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Point of Use Water Treatment with Forward Osmosis for Emergency and Population Migration Relief

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Point of Use Water Treatment with Forward Osmosis for Emergency and Population Migration Relief

University Scholar and Honor Scholar Thesis

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1. Introduction and Background

1.1. *Water's Role in Emergency and Population Migration Scenarios*

Globally, 780 million people do not have access to an improved water source [1]. Many of these people are victims of emergencies and/or forced population migration, where lack of safe water can cause death.

Emergencies and population migration have a massive impact on populations around the world. There has been a total of 1,934 emergencies reported between 1995 and 2004 [2] and this number is on the rise [3]. Emergencies can include natural disasters, complex emergencies, and disease outbreaks. Between 1995 and 2004, natural disasters alone affected 2.5 billion people, caused 890,000 deaths, and cost 570 billion USD in economic consequences [4]. Population migration is typically caused emergencies, and results in camps of refugees, internationally displaced peoples, or entrapped peoples.

In both emergency and population migration scenarios, access to safe drinking water plays a critical role in saving lives. Excess mortality is often contributed to diarrheal illness caused by unsafe drinking water [5]. In the 1988 flooding disaster in Bangladesh, diarrheal illness was found as the largest cause for death for people under the age of 26 [6]. Some emergency scenarios are caused by unsafe drinking water as well, such as outbreaks of cholera, typhoid fever, shigellosis, dysentery and hepatitis A and E [7]. For these reasons, the first priority for emergency mitigation is to provide potable water, sanitation and site panning to prevent diarrheal illness [8].

1.2. *The Promise and Challenges of Appropriate PoUWT Technologies*

There are two conventional methods of providing potable water during emergencies and population migration scenarios. The first is to package purified and transport it to the site by trucks, air, or foot to the site. Distributing water in this way is costly, and logistically difficult. Another standard practice is to recommend boiling. Though boiling does improve the microbiological quality of waters [9], it has been shown to be ineffective in certain scenarios due to lack of fuel availability, and poor communication of proper boiling and safe water storage (SWS) techniques [7].

A promising alternative to providing access to safe drinking water in emergency and population migration contexts is through the use of point-of-use water treatment (PoUWT) technologies. In the development context, water is increasingly being provided to people in need by PoUWT technologies such as flocculants, disinfectants, ceramic filters, sand filters and SODIS. These technologies have been proven to be effective in many controlled studies [7], which is why the World Health Organization (WHO) promotes PoUWT to produce safe drinking in the development context. The effectiveness of PoUWT in the development context has led to an exponential increase in its use for emergency and population migration scenarios from 1999 to 2007 [7]. PoUWT is not recommended for the acute emergency stage, as it has shown to have a no more than 20% uptake in this stage [7]. However, it has been shown to be effective in the late emergency stage, where there is more a focus on public health programs than acute needs. Therefore, PoUWT can play a critical role in filling the gap between acute emergency relief and the post emergency stage, where the health profile of the community mirrors that of a normal community and the focus of humanitarian aid shifts from relief to development. PoUWT has

been shown to be particularly effective for disaster relief, complex emergencies where relief cannot progress into development and in response to outbreaks caused by unsafe drinking water [7].

There are six metrics that should be considered when selecting an appropriate PoUWT technology. System operations and maintenance is one of the most critical metrics. Any PoUWT technology must be simple, durable, robust, and easy to operate and maintain. Additionally, an appropriate PoUWT technology must have adequate contaminant deactivation, or removal, for the given source water. Treatment for bacteria, viruses and protozoa is a must, but treatment for more persistent contaminants, such as toxic organics and heavy metals, is also worthy of concern because these contaminants are increasingly being found in waters in disaster-prone regions of the world [10], [11]. The total lifecycle cost of materials, distribution, training, and follow-up is also an important factor for selecting a PoUWT system. Obviously, cost can be a limiting factor in emergency situations. Material availability can also play a major role in PoUWT, as it can affect distribution costs, community acceptance and project sustainability. The technology must also have an adequate water production capacity for its suited use. Ideally, the water purification technology must have a flexible production capacity for both household-scale and community-scale use. A final important metric is community-technology interaction. This can include a broad range of things that impact the acceptance of PoUWT technologies, such as: taste of water, ease of use, historical experiences with water, social/cultural aspects, and much more.

The metrics outlined above are useful for evaluating and improving PoUWT technologies; however, since many of the metrics are qualitative and based on community-specific considerations, making objective comparisons between technologies difficult. An object comparison between the efficacies of various PoUWT options can be made with quantitative data about water treatment method such as treatment efficiency, cost per liter of water, community compliance rate, and community diarrheal illness reduction. Table 1 summarizes these metrics for PoUWT technologies that have documented use in emergency situations. Boiling was not included in this review, as few studies could be found on its efficacy.

Table 1. Existing PoUWT technologies surveyed in the literature [7], [12], [13].

	Flocculent / Disinfectant Powders (PuR)	Chlorine Tablets (Aquatabs)	Sodium Hypochlorite (SWS)	Ceramic Filtration	BioSand Filtration	Solar Disinfection
Treatment Efficiency (%)	Bacteria: >99 Viruses: >99 Protozoa: >99	Bacteria: >99 Viruses: >99 Protozoa: >99	Bacteria: >99 Viruses: >99 Protozoa: >99	Bacteria: 99 Viruses: 68 Protozoa: >99	Bacteria: 90 Viruses: 68 Protozoa: 99	Bacteria: >99 Viruses: 99 Protozoa: 90
Cost Per Liter (USD/L)	0.0035	0.0005	0.00008-0.00033	0.001-0.004	0.0008-0.007	0.0006
Compliance Rate* (%)	10 to 95.4	10 to 30	3 to 76.7	23 to 96	Not Available	Not Available
Diarrheal Illness Reduction (%)	19 to 83	5	25 to 84	Not Available	Not Available	Not Available

* Only raw material costs included

Most of the systems in Table 1 have high treatment efficiency and are reasonably priced. However, there are large discrepancies in compliance rate and diarrheal illness reduction for all PoUWT options for which data could be found. This is because these metrics, though partially driven by cost and ease of operations and maintenance, are largely driven by training, follow-up and implementation programming.

Although many of the technologies in Table 1 have been shown to be effective, none have been shown to remove a broad range of persistent contaminants. Moreover, few water treatment technologies are capable of removing persistent contaminants without large chemical or electrical inputs.

1.3. Forward Osmosis (FO)

Forward Osmosis (FO) is an emerging water purification technology that could be used to remove biological, inorganic, and organic contaminants [14], [15]. Engineered FO processes exploit osmosis, which is defined as the transportation of water from a region of higher water potential, to a region of lower water potential.

Figure 1 is diagram for how this works for water purification. A concentrated draw solution is used to draw water from a contaminated source across a selectively-permeable membrane. This membrane allows water to pass, while rejecting the contaminants. The result is concentrated feed water, which can be diluted into the source, and a dilute draw solution. This draw solution can be made of either removable or edible solutes, so that the end product can either be pure water, or a consumable hydrating solution.

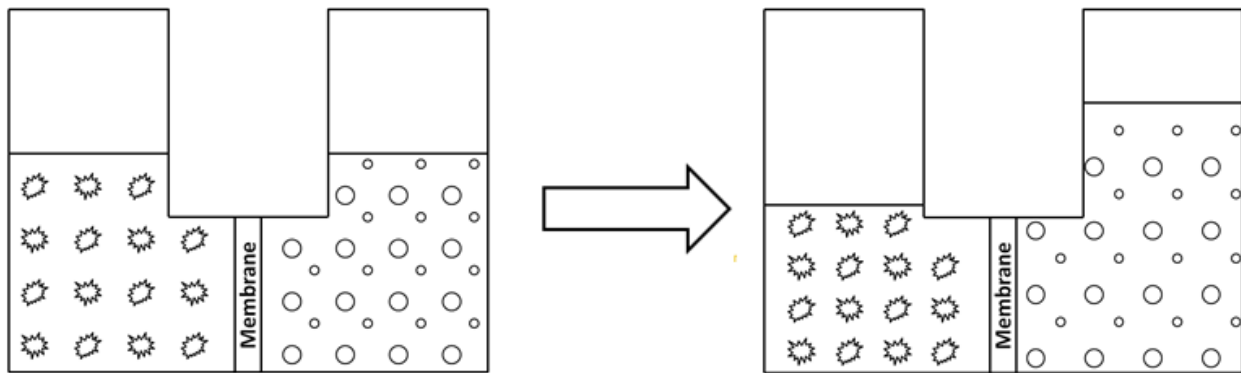


Figure 1. Diagram of the forward osmosis process.

The generalized equation describing water transport for FO is:

$$J_w = A(\sigma_D \pi_D - \sigma_F \pi_F) \quad (1)$$

Where J_w is the water flux, A is the pure water permeability, σ is the reflection coefficient. and π is the osmotic pressure. The subscripts D and F denote the draw solution side and feed solution side respectively.

1.4. Hydration Technology Innovations' Osmotic Water Purification Systems

Hydration Technology Innovations™ (HTI) is already creating a series of osmotic water purification systems that utilize a sugar-nutrient-electrolyte solution as a draw solution. The result is a hydrating drink, similar to Gatorade® or Pedialyte®, which can also alleviate users from malnutrition and diarrheal illness, two of the most prolific killers in emergencies and population migration.

Two systems of particular interest are the HydroWell® and Village System®. Both systems use essentially the same process, but the HydroWell® is designed for a household-scale use, producing 0.7 to 1.2 L/hr, while the Village System® is designed for community-scale use, producing 600 to 800 L/hr per module. The membrane used in these systems is a cellulose triacetate membrane with an integrated polyester mesh support [16].

HTI's process is depicted by Figure 2. Draw solution is fed into a spiral-wound membrane module, similar to that described by Childress et. al. [14]. This module rests in a container of feed water. As water is drawn into the membrane envelop, the product is pushed out of the module into a separate storage container.

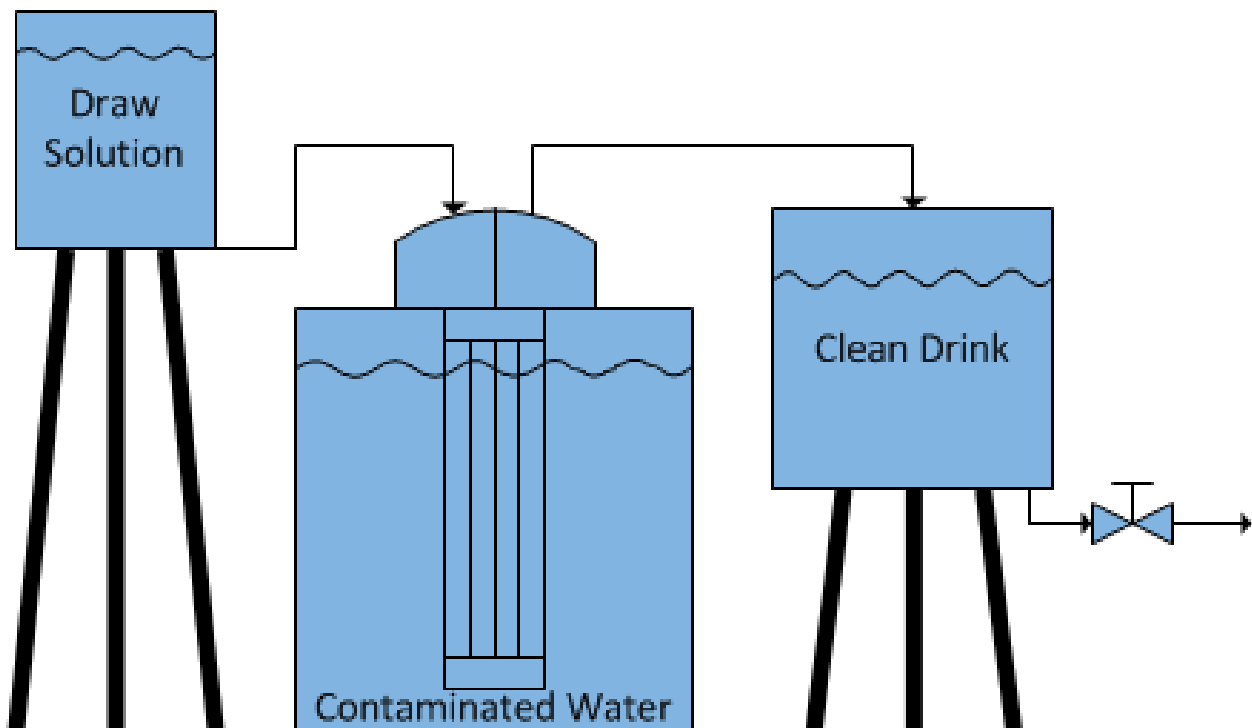


Figure 2. Diagram of HTI's process.

HTI's systems have two major system components, the containment vessels and membrane module, and two major chemical feedstocks, the cleaning reagents and draw solution. The containment vessels can be made of a variety of materials and should not be problematic in any scenario. However, the membrane is susceptible to fouling, like most filters. Fouling can reduce flux, increase contaminant passage, and reduce the membrane's longevity [17–19]. Since the membrane needs to be made in high-

end manufacturing facilities, it is of the utmost importance that it has a high longevity and low failure rate. Therefore, fouling control is critical. Fouling control is typically achieved through the first major chemical feedstock: a cleaning reagent. HTI recommends the use of sodium metabisulfite (SMBS). The final system feedstock, the draw solution, is primarily composed of sugars and electrolytes. HTI has proprietary solutions that they sell; however, it is possible to make similar solutions from a variety of sources. Though this is not dealt with in this paper, novel draw solution design for this system is an interesting area for future studies.

1.5. Research Objectives

The purpose of this work is to evaluate HTI's systems for emergency and population migration relief, and to establish a foundation upon which future system improvements can be made. This evaluation will be based on the metrics for an appropriate PoUWT technology established in Section 1.2. HTI's two systems already have a flexible water production capacity; however, there are still questions remaining about contaminant removal, lifecycle cost, material availability, operations and maintenance, and community-technology interaction. Three key areas were explored in this paper: contaminant removal, lifecycle cost, and material availability.

Though the HydroWell® and Village System® have been shown to meet or surpass reductions in bacteria, viruses, and cysts specified by the US Environmental Protection Agency [20], no data has been published on their removal of more persistent contaminants, such as heavy metals. Moreover, though many studies have been conducted on heavy metal rejection for reverse osmosis (RO) systems [21], [22], none have been done on the rejection of heavy metals in FO systems. Inorganic contaminant removal in the RO and FO modes are examined in this work.

For HTI's systems to be a viable PoUWT option, it must be cost competitive with existing technologies. Due to the high cost of the membrane and draw solution, HTI's systems will cost more than the PoUWT options outlined in Table 1. However, it is important to note that HTI's systems produce a potable drink that can alleviate diarrheal illness and malnutrition as well as hydrate the user, as opposed to just water. Regardless of the systems' technical advantages, it will still be important to minimize costs. In this work, the primary system costs are identified and used to model the overall system cost as a function of process variables. This model was used to determine a cost-minimal operating condition and to conduct a sensitivity analysis on the impact of cost reductions in key areas.

HTI's recommended cleaning reagent, SMBS, may be available in limited supply in different regions of the world. Therefore, it is important to assess the efficacy of other common cleaning reagents for HTI's membrane. Some reagents can degrade the membrane, so this work studied the impact of various cleaning reagents on membrane performance.

2. Materials and Methods

2.1. Determination of Contaminant Rejection

2.1.1. Contaminant Rejection in the Reverse Osmosis Mode

HTI's 081118 membrane (HTI, Albany, OR) contaminant rejection was tested with a lab-scale cross-flow reverse osmosis system. Copper nitrate trihydrate (Acros Organics), lead nitrate (Fischer Scientific), chromium nitrate nonahydrate (Acros Organics), and diarsenic pentoxide (Acros Organics) were tested as model heavy metal contaminants. Feed solutions of 0.01M NaCl () and 10 ppm of each heavy metal were adjusted to a pH of 5.0 ± 0.1 with 0.1M NaOH_(aq) (Fischer Scientific) or 0.1M HCl_(aq) (Sigma Aldrich). All tests were conducted at 104 psi, 25°C and 0.6 L/m cross-flow.

2.1.2. Contaminant Rejection in the Forward Osmosis Mode

HTI's membrane was tested in a lab-scale cross-flow forward osmosis system, using the same feed solutions as those used in the reverse osmosis testing. A draw solution of 260 g/L food-grade sugar (Dominos, Yonkers, NY) was used to produce the same mean area normalized flux, about 2.4 LMH, as that in the reverse osmosis testing. All tests were conducted at 25°C and 0.6 L/m cross-flow.

2.1.3. Determination of Inorganic Contaminant Concentrations

All tests were conducted with an inductively coupled plasma mass spectrometer (ICP-MS). The feed, draw, and permeate sample solutions were run at 10, 5 and 1 times dilution respectively. Triplicates were conducted for all trials and mean values were reported.

2.2. Lifecycle Cost

2.2.1. Cost Model

The draw solution and membrane module are the two primary material costs. These costs are related to the total cost per volume of drink produced (\dot{C}_{total}) by Eq. 2:

$$\dot{C}_{total} = \left(\frac{C_m}{L_m}\right) \left(\frac{1}{\dot{Q}}\right) + \left(\frac{C_b}{V_b}\right) \left(\frac{1}{D}\right) \quad (2)$$

Where C_m is the cost of the membrane module, L_m is the lifetime of the membrane module, \dot{Q} is the drink product flow rate, C_b is the cost of the draw solution per bag of draw solution, V_b is the volume of draw solution per bag of draw solution, and D is the dilution factor, which is equivalent to the total volume of product produced divided by the volume of draw solution used to produce that product. $\frac{C_m}{L_m}$ and $\frac{C_b}{V_b}$ are considered the membrane and draw solution cost constants, respectively.

2.2.2. HydroWell® Testing

To determine optimal process flow conditions, tests were conducted with modified HTI HydroWell® systems (HTI, Albany, OR) that are illustrated in Figure 4. These systems were retrofitted with needle valves (NoShok) to control the draw solution flow rate, and graduated cylinders to measure the draw solution flow rate. Product flow rate, draw solution flow rate, and feed water flow rates were measured each hour. Draw solution provided by HTI was used. All tests were conducted at 22°C.

2.3. Material Availability: Membrane Degradation Study

Membrane samples from HTI's Hydrowell® system were soaked for 24 hours in hydrogen peroxide (Acros Organics), sodium hypochlorite (Acros Organics), ethanol (Acros Organics), sodium dodecyl sulfate (Acros Organics), Minncare® (Mar Cor Purification, Philadelphia, PA), and sodium metabisulfite (Acros Organics), at the concentrations shown in **Table 2**.

Table 2. Test matrix of cleaning solutions used in the membrane degradation study.

Reagents	Concentration (% Mass)
Minncare® (MC)*	100
Ethanol (EtOH)	50
Sodium Hypochlorite (NaClO)	0.5
Hydrogen Peroxide (H ₂ O ₂)	0.1
Sodium Dodecyl Sulfate (SDS)	0.4
Sodium Metabisulfite (SMBS)	14

**A proprietary blend of peracetic acid, acetic acid, and hydrogen peroxide.*

These cleaning reagents and concentrations were chosen based on reagents and values found in the literature [23–25]. The 24 hour soak time in the cleaning reagents was chosen based on the expected time of exposure to the cleaning reagents during the membrane's lifetime, given a consistent cleaning protocol. These membranes were soaked in DI water for 24 hours prior to characterization. The membranes were characterized with pure water permeability tests, and sodium chloride rejection tests. Pure water permeability tests were conducted at 0.5 LPM cross-flow, 25°C, and 150, 200, 250 and 300 psi with a deionized water feed. Sodium chloride rejection was determined at 0.5 L/m, 25°C, and 225 psi with a 2000 mg/L NaCl feed solution.

3. Results and Discussion

3.1. Contaminant Rejection

It has been shown that water flux can impact the observed rejection in RO systems [21], therefore it was important to insure that fluxes were consistent between RO and FO tests. Fluxes were measured throughout each experiment. The average flux of all experiments was 2.4 LMH, with a standard deviation of 0.8 LMH, which is within typical error for the systems used.

Figure 5 is a summary of all the observed rejection data from tests in both the RO and FO cross-flow systems. All average observed rejections exceed 97.6% for both tests, which is very high. It has been shown that cations with higher valences are rejected more easily than cations with lower valences, because hydrated radius increases with valence, thus lowering diffusivity [22]. Previous studies of HTI's membranes also show high rejection of monovalent salts [16], [26]. Moreover, previous studies show comparably high rejections for cellulose acetate membranes [21], [22]. Therefore, the high observed rejections were expected. Arsenic and chromium should show higher rejections in the RO testing due to

their higher valence; however, since rejections are so high for all species, there was no discernible difference within the experimental error.

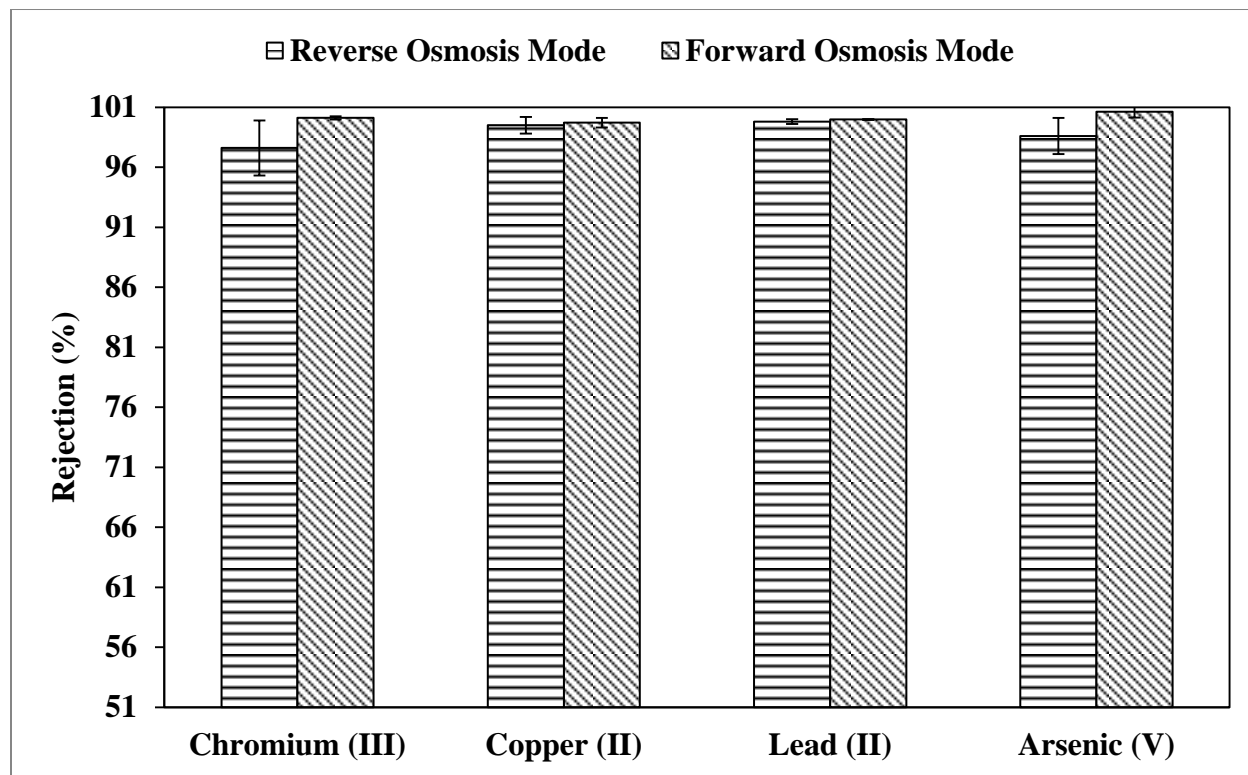


Figure 5. Removal of chromium (III), copper (II), lead (II) and arsenic (V) at pH 5, 0.01M NaCl, 2.4 LMH flux, 0.6 L/m cross-flow and 25°C.

The sugar draw solution used for the FO studies was composed of mostly nonpolar solutes. Having a nonpolar draw solution should negate any charge effects that could impact rejection. Without charge effects, the FO and RO process should behave similarly in terms of rejection. The data gathered show an increase observed rejection in the FO mode relative to the RO mode. However, it is important to qualify these observed rejections with the experimental limits of the test. In the FO tests, the permeate is diluted into a bulk draw solution. From this dilution, and the minimum detection limit of the ICP-MS, it is possible to calculate the maximum observable rejection. For the chromium, copper, lead and arsenic tests, the maximum observable rejections are 99.5, 99.5, 99.9 and 99.5 percent respectively. All observed rejections exceeded these figures for the FO tests, but it can only confidently be said that the maximum observable rejections have been achieved. The maximum observable rejection values are all within the experimental error of the RO tests, which suggests that rejection data in the RO and FO mode are similar.

This study does not necessarily indicate the performance of HTI's system for all conditions. Heavy metal rejection is largely dependent on the feed water. For instance, pH can change both the speciation [27–31] and membrane properties [32]. Moreover, the presence of other solutes, such as natural organic matter or electrolytes, can significantly impact the rejection by either complexing with the heavy metal,

or by contributing to charge effects [33–36]. Beyond considerations of the feed water, HTI’s system is stagnant on the feed water side, unlike the cross-flow systems used to characterize HTI’s membrane. This results in significant concentration polarization differences that can impact salt flux. Additionally, the tests conducted were at a higher area normalized flux than that of HTI’s systems, which could lead to a higher observed rejection. However, the results shown in Figure 5 show very high heavy metal reductions. Similarly high rejections should be observed for a variety of feed waters and system designs.

3.2. Lifecycle Cost

3.2.1. Cost Model

Data collected from HTI’s HydroWell® system is presented in Figure 6, with a fourth order polynomial line fit. Though this line has no physical significance, it allows for modeling of the system’s behavior. Note that the product flow rate and dilution factor are inversely related. This is an expected result. If the draw solution flow rate is slow, each volume of draw solution has a long residence time within the membrane module and the draw solution is diluted significantly by the permeate before exiting the module. The dilution results in a lower mean osmotic pressure in the membrane module, which, by Eq. 1, results in a low product flow rate. On the other hand, if the draw solution flow rate is fast, each volume of draw solution has a small residence time and the draw solution is still concentrated while exiting the module. This results a high mean osmotic pressure throughout the system, which leads to a high product flow rate.

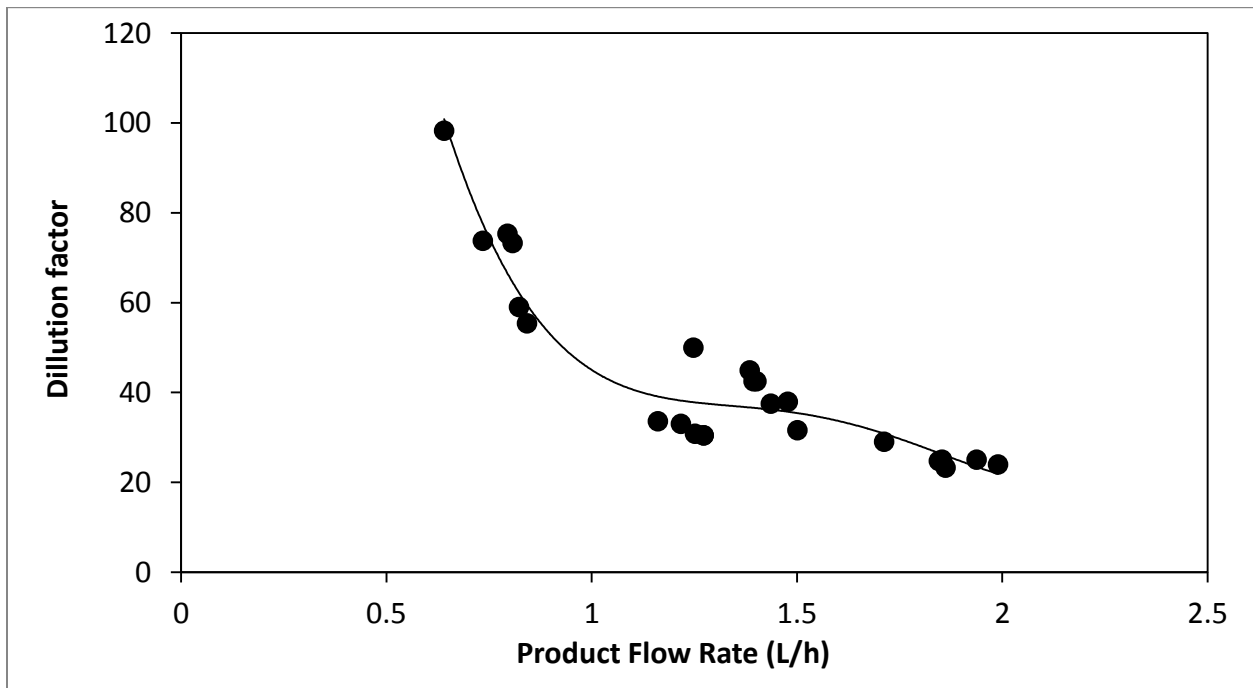


Figure 6. Dilution factor as a function of product flow rate from HydroWell® data at ~22°C

Since product flow rate and dilution factor are related inversely, there must be a cost minimal operating condition according to Eq 2.

3.2.2. Sensitivity Analysis

To determine the cost minimal operating condition, the polynomial equation found from Figure 6 was combined with Eq 2. Commercial values were used for membrane and draw solution cost. These values were \$300.00 and \$5.00, respectively. Values provided by HTI were used for membrane longevity and draw solution volume per bag. These values were 90 days and 410 mL, respectively. The result was that the system could be operated at draw solution and product flow rate of 0.06 and 0.6 L/hr respectively at a minimal cost of 0.34 USD/L.

Cost reductions can be achieved through decreasing the membrane or draw solution cost constants. The membrane cost constant can be decreased by reducing manufacturing and distribution costs, or extending the membrane's longevity. The latter can be actualized by using better cleaning reagents and pretreatment systems that remove harmful foulants. The draw solution cost constant can be decreased by reducing manufacturing and distribution costs. This can be done by locally sourcing the draw solution, and having methods of creating draw solution on-site. A sensitivity analysis of these cost reductions was conducted. The results are illustrated Figures 7 and 8.

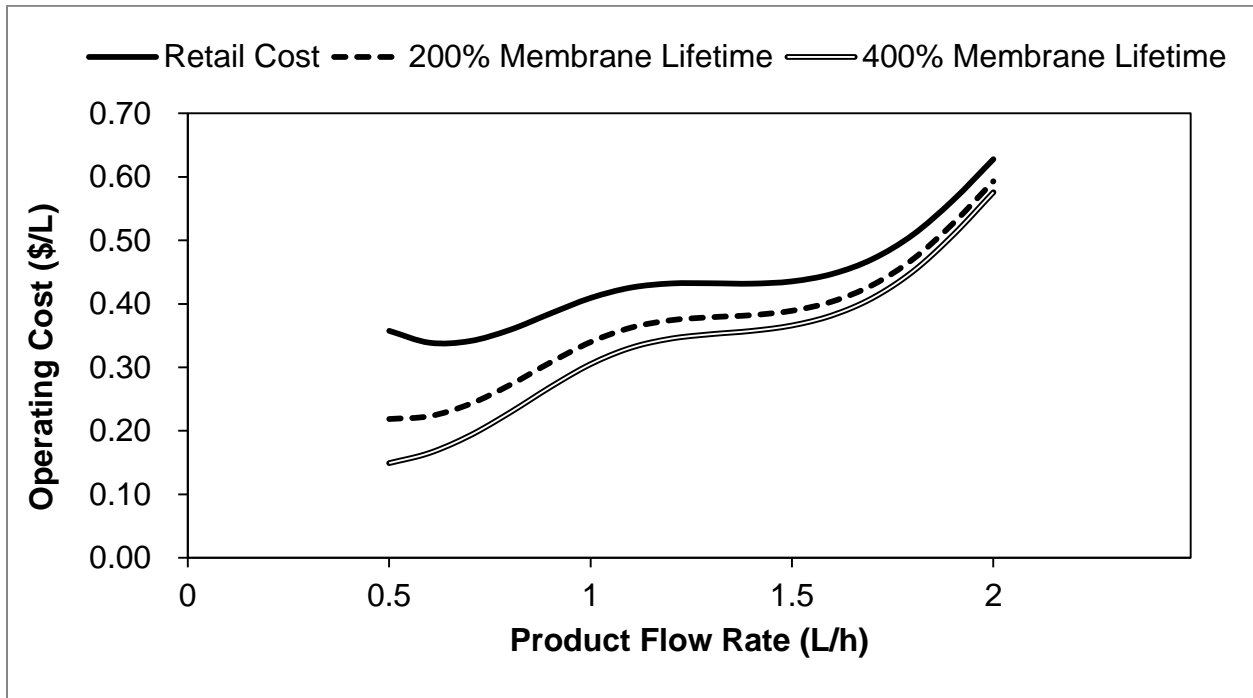


Figure 7. Cost sensitivity to a 200% and 400% extension of membrane longevity, based on the cost model developed in Section 3.2.1.

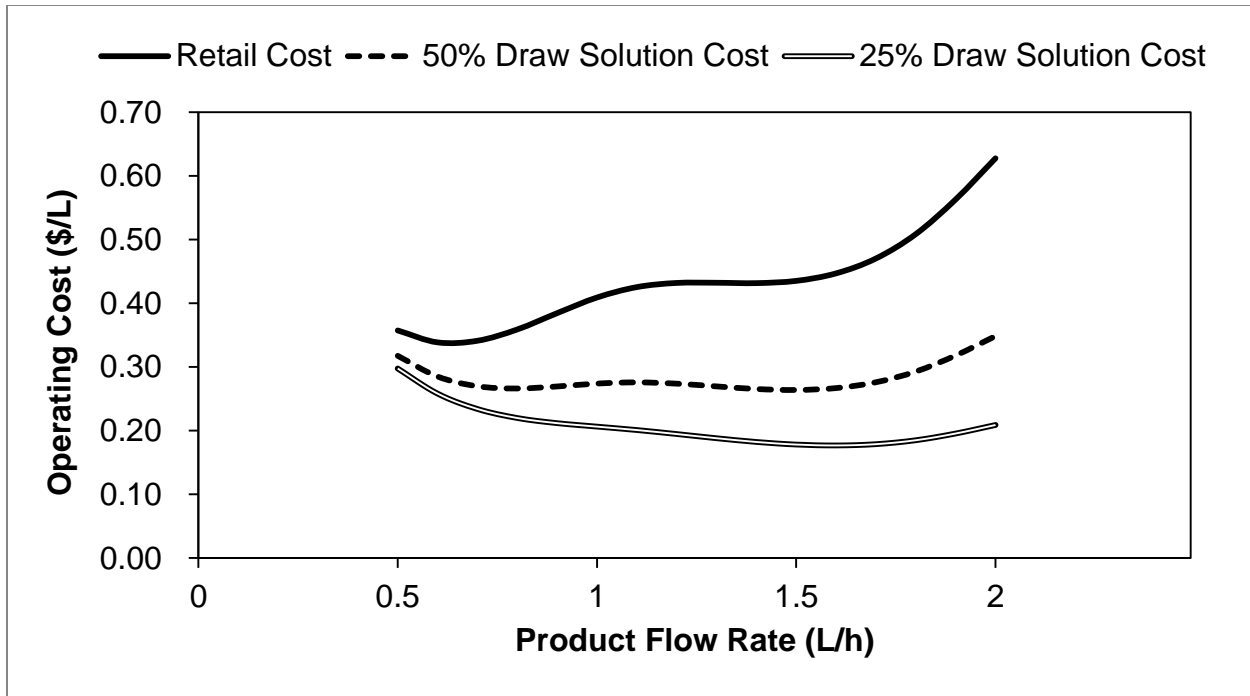


Figure 8. Cost sensitivity to 50% and 25% reductions in draw solution cost, based on the cost model developed in Section 3.2.1.

As the membrane cost constant decreases, the cost optimal product flow rate shifts to the left. This behavior occurs because as the membrane cost constant becomes smaller relative to the draw solution cost constant, the draw solution becomes the cost-driving material. Therefore, it is desirable to increase the dilution factor, so that the maximum amount of product is produced per liter of draw solution. However, a high dilution factor will result in a low product flow rate.

Conversely, as the draw solution cost constant decreases, the cost optimal product flow rate shifts to the right. This behavior occurs because as the draw solution cost constant becomes smaller relative to the membrane solution cost constant, the membrane becomes the cost-driving material. Therefore, it is desirable to maximize the product flow rate so that the maximal volume of product is produced before membrane failure. However, a high product flow rate means a low dilution factor, and, depending on the draw solution, there is a minimal dilution factor of operation. For HTI's draw solution, this number is about 13. If the dilution factor drops below this point, the product will be too saline for hydration.

A combination of minimizing the draw solution and membrane cost constants can significantly reduce the overall system cost. Initial calculations show that the draw solution can reasonably be reduced to a cost of 0.60 USD per bag. Furthermore, it might be reasonable to reduce the cost of the membrane to 200.00 USD in humanitarian situations. In this case, the minimum operating cost would be as low as 0.10 USD/L. Though this price is still high relative to other water purification systems, it must be considered along with the superior contaminant removal and additional benefits of HTI's process.

3.3. Material Availability: Membrane Degradation Study

Figures 9 and 10 show the impact of select cleaning reagents on the water permeability and NaCl rejection of HTI's membrane. Hydrogen peroxide, sodium dodecyl sulfate (SDS) and sodium metabisulfite (SMBS) all have a statistically negligible impact on the membrane, which means that they are all viable cleaning reagents. Ethanol and sodium hypochlorite increase the permeability and decrease the rejection, indicating that they are causing degradation in the membrane's performance. The sodium hypochlorite causes degradation by oxidizing the alcohol groups to carboxyl, aldehyde and ketone groups [37]. The ethanol could cause degradation by either dehydrating the membrane, which could cause cracking upon rehydration, or by de-acetylation [38]. Interestingly, Minncare® increased water permeability while maintaining similar salt rejections to the water control. This result was unexpected, but still implies that Minncare® would be an effective cleaning reagent. Further studies could illuminate the mechanistic cause to this behavior.

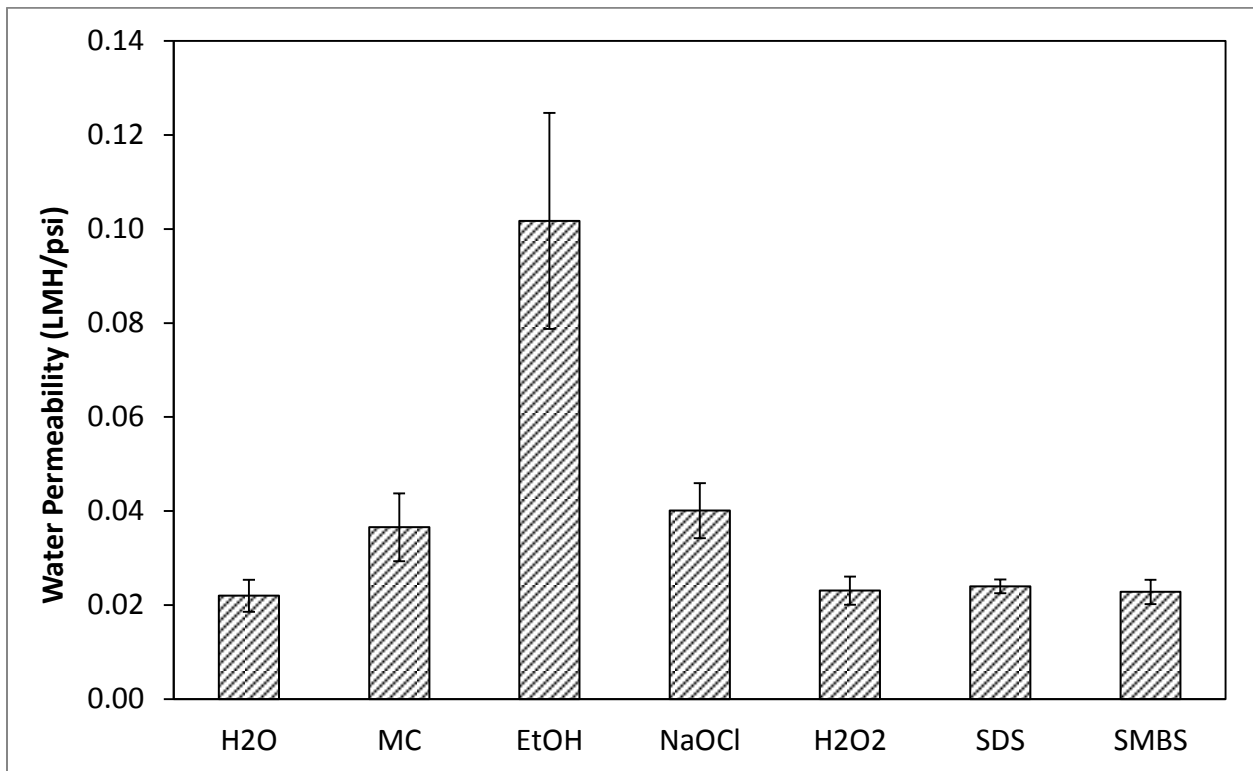


Figure 9. Water permeability of HTI's 081118 membrane after 48 hours of exposure to cleaning reagent. Data gathered at 0.5 L/m, 25°C, and at pressures of 150, 200, 250 and 300 psi.

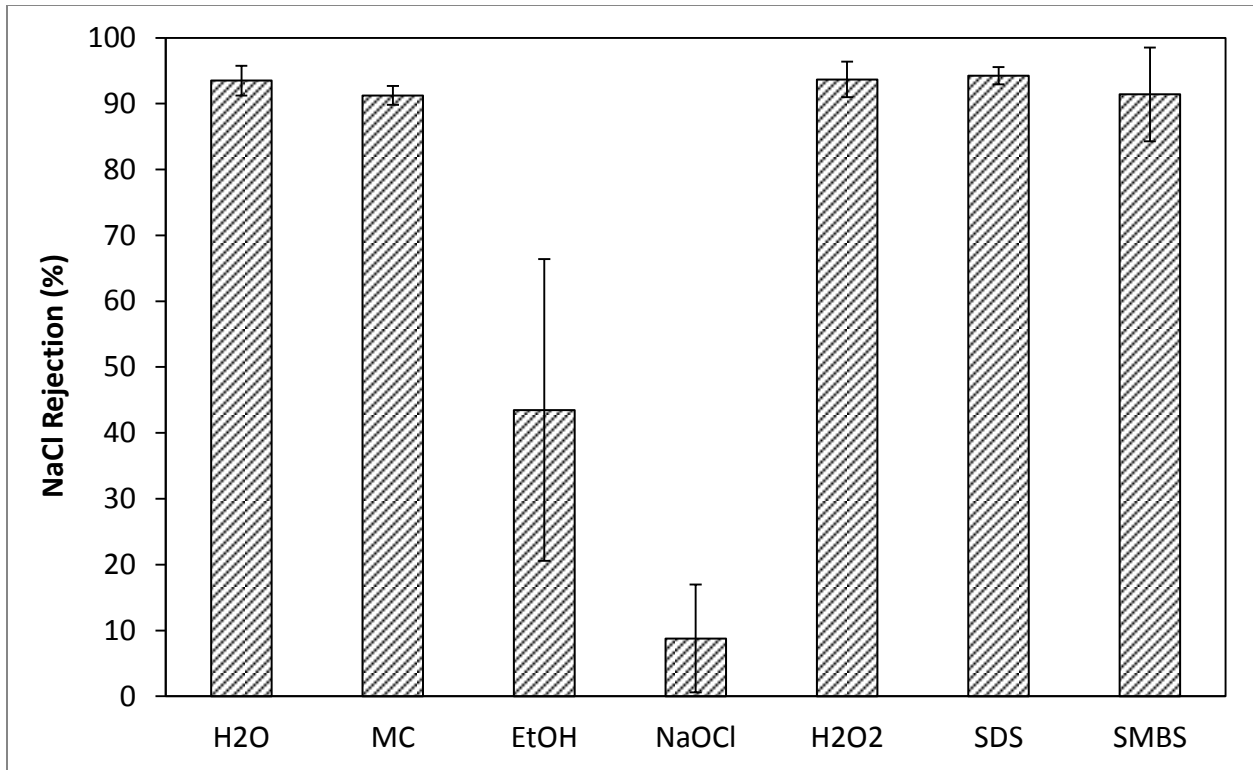


Figure 10. Sodium chloride rejection of HTI's 081118 membrane after 48 hours of exposure to cleaning reagent. Data gathered at 0.5 L/m, 25°C, and 225 psi with a feed of 2000 mg/L NaCl.

4. Conclusions

HTI's osmotic water purification systems have been proven to meet four of the six criteria outlined for a PoUWT technology. Between the Village System® and HydroWell®, there is the possibility for household-scale and community-scale production capacity. Additionally, HTI's systems have contaminant removal capabilities that exceed any PoUWT technology that has been well documented for emergency relief and population migration scenarios. Though the cost per liter of product may be high compared to other PoUWT technologies, HTI's systems have the potential to be lowered to economically feasible levels. Furthermore, they have an additional value proposition over existing PoUWT technologies, in that they produce a drink that can alleviate malnutrition and diarrheal illness, and can remove persistent contaminants such as heavy metals. Finally, though the membrane must be shipped to the site, most of the systems' materials are readily available in many countries. A variety of cleaning reagents can be used, and the draw solution can be made from many different combinations of sugars and electrolytes.

Further evaluation must be conducted in order to fully evaluate HTI's systems' efficacy in emergency relief and refugee scenarios. HTI's systems have been shown to be technically sound; however, one of the most important aspects to the success of these technologies are how they are received by the community. This will largely determine the effectiveness of the system at reducing diarrheal illness and maximizing compliance rate. Long term operations and maintenance studies must be conducted to determine ease of use, robustness, and durability under extreme conditions. Furthermore, the

community-technology interaction must be evaluated. Moreover, improvements to the current system design may need to be made in order to optimize its efficacy for emergency and population migration relief. Further work could result in a system that could save the lives of those most in need.

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