturing of ceramic pot filters for household water treatment. 1st edn, Center for Disease Control and Prevention,* Atlanta, GA, USA.

Clasen, T.F., Bastable, A. (2003). “Fecal contamination of drinking water during collection and household storage; the need to extend protection to the point of use.” *J. Water Health*, **1**(3), 109-115.

Hubbel, L., Elmore, A.C., and Reidmeyer, M. (2015). “Comparison of a native clay soil and an engineered clay used in experimental ceramic pot filter fabrication.” *Water Science and Technology: Water Supply*, **15**(3), 569- 577.

Hunter, P.R. (2009). “Household water treatment in developing countries: comparing different intervention types using meta-regression.” *Environmental Science and Technology,* **43**(23), 8991-8997.

Kalman, E.N., Oyanedel-Craver, V.A., and Smith, J.A. (2011). “Ceramic filters impregnated with silver nanoparticles for point-of-use water treatment in rural Guatemala.” *Journal of Environmental Engineering,* **137**(6), 407-415.

Lantagne, D., Klarman, M., Mayer, A., Preston, K., Napotnik, J., and Jellison, K. (2010). “Effect of production variables on microbiological removal in locally-produced ceramic filters for household water treatment.” *International Journal of Environmental Health Research,* **20**(3), 171-187.

Roberts, M. (2004). *Field test of silver-impregnated ceramic water filters.* People-Centered Approaches to Water and Environmental Sanitation, 30th WEDC International Conference, Vientiane, Lao PDR.

Soppe, A.I.A., Heijman, S.G.J., Gensburger, I., Shantz, A., van Halem, D., Kroesbergen, J., Wubbles, G.H., and Smeets, P.W.M.H. (2015). “Critical parameters in the production of ceramic pot filters for household water treatment in developing nations.” *Journal of Water and Health,* **13**(2), 587-599.

van Halem, D., Heijman, S.G.J., Soppe, A.I.A., van Dijk, J.C. and Amy, G.L. (2007) Ceramic silver-impregnated pot filters for household drinking water treatment in developing countries: material characterization and performance study. *Water Science and Technology: Water Supply,* **7**(5-6), 9-17.

World Health Organization (2011). *Evaluating household water treatment options: health-based targets and microbiological performance specifications*. *WHO Press,* Geneva, Switzerland.

World Health Organization and United Nations Children's Fund. (2014). *Progress on sanitation and drinking-water – 2014 update*. *Joint Monitoring Programme for Water Supply and Sanitation,* WHO, Geneva, Switzerland.

VITA

Travis Dean Gardner was born in Washington, Missouri, USA. In May 2015, he received his B.S. in Environmental Engineering from the Missouri University of Science and Technology, Rolla, Missouri, USA. As an undergraduate student, Travis dedicated time to the Water Environment Federation, serving as president for one semester among other positions held. He was also involved in Engineers Without Borders, Chi Epsilon Civil Engineering Honor Society, and the Association of Environmental and Engineering Geologists. Travis interned for Freeport McMoRan Inc. in the summer of 2014 and for CDM Smith in the summer of 2016. He has served as a graduate teaching assistant for Field Methods and International Engineering and Design in the Geological Engineering Department. In May 2017 he received his Master's Degree in Geological Engineering from Missouri University of Science and Technology.