International Journal for Service Learning in Engineering
Vol. 8, No. 1, pp. 62-77, Spring 2013
ISSN 1555-9033

Designing a Low-Cost Ceramic Water Filter Press

Michael Henry
BS, Immunology and Infectious Disease
The Pennsylvania State University
University Park, PA 16802
Mhenry12@gmail.com

Siri Maley
BS, Mechanical Engineering
The Pennsylvania State University
University Park, PA 16802
sirikmaley@gmail.com

Khanjan Mehta*
Humanitarian Engineering and Social Entrepreneurship (HESE) Program
The Pennsylvania State University
University Park, PA 16802
khanjan@engr.psu.edu

*Corresponding Author

Abstract -- **Diarrheal diseases due to unsanitary water are a leading cause of death in low- and middle- income countries. One potential solution to this problem is widespread access to point-of-use ceramic water filters made from universally-available materials. This increased access can be achieved by empowering local artisans to initiate self-sustaining and scalable entrepreneurial ventures in their communities. However, a major barrier to the start-up of these businesses is the prohibitively expensive press used to form the filters. This article reviews filter press technologies and identifies specific functional requirements for a suitable and affordable filter press. Early-stage field-testing results of a proof-of-concept design that can be manufactured by two people in two days at one-tenth of the cost of popular filter presses is presented.**

Index Terms - Ceramic Water Filter, Filter Press, Filtration, Global Health

INTRODUCTION

The water crisis affects millions worldwide and it is expected to worsen over the coming years and decades. It is estimated that in 2010, 1.8 billion people consumed water deemed “unsafe,” and 783 million regularly used water sources unprotected from contamination.[1] Children are the most affected by ingestion of contaminated water: 15% of deaths in children under five years old are associated with the nearly 2.5 billion cases of diarrhea each year.[2] This means that every year, 3.4 million children die as a direct result of diarrhea and other diseases caused by water-borne microbes, making it the second leading cause of death of children, especially in low- and middle-income countries.[3]

Though many factors contribute to water contamination, climate change, poor infrastructure, and failed aid projects continue to exacerbate the problem. Climate change often stresses water supplies in areas that are already water scarce, forcing residents to use unsanitary sources.[4] The continued lack of sanitation infrastructure in many countries also leads to contamination of drinking water and affects health and development in these areas.[5] Indeed, much of the water used in developing countries shows evidence of fecal contamination. These systemic problems limit progress on many worldwide development goals, such as improving life expectancy, child health, and economic productivity.[6] From our team's work with ceramic water filters in Kenya, we have witnessed first-hand the daily burdens faced by some of the 16 million people there who lack clean water or must travel long distances in search of clean water supplies for their families.[7] Both the constant travel and the consumption of unsafe water limit the economic productivity and quality of life for the entire household. Family members miss much time from school and work due to water-borne illnesses and water retrieval, and children often suffer from poor nutrient uptake and underdevelopment due to water contamination.[6,8,9]

Despite the efforts of many non-governmental organizations (NGOs) and world governments, water infrastructure projects such as dams, treatment facilities, and piped-water networks have thus far failed to remedy these major health problems. Since assistance by the World Bank first began in 1961, top-down development has been severely hampered by lack of political stability and public funding in many of the areas that are most affected by the water crisis.[10,11] In most African countries, recent foreign infrastructure efforts have had a failure rate of well over 50%, amounting to several hundred million dollars of lost investment (without accounting for the damage to local livelihoods).[12]

While infrastructure efforts are absolutely necessary, stakeholders from all sectors must cooperate to resolve the crisis. From the private enterprise sector, a point-of-use, market-centric approach is needed to help combat the infrastructural and oversight-related shortfalls of top-down methods. By making water filters that are effective and affordable to the billions of people living on a few dollars per day, we can help improve access to clean water while also empowering local entrepreneurs and stimulating local economies.

This paper discusses the opportunities of a market-centric approach to low-cost water filtration systems. We begin by analyzing the current state of several point-of-use water purifying methods. We then conduct an in-depth discussion and feasibility assessment of ceramic water filter technology, focusing on the most commonly used filter press in resource-constrained settings. The cost of this press, estimated at over $3,000, is a fundamental limiting factor to its application in the places where it is needed most. We derive comprehensive functional requirements for the filters, press and venture ecosystem in the context of a developing country (Kenya). Finally, we propose technical specifications and a design approach for a low-cost filter press and present early-stage prototyping and field-testing results in which our goal was to make a press that could be manufactured by two people in two days with materials under $200. This paper seeks to act as a starting point to inform and inspire other engineers working on improving the design of the filter press in order to develop practical and affordable ceramic filter ventures with the potential of mitigating the global water crisis.

Point-of-Use Water Purification Solutions

Requirements for Point-of-Use Water Purification Technologies

When operating in resource-constrained contexts, water purification solutions must fulfill a variety of requirements in order to be successful. First and foremost, they must improve health by filtering out particulates as well as the majority of harmful microbes: from protozoans such as *Cryptosporidium* or *Giardia*, to bacteria like *Vibrio cholerae* or *Salmonella typhi*, to viruses such

International Journal for Service Learning in Engineering
Vol. 8, No. 1, pp. 62-77, Spring 2013
ISSN 1555-9033

as Hepatitis A.[13] However, the technologies must accomplish this while ensuring the clean water is still affordable to those in extreme poverty, potentially living on less than US $1.25/day.[14] Additionally, technologies must be appropriate and applicable to wherever water quality must be improved. Successful processes also should not further contribute to other health or environmental ailments such as fossil fuel pollution and the resultant respiratory illnesses. Both the filtration process and the consumable water must be socio-culturally acceptable to the users. For instance, operation and maintenance must be within local education levels, and different-tasting water should need to be remedied or avoided. Finally, successful cleaning processes must resolve how to preserve sanitation while storing water (or how to clean only what is needed at the time).

Review of Current Point-of-Use Water Purifiers and Methods of Obtaining Potable Water

TABLE I

METHODS OF OBTAINING CLEAN DRINKING WATER IN DEVELOPING COUNTRIES

	Harmful Items Removed				
Method	Particulates	Bacteria	Protozoa	Viruses	Inexpensive
Cloth filtration	x	x	x		x
Boiling		x	x	x	
Bore wells	x	x	x	x	
Chlorination		x		x	
Bottled Water	x	x	x	x	
Ceramic filters	x	x	x	x	x

Several products and methods already exist that have the potential to clean contaminated water or help residents obtain clean water in resource-limited contexts where centralized purification is not an option (Table 1). The simplest method is cloth filtration. A field test in Bangladesh showed that using a sari (a cloth covering often worn by women in the Indian subcontinent) to filter contaminated water reduced cholera by up to 48%.[15] However, the remaining contaminants still contribute significantly to morbidity, as incomplete filtration of cholera means smaller microorganisms and viruses can pass through the cloth filters. Boiling water is a very popular practice for effectively killing bacteria, viruses, and protozoans. However, it consumes considerable fuel, which can be costly and/or difficult to obtain. Those already fetching water must also fetch additional biofuel to boil it, and the burning contributes to air pollution.[6] Further, those who burn wood and other biofuels in order to boil water are also at much higher risk of contracting respiratory diseases.[16] Drilling bore wells to access groundwater uncontaminated by surface-water microbes is also popular. However, its widespread implementation is limited by its cost. Even the relatively inexpensive “Indian Mark II” design from UNICEF is about $1,300. It also does not allow for drilling near sanitation systems, as sewage may seep into the well.[6]

Another option is adding chlorine to water. This usually comes in a tablet or powder form, such as WaterGuard, which is available in Uganda. It also has the advantage of preserving sanitation, as the residual chlorine continues to clean the water while it’s being stored. Chlorination is one of the more viable widespread purification options. However, a consistent supply of the additive is needed in order to continuously clean water and maintain health, which may not always be possible in poor areas. Also, while it is effective against bacteria and viruses,

International Journal for Service Learning in Engineering
Vol. 8, No. 1, pp. 62-77, Spring 2013
ISSN 1555-9033

it is not effective against water-borne protozoans such as Giardia and Cryptosporidium. Field tests have also shown that the residual taste and smell of chlorinated water is often unacceptable to users.[17] Though distribution is increasing, several obstacles remain before chlorine tablets might attain considerable market share.[18]

Additionally, an obvious option for clean water access is simply buying bottled water. In fact, this is currently the greatest source of competition to purification technologies in many under-resourced countries. The limited availability of point-of-use purification technologies means that those who cannot afford bottled water often simply consume contaminated water.[19]

Review of Ceramic Water Filters

One solution that can potentially meet all necessary requirements is a ceramic point-of-use water filter (see Table 1). These filters work by using porous materials which allow water to flow through while restricting the passage of potentially harmful microbes. The idea began over a thousand years ago, when porous clay and sandstone were used to filter water in Sri Lanka. The pores are large enough to allow the passage of water but not the microbes that cause water-borne disease.[20] Modern filters are made by mixing clay with sawdust, rice husks, or other flammable organic materials. After being shaped into a filter with a press, they are fired in a kiln. The organic material burns out, leaving small pores of about one micron in size, which can filter out the majority of harmful microbes.[17] These simple clay filters can remove between 97.86% and 99.97% of *E. coli*, an important indicator of the amount of contamination present in a sample of water. The filters also remove particulates and protozoans (which are larger than bacteria). Further, with the addition of colloidal silver (a broad-spectrum antimicrobial) the filters have 100% effectiveness in tests for removal of *E. coli.*[21] Studies have also shown that silver is a potentially strong anti-viral compound.[22,23,24]

Ceramic water filters first came to be used in large numbers toward the end of the 1980s.[21,25] The modern-day design was created at the Central American Industrial Research Institute by Dr. Fernando Mazariegos in 1981. Potters for Peace (PFP), an NGO that supports potters in Latin America, began the first large-scale filter production in 1998 in the aftermath of Hurricane Mitch. The PFP implementation model is to fund the construction of filter factories and then train and support local artisans who manage filter production. They have since expanded from Nicaragua throughout Central America and to parts of Africa and the Middle East.[26] Though all of these efforts are significant—there were hundreds of thousands being used worldwide as of 2008 and the numbers are increasing—unsafe water remains a very difficult reality for many.[27] Figure 1 shows an example of what the set-up of the filter and its receptacle might look like.

International Journal for Service Learning in Engineering
Vol. 8, No. 1, pp. 62-77, Spring 2013
ISSN 1555-9033

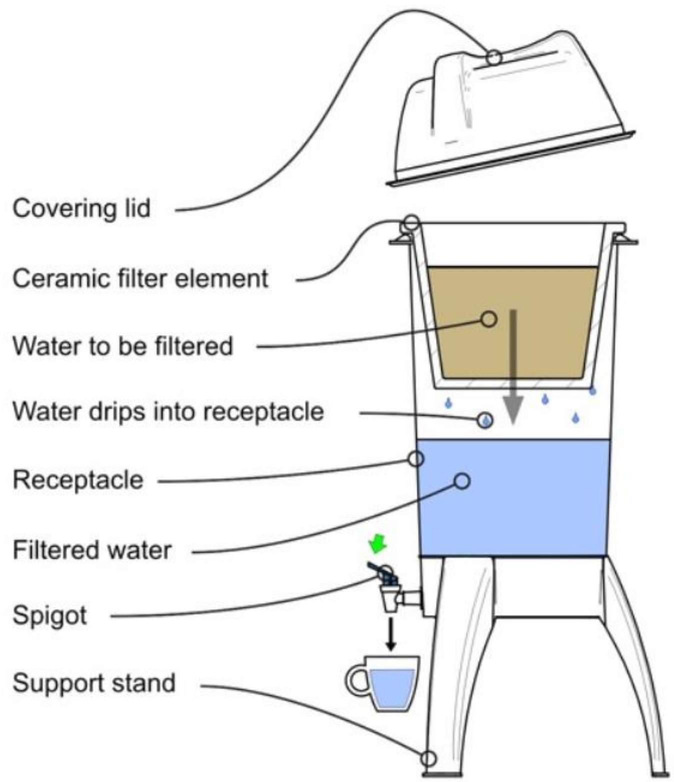

FIGURE 1
CERAMIC WATER FILTER SYSTEM [1]

Feasibility Assessment of Current Ceramic Water Filters

Current ceramic water filter technology fulfills many of the water purifier requirements of affordability, acceptability, and filtering efficiency. Economically, the component clay and organic burnout material are both readily available across the developing world, creating sustainable and reliable local supply chains (although research may need to be done to ensure that local clay in different areas can be used to form working filters). The plastic bucket and tap which hold and dispense filtered water are also widely available. The colloidal silver that helps eliminate viruses is not locally-sourced and can be a bottleneck to scale-up. However, in areas where waterborne viruses such as hepatitis are not a concern, the filter element by itself does a satisfactory job of removing protozoans and bacteria.[21] Recently, there has been growing interest in low-cost substitutes for the colloidal silver. For example, an extract from Moringa seeds has been shown to have promising antimicrobial characteristics useful for water purification.[29]

In addition to the low capital cost, the return on investment for each filter is very high. A $5-$15 filter has a mean lifetime of 2-3 years (with proper upkeep). This means that not only can users afford the investment, they will also earn back much more than its cost by way of fewer sick days and medical expenses.[21] A study in Cambodia has shown that families who use a ceramic water filter average 54% fewer instances of diarrheal disease when compared to families who do not use the water filter.[30]

Despite their estimated lifetime, however, ceramic filter usage times can decrease due to improper upkeep or overly turbid water. Their relative fragility means improper handling can

International Journal for Service Learning in Engineering
Vol. 8, No. 1, pp. 62-77, Spring 2013
ISSN 1555-9033

lead to cracks in the filter body. Users must also scrub the inside every few weeks in order to unclog pores, but they must avoid touching the outside of their filters as that risks re-contaminating the output water. Finally, while filters can remove particulates, severe turbidity requires more frequent filter cleaning. It can also decrease filter lifetime, as the resultant clogged pores impede the flow rate.[17] All of these issues must be addressed through proper processes (manufacturing, transport, etc.) and user education. Some problems are also design-related: it may be possible to improve filter durability, and the bucket design should ease cleaning and protect the outside of each filter. Turbidity might also be addressed via other design changes, such as incorporating cloth filtration into the bucket above the ceramic filter.

Despite their benefits, the production of ceramic water filters also has some negative environmental and economic obstacles. Burning wood to fire the filters in the kiln contributes to deforestation and air pollution. However, this may be avoided by utilizing alternative local biofuels, such as corn husks or other farm waste, which would otherwise be discarded. Another issue of substantial concern is quality testing, as microbiological testing is often expensive and requires skill.[25] However, several new products are being introduced that easily and inexpensively test water, such as the Hach Pathoscreen kit.[31] The biggest challenge to the dissemination of ceramic water filters is the extremely high cost of the filter press. The technology has progressed significantly since it first began, but still requires improvement.

Review of Current Water Filter Press Technology

Inspired by the Chinese and Indian terracotta flower pot industry, the pioneering Central American Industrial Research Institute began forming filters with hydraulic presses in the 1980s.[32] This resulted in much more efficient filter production and performance versus the initial hand-pressing system. Today, the mechanical pressing practice has evolved into the widely-used Potters Without Borders (PWB) press shown in Figure 2.

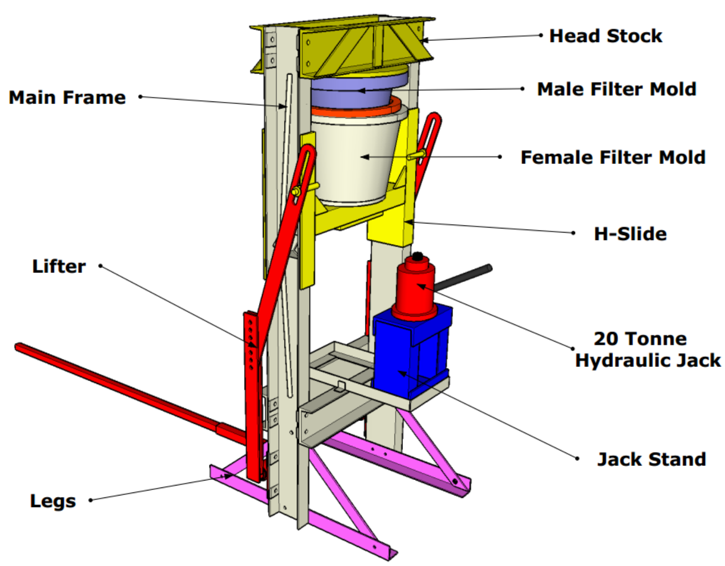

FIGURE 2
POTTERS WITHOUT BORDERS CERAMIC WATER FILTER PRESS[19]

Filter presses require several main components: male and female filter molds, a compression mechanism, and a containing frame. In the PWB model, a custom-brushed aluminum male mold is mounted below the top cross beam of the frame, while the female counterpart is set underneath on a 20-ton hydraulic jack. Additionally, all presses must have a process for removing the formed filter; in the PWB press, a plate at the bottom of the female mold is pushed up to remove the flat-bottom filter.[25]

Several groups have attempted to modify the PWB press. For example, Creative Machines made a simple, high strength (withstanding up to 20 tons of pressure) press frame that can be disassembled enough to be checked on an airplane, so that filter technicians from PWB or other organizations could bypass the expensive shipping process by carrying the press with them.[33] Pure Home Water (Ghana) endeavors to improve the entire filter ecosystem, particularly emphasizing larger-scale storage tanks.[34] Other teams have experimented with different filter mold materials (e.g. concrete) or shapes that allow forming at lower pressure (e.g. round-bottom, as seen in Figure 3).[35] Concrete molds help because they are cheaper to make and easier to reproduce than brushed aluminum molds, and molds which create round-bottom filters require less pressure. Despite these and other isolated attempts as well as some reports from PFP and PWB factories and technicians, information on design and construction of filter presses remains highly decentralized; there is no single source of information for the requirements and progress of filter press development.[19]

FIGURE 3
FLAT-BOTTOM CERAMIC WATER FILTER VS ROUND-BOTTOM FILTERS[36]

International Journal for Service Learning in Engineering
Vol. 8, No. 1, pp. 62-77, Spring 2013
ISSN 1555-9033

The filter press venture is part of a larger production ecosystem, including the kiln and fuel, workspace, and additional administrative and training costs. There are many types of kilns (different materials, heat transfer paths, and capacities) varying in availability across the developing world. Different biofuels are also available in different locations, though firewood is by far the most common (and among the most environmentally damaging). Additionally, Kai Morrill, President of PWB, cites the factory building and land as another major investment. Finally, training personnel, transporting machinery, handling administration and marketing, and continuing routine maintenance all add to the venture's costs.[19]

Feasibility Assessment of the Current Filter Press Technology

The PWB ceramic water filter press has several benefits with respect to engineering robustness and operation. Its high-strength design allows the pressing of flat-bottom filters while preventing most linear and torsional deformation and maintaining consistent filter thickness. These flat-bottom filters require higher pressure formations but also provide more surface area and therefore higher flow rates. Further, though its initial construction is complex and expensive, press operation is relatively simple, allowing three or four local artisans to produce 50 filters/day.

Despite this successful implementation, the PWB press does have some shortcomings that limit more widespread use. Most saliently, the devices are $2,300 dollars each, or over $3,000 including labor and other requirements.[25] Additionally, presses for some locations are made internationally and shipped into the country where they will be used, incurring large shipping charges and excluding local artisans from the increased revenue.[19] All told, the full cost of starting up a PFP or PWB filter factory can range from $5,000 to $8,000, leading the NGOs to set up the factories themselves and subsidizing these capital costs.[19,20]

Even at its high cost, the PWB press suffers from some durability limitations. These stem primarily from faults in the expensive U-channel uprights, particularly with steel sold in rural developing country markets, which is often sold flat and must be bent in the U-shape manually.[19] These channels undergo significant loading during the pressing procedure and often bow over time. Additionally, errors with straightness tolerances can lead to misalignment of the male and female molds, causing thickness variation in the filters that compromises their effectiveness. Even with more consistent US market steel (and its high shipping fees), the PWB factory in Yemen needed repair after approximately 50,000 filters (equating to under 3 years at 50 filters/day).[19]

In terms of ecosystem feasibility, the PWB/PFP factory model presents opportunities for partnering with local entrepreneurs to reduce costs. For instance, a partnership with a local pottery business could provide access to a kiln, fuel, clay and organic burnout material as well as workspace and extensive experience with ceramics.[19] Operation diversification is also possible through these relations; for instance a Yemeni PWB factory also produced ovens, planters, and pots in order to obtain income before filter demand grew and made the enterprise profitable.[37] However, differences in material from local supply partners may result in clay or burnout material that cannot form durable filters or small enough pores, and the kilns and fuel available may not be appropriate or environmentally sustainable for firing the filters. Additionally, while local partnerships may help reduce workspace costs, such facilities may not have more expensive running water and electric utilities, which, though not required, allow increased operating efficiency.[38]

Requirements for a Low-Cost Water Filter Venture

Our team has researched ceramic water filtration as a method to create self-sustaining and self-scaling ventures for emerging markets in order to successfully empower local populations, avoid long-term foreign support, and provide maximum systemic health benefits to the communities. Based on the development history as well as engineering and socio-cultural assessments provided above, we have endeavored to define requirements for a self-perpetuating, scalable water filter venture. Searches on research databases reveal no studies solely on comprehensive development of water filter press ventures and the ecosystems they operate within. Therefore, the requirements we have identified arise from several sources: the discussion of general water purification technologies, the examination of ceramic water filter production and use, and knowledge we have derived from operating ventures in resource-limited contexts including Kenya, India, Nicaragua, and Tanzania. Additionally, a great deal of information was gleaned from conversation with Kai Morrill, Robert Pillers, Peter Chartrand, and Burt Cohen of Potters Without Borders.

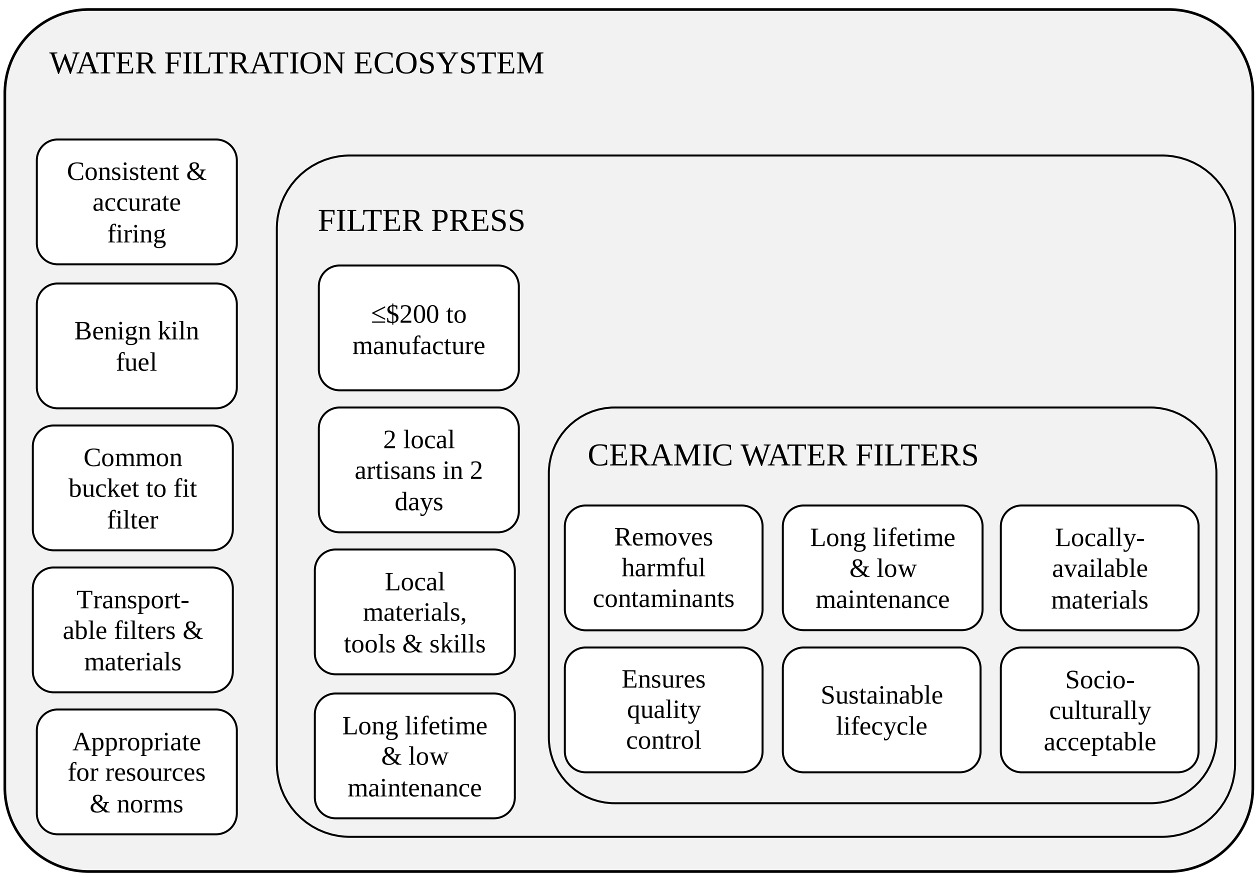

FIGURE 4
Requirements for Low-Cost Water Filter Venture

As previously mentioned, in order to accomplish all health, contextual, and socio-cultural goals, successful water filters must meet many varied standards. Scientifically, filters must improve health by removing (and safely storing) particulates, protozoans, bacteria, and viruses while not exposing users to other health problems. They must be easily and reliably tested after production to ensure quality control. Their entire lifecycle must also be environmentally and technically sustainable and implementable across all the contexts in which filters are needed. Each filter must have a long lifetime with simple and minimal maintenance. Additionally, the clay and organic burnout materials must be locally-sourced, readily available, environmentally benign, and affordable. Socio-culturally, the filters' production and use (including manufacturing, cleaning, and necessary transport) must be acceptable and executable by their respective populations in terms of appropriate costs, water taste, skill sets, press technology, and ecosystem use. See Figure 4 for a summary of the requirements of a ceramic water filter venture, which guides our current goals.

The filter press, in addition to facilitating filter success, must also meet several economic and socio-cultural metrics. To facilitate economic viability with respect to the target market's access to capital and expected return on investment, we have limited the press's target manufacturing cost to US $200. Additionally, construction must be limited in difficulty and duration in order to ensure the venture is self-sustaining and self-scaling; we have set construction targets at two days of work by two local workers. The press must be produced in-country (eventually *en masse*) using locally-sourced materials, tools, and skills. Once complete, the press must continue effective operations for at least five years with minimal maintenance. A greater number of presses serving more localities is ideal because it eliminates the need for long-distance shipping, which would be expensive and potentially dangerous to the fragile filter elements.

Finally, the filter ecosystem includes all supporting technology, most notably the kiln and fuel, bucket and spigot, and all transportation requirements. The locally-available kiln technology must be able to fire the filters and burn off the organic fragments while maintaining the correct filter shape and pore size. Environmentally benign fuel that does not expose users to any health risks should be available. Additionally, the filter must nest within a common locally-sourced bucket size(s) that fits an appropriate spigot, likely a 20L bucket on a stand. Though the assembled press may not need to be transported, all raw materials, filters, and bucket assemblies must be movable on foot, by motorbike, or by pickup truck/van. All ecosystem activities and maintenance must be achievable within local resources and socio-cultural norms.

Derived Engineering Specifications for Filter Presses

Though there are a variety of engineering requirements across the entire venture system, the filter press section makes for a logical and accessible starting point. The PWB press meets many of the stated requirements, but suffers a major shortfall in affordability and material sourcing. For this reason, we began our venture by concentrating on designing and prototyping an easy-to-construct, $200, locally-sourced filter press.

Examination of the PWB press reveals that the hydraulic jack and the structural steel members contribute most significantly to its cost, in addition to often being difficult to source locally. Using lower-cost, locally-available alternatives results in two main engineering specification changes: the jack will provide less pressure, and the frame members will begin failing under lower loads (since local steel may be expected to be of lower-strength alloys which yield under lower pressure) [2]. As such, a primary engineering requirement for this affordable local filter press is that it require a lower filter formation pressure.

Even with the lower formation pressure, however, the press frame members and connections must still withstand repeated loading. It must also be constructed from locally-available metal bars, which may differ by location and vary in straightness (they may be bent or warped). The male and female molds and the filter removal mechanism must also be available for local production or purchase, and the entire press must be constructed, maintained, repaired, and operated using locally-available tools and skill sets. Finally, these stipulations cannot compromise the longevity of the press.

LOW-COST FILTER PRESS DEVELOPMENT

Though the requirement generation process produced numerous functional specifications for the low-cost filter press, the critical design decision was to attempt to lower the filter formation pressure. Subsequently, we took on the challenge of building a filter press using a 2-ton car jack instead of the 20-ton hydraulic jack used by PWB. In the PWB design, the pressure target is set based on the shape of the resultant filter: flat-bottom filters require higher formation pressures than rounder versions.[19] As such, we determined that we would have to produce a rounder filter, producing final products similar to those in Figure 3. Fortunately, it has been proven that lower pressure formation does not affect final pore size, and therefore filtering ability.[40] However, this shape change creates multiple problems in both production and use. First of all, flat bottom filters provide more surface area for filtration and thus a faster flow rate and more water for the user.[19] Rounding the filtering surface decreases this area, lowering the flow rate. Since the diameter of the filter is dictated by the relatively standardized buckets they fit in, we could not compensate for the decreased surface area of the rounded shape by increasing the width.

A secondary problem with rounder filters relates to their removal from the press molds after formation. Unlike the PWB press, round-bottom filters cannot be safely and uniformly pushed up from the bottom of the female mold.[19] To address this problem, we opted for an inverted design (see Figure 5): the car jack was mounted to the frame headstock and the female mold was suspended on the underside of the jack elevator. The male mold sat on the base with a “halo” around its rim in order lift the filter out after pressing.

After removal, the round-bottom filters must also be dried and fired differently from flat-bottom versions, as they cannot be balance upright and laying them upside-down on a flat surface would cause the inside to dry and fire more slowly.[19] To mitigate this, we suspended the filters on special racks, allowing airflow around all sides. Another arrangement for drying the round-bottom filters can be seen in Figure 3. However, these drying racks contribute to an increased capital cost. Forming the clay around the male mold (rather than simply placing it into the flat-bottom female mold) also slightly extends the time required to prepare each filter for pressing.

Despite these issues, there are benefits to the use of round filters. The car jack is a fraction of the cost of the hydraulic jack and readily available in any country. We were also able to employ locally-sourced steel for the frame and readily available, inexpensive aluminum bowls for the male and female molds. These standard bowls are common throughout the region, create correctly curved filters that fit within the commonly-used 20L plastic bucket, and can withstand the repeated filter press loadings when stacked two or three thick. In addition, we eliminated the large steel legs and jack stand, further reducing costs. In total, these cost reductions brought the final filter press to less than 10% of the original PWB cost, very close to our $200 target.

International Journal for Service Learning in Engineering
Vol. 8, No. 1, pp. 62-77, Spring 2013
ISSN 1555-9033

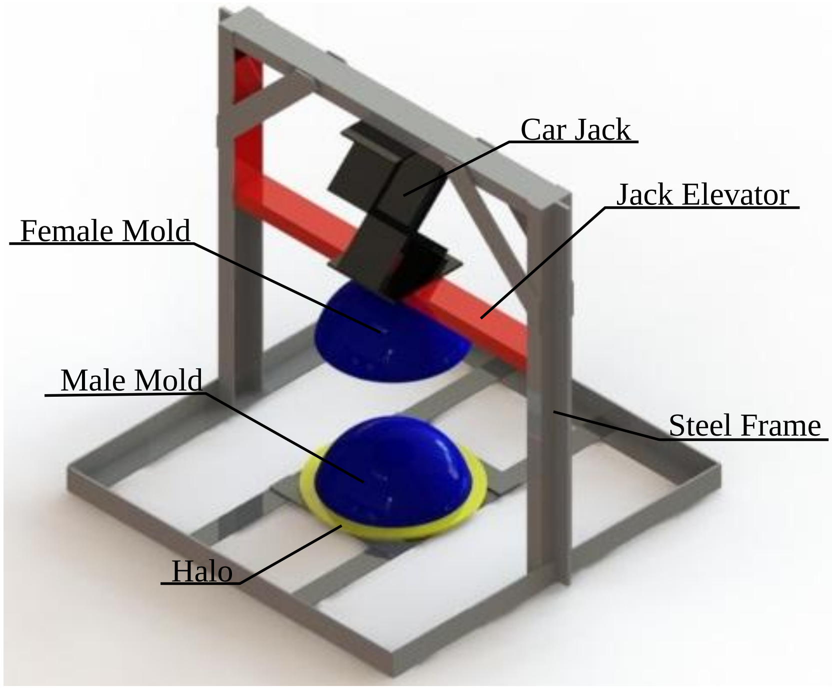

FIGURE 5
OUR CERAMIC WATER FILTER PRESS

Prototyping Results

Our initial two prototypes were essentially concentrated on assessing construction techniques for the round-bottom affordable filter press. The original prototype was bolted together from pre-punched aluminum channels in order to determine geometric tolerances (perpendicularity) and assess the benefits of bolting versus welding. It was determined that the required perpendicularly tolerances could be maintained without special equipment, however the jack elevator track must receive special attention as a canted elevator results in inconsistent filter thickness. Further, it was determined that welding would maintain the necessary yield strengths and geometric tolerances more easily and with less maintenance than using nuts and bolts.

These construction lessons were applied to our field tests in Kenya in May 2012. The flat-bar frame steel, aluminum bowl molds, buckets, spigots, and car jack were all readily available at relatively low prices. The steel U-channel (see Figure 2) was not immediately available locally. In its place, we substituted selected steel Z-bars and joined them together along their back flange. This formed a track with a 1/16” tolerance around the jack elevator uprights, which were shimmed and greased appropriately. The additional flange also enhanced shear and bending rigidity and provided additional weld area. However, the lack of appropriate profiles also limited options for mounting the male mold and cross bracing the upright frame; flat stock was used for these purposes, but angle iron would be more appropriate for the requisite loading conditions. Though not available in the local markets at the time, similar angle profiles were observed in local construction projects. *En masse* press production would likely need to pursue a partnership with a larger provider in order to maintain adequate supply of the correct steel channels.

FIGURE 6
LOW-COST WATER FILTER PRESS

The Kenyan press exhibited the ability to maintain all geometric tolerance requirements in terms of load distribution, jack-elevator alignment, and mold orientation. It pressed several filters with consistent thickness and shape, although these were not microbiologically tested since the team's time in-country came to an end. Though further prototyping and development is required to produce a market-ready model, this initial proof of concept prototype demonstrates that such an "inverted," round-bottom filter press is achievable within the affordability, availability, and acceptability limits of developing world ventures.

Next Steps

Further development of the low-cost water filter venture will take several different paths. Scientifically, filters must be completed and tested in a laboratory setting. In terms of press engineering, additional work must be done to ensure quality control and consistent manufacturing: multiple press prototypes should be built and comprehensively tested in-country. Both the press and the filter-bucket system must be piloted extensively to determine mean lifetimes and failure modes. The final filter shape might also be refined while adhering to the requirements set forth in this paper. The venture ecosystem must also be established: material suppliers as well as ceramic artisan partnerships (for kilns, clay, burnout, fuel, and experience) need to be formed. Interested teams could also investigate avenues for maintaining a consistent and affordable supply of colloidal silver for filters in areas where viruses are common. There are also additional peripheral issues to investigate, including addressing high turbidity water (by potential integration of cloth filtration) as well as investigating different clay consistencies and other organic burnout materials. With sufficient microbiological, engineering, and business expertise, the venture has the potential to be greatly augmented.

CONCLUSION

Ceramic water filters are a promising way to reduce the burden of water-borne illnesses at an affordable cost. Though other technologies are also available which may eventually meet point-of-use purification requirements, ceramic filters have long lifetimes and can remove all types of harmful material while using primarily local resources. The proof-of-concept filter press presented in this paper verifies the potential for pressing round-bottom filters at much lower pressures and therefore much lower cost than flat-bottom alternatives. This new press design can, in theory, be built by two local metal workers in two days for US $200 using only locally-available materials. Further manufacturing improvements and filter studies will enable the development of self-sustaining and scalable filter production ventures that improve health, empower local populations, stimulate emerging economies, and deliver systemic benefits to the communities.

ACKNOWLEDGMENT

We would like to acknowledge several people from diverse groups who helped make this study a success. First, we appreciate the help of Kai Morrill, Robert Pillers, Peter Chartrand, and Burt Cohen from Potters without Borders for their patience in discussing with us their past experiences in filter press construction to create a jumping-off point for our analysis. We are grateful to Steve Carpenter and his “Reservoir Studio” at Penn State where the initial prototypes of our press were constructed. Finally, we are deeply indebted to our collaborators at the Children and Youth Empowerment Centre (CYEC) and Wambugu Agricultural Training Center, both in Nyeri, Kenya, for helping us to construct our first filter press in the field.

REFERENCES

[1] M. Bolton, "Rural Water Filter," in *Good Design - Energy Systems*, Chicago, 2009.

[2] ASM International, ASM Handbook Volume 01: Properties and Selection: Irons, Steels, and High-Performance Alloys, Russell Township, OH: ASM International, 1990.

[3] K. Onda, J. LoBuglio and J. Bartram, "Global Access to Safe Water: Accounting for Water Quality and the Resulting Impact on MDG Progress," *Int. J. Environ. Res. Public Health,* vol. 9, no. 3, pp. 880-894, 2012.

[4] G. A. Preidis, C. Hill, R. L. Guerrant, B. S. Ramakrishna, G. W. Tannock and J. Versalovic, "Probiotics, Enteric and Diarrheal Diseases, and Global Health," *Gastroenterology,* vol. 140, no. 1, pp. 8-14, January 2011.

[5] A. Pruss-Ustun, R. Bos and J. Bartram, "Safer Water, Better Health: Costs, benefits, and sustainability of interventions to protect and promote health," World Health Organization, Geneva, 2008.

[6] S. Wolf, "Does Aid Improve Public Service Delivery," Economic Commission for Africa, Addis Adaba, 2007.

[7] M. J. Botting, E. O. Porbeni, M. R. Joffres, B. C. Johnston, R. E. Black and E. J. Mills, "Water and sanitation infrastructure for health: The impact of foreign aid," *Globalization and Health,* vol. 6, no. 12, 2010.

[8] K. Vairavamoorthy, S. D. Gorantiwar and A. Pathirana, "Managing urban water supplies in developing countries - Climate change and water scarcity scenarios," *Physics and Chemistry of the Earth,* vol. 33, no. 5, pp. 330-339, 2008.

[9] S. A. Jones and C. Silva, "A practical method to evaluate the sustainability of rural water and sanitation infrastructure systems in developing countries," *Desalination,* vol. 248, no. 1-3, pp. 500-

509, 15 November 2009.

[10] Water and Sanitation Program, "Citizen's Report Card on urban water, sanitation, and solid waste services in Kenya: Summary of results from Nairobi, Kisumu, and Mombasa," Nairobi, 2007.

[11] J. W. B. Bredie and G. K. Beeharry, "School Enrollment Decline in Sub-Saharan Africa: Beyond the Supply Constraint," World Bank, Washington, DC, 1998.

[12] UNICEF, "Children and water: global statistics," 26 May 2012. [Online]. Available: http://www.unicef.org/wash/index_31600.html. [Accessed 19 November 2012].

[13] A. Huq, M. Yunus, S. S. Sohel, A. Bhuiya, M. Emch, S. P. Luby, E. Russek-Cohen, G. B. Nair, R. B. Sack and R. R. Colwell, "Simple Sari Cloth Filtration of Water Is Sustainable and Continues To Protect Villagers from Cholera in Matlab, Bangladesh," *mBio,* vol. 1, no. 1, April 2010.

[14] A. Gadgil, "Drinking water in developing countries," *Annual Review of Energy and the Environment,* vol. 23, pp. 253-286, November 1998.

[15] T. A. Ogunyoku, D. M. Nover, E. R. McKenzie, G. Joshi and W. E. Fleenor, "Point-Of-Use Drinking Water Treatment in the Developing World: Acceptance, Project Monitoring and Revision," *International Journal for Service Learning in Engineering,* vol. 6, no. 1, pp. 14-32, Spring 2011.

[16] D. Behera and S. K. Jindal, "Respiratory symptoms in Indian women using domestic cooking fuels," *Chest,* vol. 100, no. 2, pp. 385-388, August 1991.

[17] J. Hagan, N. Harley, D. Pointing, M. Sampson and V. Soam, "Ceramic Water Filter Handbook," Resource Development International, Cambodia, 2008.

[18] Engineering for Change, "Rabbit Ceramic Water Purifier," [Online]. Available: https://www.engineeringforchange.org/solution/library/view/detail/Water/S00067. [Accessed 21 November 2012].

[19] V. A. Oyanedel-Craver and J. A. Smith, "Sustainable Colloidal-Silver-Impregnated Ceramic Filter for Point-of-Use Water Treatment," *Environ. Sci. Technology,* vol. 42, no. 3, pp. 927-933, 2008.

[20] J. Brown and M. Sobsey, "Independent Appraisal of Ceramic Water Filtration Interventions in Cambodia: Final Report," University of North Carolina School of Public Health, Chapel Hill, 2006.

[21] N. E. Bogdanchikova, A. V. Kurbatov, V. V. Tret'yakov and P. P. Rodionov, "Activity of colloidal silver preparations towards smallpox virus," *Pharmaceutical Chemistry Journal,* vol. 26, no. 9-10, pp. 778-779, 1992.

[22] H. H. Lara, N. V. Ayala-Nunez, L. Ixtepan-Turrent and C. Rodriguez-Padilla, "Mode of antiviral action of silver nanoparticles against HIV-1," *Journal of Nanobiotechnology,* vol. 8, no. 1, 2010.

[23] S. Galdiero, A. Falanga, M. Vitiello, M. Cantisani, V. Marra and M. Galdiero, "Silver Nanoparticles as Potential Antiviral Agents," *Molecules,* vol. 16, no. 10, pp. 8894-8918, 2011.

[24] Hach Company, "Analytical Procedure: Pathoscreen Field Kit," Loveland, 2012.

[25] Potters without Borders, "The Difficulty of Improving Simplicity – Ceramic Water Purifier," 2012. [Online]. Available: http://www.potterswithoutborders.com/2012/07/the-difficulties-of-improving-simply/. [Accessed 25 November 2012].

[26] Potters for Peace, "Water Filter Project," 2012. [Online]. Available: http://pfp.he207.vps.webenabled.net/?page_id=63. [Accessed 21 November 2012].

[27] K. Morrill, R. Pillers, P. Chartrand and B. Cohen, Interviewees, *Email Correspondence.* [Interview]. 9 October 2012.

[28] Potters without Borders, "Portable Water Filter Press," 5 April 2009. [Online]. Available: http://www.potterswithoutborders.com/2009/04/portable-water-filter-press/. [Accessed 3 December 2012].

[29] D. van Halem, "Ceramic silver impregnated pot filters for household drinking water treatment in developing countries," 2006.

[30] K. Morrill, *Evolution of the Mani Press,* 2012.

[31] R. Boni, "Yemen Silver Filter Factory Update," 28 May 2008. [Online]. Available: http://www.potterswithoutborders.com/2008/05/yemen-silver-filter-factory-update/. [Accessed 17 December 2012].

[32] Potters without Borders, "FAQ's," 15 May 2006. [Online]. Available: http://www.potterswithoutborders.com/faqs/. [Accessed 17 December 2012].

[33] United Nations Development Programme, "Poverty Reduction and the MDGs," 2012. [Online]. Available: http://web.undp.org/africa/poverty.shtml. [Accessed 14 December 2012].

[34] CDC, "Household Water Treatment Options in Developing Countries: Ceramic Filtration," January 2008. [Online]. Available: http://www.cdc.gov/safewater/publications_pages/options-ceramic.pdf. [Accessed 27 April 2013].

[35] International Institute for Environment and Design, "Where every drop counts: tackling rural Africa's water crisis," March 2009. [Online]. Available: http://pubgs.iied.org/pdfs/17055IIED.pdf. [Accessed 17 December 2012].

[36] A. E. DuBois, J. A. Crump, B. H. Keswick, L. Slutsker, R. E. Quick, J. M. Vulule and S. P. Luby, "Determinants of Use of Household-level Water Chlorination Products in Rural Kenya," *International Journal of Environmental Research and Public Health,* vol. 7, pp. 3842-3852, 2010.

[37] R. S. Ferreira, T. H. Napoleao, A. F. S. Santos, R. A. Sa, M. G. Carneiro-da-Cunha, M. M. C. Morais, R. A. Silva-Lucca, M. L. V. Oliva, L. C. B. B. Coelho and P. M. G. Paiva, "Coagulant and antibacterial activities of the water-soluble seed lectin from Moringa oleifera," *Letters in Applied Microbiology,* vol. 53, no. 2, pp. 186-192, 2011.

[38] S. L. Kleiman, "Ceramic Filter Manufacturing in Northern Ghana: Water Storage and Quality Control," Massachusetts Institute of Technology, Cambridge, 2011.

[39] The Ceramics Manufacturing Working Group, "Best Practice Recommendations for Local Manufacturing of Ceramic Pot Filters for Household Water Treatment," Centers for Disease Control and Prevention, Atlanta, 2011.

[40] M. Peter-Varbanets, C. Zurbrügg, C. Swartz and W. Pronk, "Decentralized systems for potable water and the potential of membrane technology," *Water Research,* p. 245–265, 2009.