Mechanical Water Purification System

A Major Qualifying Project
submitted to the faculty of

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment for the
Bachelor of Science Degree
In Mechanical Engineering

Submitted by:
Minh-Chau Doan, ME
Marisol Sanchez, ME
Hajera Siddiqui, ME
Kai Yeaton, ME

Advised by:
Professor Fiona Levey, ME

Date of Submission:
April 6, 2021

Table of Contents

Abstract

The clean water crisis in the Caribbean Islands can be attributed to the unpredictable natural disasters that occur every year. These natural disasters can contaminate freshwater sources and damage water infrastructure. This proposal combines human power, in the form of pedaling, and reverse osmosis for purifying seawater in the Caribbean Sea after natural disasters. The final results demonstrated that the functioning prototype was able to filter diluted seawater, however the design was not fully sustainable in terms of efficiently using human power. To accommodate a family of five, the device was able to produce 0.76 gallons of clean drinking water per hour. Future considerations were suggested for producing water at a faster rate with less human effort.

1.0 Introduction

As the human population increases, so does the clean water crisis. To this day, the clean drinking water shortage has affected 780 million people worldwide. Only 3% of the world's total supply of water is considered freshwater. The remaining 97% of the world's water is either undrinkable salt water or frozen in glaciers. Natural disasters can cause damage to clean water infrastructure, creating a shortage of drinking water. Clean water for communities in the Caribbean Sea is heavily affected by a variety of natural disasters, including floods and tropical storms. Clean water sources in the Caribbean Sea region can be contaminated by inundation from seawater and also by infrastructure damage from natural disasters. In the wake of these disasters, access to clean water is a top priority to ensure the survival and health of the victims. With the right resources, these coastline communities can take advantage of their proximity to a large water source: the ocean. The goal of this MQP project was to investigate the feasibility of using reverse osmosis and human power to desalinate seawater. Potential applications of such a device would make clean drinking water more accessible to communities in the Caribbean Sea region during a disaster relief situation.

2.0 Background

2.1 Project Region, Disaster, and Water

The Caribbean region has increasingly unpredictable weather patterns that cause continuous water insecurity. One the islands, surface water, spring water, and groundwater are the natural freshwater sources which get replenished through rainfall. However, unpredictable rainfall and drought have been contributing to an inadequate and deplenishing water supply on some islands. In Domenica, dry seasons can lead to a 50 percent decrease in water production and cause problems for people in need of clean water (Cashman, 2013). Additionally, groundwater faces problems with overharvesting, saline intrusion, and contamination. In Jamaica, improper waste disposal has led to increased nitrate levels in the Liguanea aquifer, which can lead to overgrowth of plants and algae (Cashman, 2013). Countries in the Caribbean region are looking for clean water alternatives.

Surrounded by seawater, the islands are looking towards desalination to help provide reliable clean water. Over the span of 8 years, between 2007 and 2015, 68 desalination plants were built in the region to provide 782 thousand cubic meters (207 million gallons) of purified water per day (Balch, 2015). St. Martin, St. Thomas, and the British Virgin Islands rely entirely on desalination for water (Balch, 2015). This technology has provided clean water to many people in the Caribbean region, however natural disasters still make it difficult to access these resources.

The primary natural disasters that affect water scarcity in the Caribbean region are hurricanes and earthquakes (Gibbs, 2001). The region is split amongst several tectonic plates which causes frequent seismic activity. In 2010, Hurricane Tomas damaged a water reservoir in St. Lucia and limited the water supply for 80 percent of the population (Cashman, 2013). Between 1886 and 1999 (114 years), 1050 tropical storms formed in the North Atlantic Ocean, with half of the storms having the strength of an average hurricane (Gibbs, 2001). High wind speeds and heavy rains from these storms lead to floods, property damage, damage to infrastructure and more. As a result, clean water and energy infrastructure are vulnerable to damage from these natural disasters. This project will focus on the Caribbean region because of the need for a clean water solution after natural disasters occur.

Table 1. Project Scope (Menzies, 1999; World Sea Temperature, 2020)

Region	Disaster	Water
Caribbean Sea Region: Haiti, Domenican Republic, Puerto Rico, Bahamas, Barbados, Aruba, and more.	**Hurricanes, Tsunamis, Tropical Storms:** Storm Season is from June to November. More frequent storms occur in September. Yearly number of storms is approximately 8.	**Seawater:** Salinity of about 35 ppt Ocean temperature ranges from 80 - 85 F throughout the year.

2.2 Clean Water Crisis

Access to clean drinking water remains an issue across the world. The World Health Organization estimates that 2.2 billion people have been living without safely managed water services as of 2017 (WHO, 2019b). Of this group, approximately 435 million people get their water from unsafe springs and wells, while 144 million people get their water from unfiltered sources such as ponds and lakes (WHO, 2019b). Due to a lack of clean water access, roughly 829,000 people die each year (WHO, 2019b). The clean water crisis continues to this day.

2.2.1 Climate Change and Clean Water Crisis

Clean water contamination often stems from natural disasters occurring in a specific region. Although natural disasters are inevitable, they are further strengthened and become more frequent due to the indirect effects of climate change. Greenhouse gas emissions have increased the Earth's temperature and have caused global warming. Due to the rising temperature, many natural disasters are not only more frequent but also longer lasting.

Drought is caused by high temperatures and lack of rainfall in a region. During a drought, bodies of water significantly decrease leaving areas with small amounts of stagnant water. This small amount of stagnant water is also prone to having higher levels of contaminants and even salinity, if located near the coast. This occurs because there is less volume to dilute, meaning higher concentrations of substances found in the water, such as pollutants. Additionally, higher temperatures affect the growth of plant life and algal blooms such as toxic cyanobacteria (Mosley, 2015).

Long-lasting, heavy rains have also profoundly affected all living things on Earth. A 2019 study found that increases in the global temperature of 2.7 to 3.6 degrees can increase the duration of heavy rainfalls by 26% (Berwyn, 2020). With an increase in global temperature, the duration of precipitation is lengthened. Residential areas that are located by nearby rivers are affected by torrential rains that can cause floods. These floods can impact water sources because wastewater and seawater can contaminate them through flooding. Flooding is a common occurrence but is more likely for coastal communities as their residential areas are often located near a body of water.

Hurricanes are also indirectly exacerbated by global warming. Warmer temperatures lead to an increase in ocean temperatures, which then causes more frequent hurricanes (EDF, n.d.). When Hurricane Katrina happened in 2005, it brought havoc everywhere it touched. In many areas, the storm's flooding reached significant water sources causing severe contamination of drinking water. The flooding caused an outbreak of E. coli that triggered gut diseases among the population. The outbreak's onset was due to the lack of clean and safe water and food sources, which caused people to resort to consuming contaminated substances (Clear Water Systems, 2018).

The major disasters that affect the Caribbean Sea countries are hurricanes and earthquakes (Gibbs, 2001). The multitudes of hurricanes that affect the area are devastating. Due to frequent hurricanes, such as Hurricane Mathew and Hurricane Maria, waterborne diseases have affected many people. Many experienced stomach-related symptoms and infections from drinking the contaminated water (Delgado, 2017).

In 2017, many hurricanes occurred in the late summer and early fall months. One of the places in the Caribbean Sea region that was devastated was Puerto Rico. Puerto Rico faced the brunt of Hurricane Maria and Hurricane Irma's effects, which caused a lot of storm runoff. However, the Caribbean region also faces drought. Drought warnings are usually issued in February and last through March. However, drought has started to last until the end of May (White, 2016).

2.2.2 Some Other Regions In Need of Clean Water

The Caribbean Sea region is not the only place on Earth that is in need of clean drinking water. For example, in 2020 Sudan saw massive flooding along the Nile river, due to torrential rain, during the months of August and September. Approximately 100,000 people lost access to drinking water because of the contamination from the flooding (Save the Children, 2020).

The country of Chad is another example of people needing access to clean drinking water. Lake Chad has been drying up the past couple of years causing drought in the country. It has decreased to about 1/20th of its original size. This has been increasingly concerning since Lake Chad is a major source of water for the people of Chad. The water of Lake Chad has also become increasingly contaminated and the aquifers for the lake are at risk of pollution. Waste is a common contaminant found in Lake Chad, making the people who drink it's water prone to waterborne diseases. Only about fifty percent of people in Chad are able to obtain safe drinking water, and most of that is utilized for farming (Enriquez, 2013).

The clean water crisis has also occurred in the Americas. For example, in 2018 Hurricane Harvey caused significant destruction and flooding in Texas. This flood caused about 800 wastewater treatment plants to spill into the environment and contaminate the Guadalupe River. After the hurricane, a study conducted on the Guadalupe River found E. coli and fecal contaminants in the water (University of Texas at San Antonio, 2018). The water from the Guadalupe River is a significant water source for cities in the area, so this finding was especially concerning. Access to clean water can be especially limited after natural disasters.

2.2.3 Current Disaster Relief Efforts

Currently, there are many programs designed for water purification for disaster situations. For example, a company called Meco produces water filtration systems for desalination, as shown in Figure 1. Meco has designed their product specifically for disaster relief and utilizes reverse osmosis for filtration (Herold, 2018). Meco's model has a flow rate that ranges from 1-3 GPM to 59-68 GPM. A typical Meco customer would receive the product pre-assembled and ready to use. Another company that specializes in reverse osmosis systems is Applied Membranes, shown in Figure 2. Applied Membranes have their systems delivered in 20' or 40' ISO containers making it easily feasible for their customers (AMI, n.d). These two companies are typical for large scale water purification, but luckily small scale efforts also exist.

Figure 1. Example of a MECO Water Filtration System (Herold, 2018)

Figure 2. Example of an Applied Membranes Desalination System (AMI, n.d)

Small scale water purification efforts have been gaining popularity, especially among disaster relief organizations. Nippon Basic Company is a company that designed a system called Cyclocean, shown in Figure 3. Cyclocean is a bicycle that utilizes pedaling as a mechanical power source for water filtration. It contains one pre-filter and three regular water filters within the system. The system has been beneficial during natural disaster situations in Japan because of its convenience and accessibility to many people (Donovan, 2018). However, this bike is limited to freshwater. The same company also developed a water filtration system for desalination, called Desaliclean, shown in Figure 4. Unfortunately, the cheapest model costs 2.2 million JPY, roughly 21,148 USD, making it inaccessible for most people (UNIDO, n.d.). Desaliclean uses a gasoline engine, which requires maintenance if there are any issues. The system also only works with seawater on the brackish side, which can be a limitation if this water is not available (Nippon Basic Co, 2006).

Timothy Whitehead, an industrial designer, has created a smaller scaled water purification system. After traveling to Zambia and seeing the water crisis conditions, he designed the Pure Water Bottle to be used for freshwater sources, as seen in Figure 5. This device contains a plunger, a double chamber, and a UV bulb. It takes approximately two minutes to get purified water free from bacteria and other particles (Donovan, 2018). The Pure Water Bottle also compares to another small scale water filtration device called the LifeStraw. The LifeStraw Community created a device that effectively filters sediments, viruses, and microplastics. Its filters have a filtration lifespan of 26,000 gallons (LifeStraw, 2020).

Figure 3. Cyclocean Device (Donovan, 2018)

Figure 4. Two Desaliclean Models (UNIDO, n.d.)

Figure 5. Pure Water Bottle (Donovan, 2018)

A non-profit organization called Caribbean Desalination Association is a group that helps with desalination and water reuse efforts (CaribDA, n.d.). This organization also works to create a movement that raises awareness over the current water problem in the Caribbean Sea region. This organization specializes in using evaporation for desalination. Caraçao was the first country in the world to do this. Figure 6 shows an example of a desalination plant currently used by the Caribbean Desalination Association (CaribDA, n.d.). Small-scale desalination devices will be discussed later in section 2.6. These devices include the popular katadyn survivor.

Figure 6. CaribDA Desalination Plant (CaribDA, n.d.).

2.2.4 Mental Health During Disaster Situations

People affected by a natural disaster can often be traumatized by the event. Survivors can experience PTSD, depression, anxiety, and many other mental illnesses after living through a destructive natural disaster. Figure 7 shows the typical mental health responses from individuals affected by natural disasters. The Pan American Health Organization (PAHO) published a study regarding the effects of natural disasters on individuals in the Caribbean Sea following natural disasters (2012). This study showed that while some people fall into a depressive state, others can show signs of resilience and persevere through their situations. A survey for a psychological response following a Barbados cave-in showed that access to water was in the top five priorities for those involved (Hackett, Ring, & Phillips, 2011). While people experience the effects of living through a traumatic effect, instincts often kick in, and people try their hardest to do what they need to survive.

Emotional reactions	Cognitive reactions	Physical reactions	Interpersonal reactions
• Fear • Grief • Anger • Guilt • Feeling depressed or sad • Feeling despair or hopelessness • Resentment • Helplessness • Emotional numbness • Feeling overwhelmed	• Trouble concentrating or remembering things • Confusion • Difficulty making decisions • Preoccupation with the event • Recurring dreams or nightmares • Questioning spiritual beliefs • Attention span • Memory problems • Self-blame	• Tension • Fatigue • Restlessness • Sleep disturbances • Bodily aches and pains • Increase or decrease in appetite • Hypertension, heart pounding • Racing heartbeat • Nausea • Quick startle response • Headaches	• Feeling more distrustful • Irritability • Sleep problems • Crying easily • Increased conflicts with family • Withdrawal from others • Feeling rejected and abandoned by others • Being judgmental; being over-controlling

Source: Adapted from New South Wales (NSW) Health, .Disaster mental health response handbook, North Sydney, NSW: NSW Health, 2000.

Figure 7. Mental Health Reactions During Natural Disasters (PAHO, 2012)

2.3 Salt Water

Although humans need freshwater to survive, only 3% of the world's total water supply is fresh. The oceans are an untapped resource, with only 300 million people consistently drinking desalinated water (USGS, 2018). Seawater can be purified to make clean water and reduce the dependence on scarce freshwater.

2.3.1 Properties of Seawater

Seawater accounts for around 70 percent of the Earth's water. It is a mixture of about 95 percent water and 5 percent substances such as salt, a myriad of particulates, atmospheric gases, and more. Compared to freshwater, seawater has a higher viscosity, density, and boiling point while also having a lower freezing point (Byrne et al., 2018). The upper 100 meters (340 feet) of the sea hold various substances such as carbohydrates, amino acids, and organic-rich particulates. The upper 100 meters of the sea is also where most dissolved inorganic carbon is transformed by photosynthesis and is produced into organic matter (Byrne et al., 2018). The salinity of seawater varies depending on the ocean's region. It can range from 34 to 37 parts per thousand (ppt) of salt (Byrne et al., 2018). The water where the North Atlantic water enters the Caribbean Sea is slightly less than 35 ppt (Menzies, 1999). The Caribbean Sea has varying salinities, all-around 35 ppt. The sea's composition of inorganic substances is widely constant, but human activities have caused disruptions.

Table 2. Principal Constituents of Seawater (Byrne et al., 2018)

Principal Constituents of Seawater			
Ionic Constituent	**g/kg of seawater**	**moles/kg**	**Relative Concentration**
Chloride	19.16	0.5405	1.000
Sodium	10.67	0.4645	0.8593
Magnesium	1.278	0.0526	0.0974
Sulfate	2.680	0.0279	0.0517
Calcium	0.4096	0.0102	0.0189
Potassium	0.3953	0.0101	0.0187
Carbon (Inorganic)	0.0276	0.0023	0.0043
Bromide	0.0663	0.0008	0.0015
Boron	0.0044	0.0004	0.00075
Strontium	0.0079	0.00009	0.000165
Fluoride	0.0013	0.00007	0.000125
*Concentrations at salinity equal to 34.7			

Human activity, as well as other natural causes, affect the chemical composition of the sea. Rivers, wind-borne particulates, and hydrothermal substances from the sea bed play a role in affecting the sea's composition (Byrne et al., 2018). Humans add pollution to coastal waters through waste, irrigation, polychlorinated biphenyls, and carbon dioxide emissions. Contamination of water by added nutrients can cause various effects, such as an increase in phytoplankton growth. Other effects include high levels of dissolved organic materials, decreased penetration of sunlight into the water, and disruption to sea life on the sea bed (Byrne et al., 2018). Ocean acidification is also a factor in the disruption of the ocean's chemical composition. Ocean acidification reduces the pH in seawater because of the increased absorbed amount of carbon dioxide in the atmosphere (Byrne et al., 2018). The sea is vast, but human activity and natural factors still have a large role in changing seawater properties.

2.3.2 Salt Water Effects on Body

The human body is not able to process highly saline water such as seawater. However, smaller amounts of salinity can be considered safe to digest (NOAA, 2018). The human kidney can produce urine with small amounts of salinity. The amount of salinity in urine is significantly smaller than that of seawater, meaning that a person who drinks saltwater would have to urinate more than they can drink in order to survive. Doing so would lead to severe dehydration (NOAA, 2018). Freshwater is considered to contain less than 1000 ppm, while seawater has 10,000 ppm to 35,000 ppm (USGS, 2018). As the human population increases, so does the demand for freshwater. As a result, interest in desalination technology has increased (USGS, 2018). While desalination produces high-quality water, the process can be expensive and energy-intensive. The advantages and disadvantages of desalination are further explored in section 2.3.3.

2.3.3 Fresh vs Brackish vs Seawater

Three different types of water were analyzed to determine the efficacy of purification. The three main types of water are fresh, brackish, and seawater. The Caribbean Sea was chosen as the area of analysis. Generally, the water types' properties can be broken into variations of concentration of dissolved salt. Freshwater contains less than 0.5% of dissolved salts, brackish water contains less than 3%, and seawater contains more than 3% of dissolved salts (NGWA, 2013). Table 3 shows the breakdown of dissolved salt by weight in the categories of water.

Table 3. Categories of Saline Water (NGWA, 2013)

General Categories of Saline Water	
Type of Water	**Part per Million (ppm)**
Fresh Water	< 1,000
Slightly Saline Water	1,000 - 3,000
Moderately Saline Water	3,000 - 10,000
Highly Saline Water	10,000 - 35,000
Ocean Water	35,000

2.4 Water Purification Methods

Water purification removes harmful contaminants such as chemicals, bacteria, sediments, and organic waste from water. Diarrhea, polio, dysentery, and other diseases are transmitted through contaminated drinking water (WHO, 2019b). Purifying water acts as a preventative measure against these diseases and contributes to a healthier lifestyle. There are a variety of water purification methods that exist. Examples of purification methods are ultraviolet light radiation, boiling, electrolysis, chlorination, oxidation, and bioremediation. However, the two main methods for desalinating water are distillation and filtration.

2.4.1 Distillation

In water distillation, water is first boiled into steam and then condensed into purified drinking water. High-quality water is produced from this method because there is a physical separation from the contaminants. Boiling helps rid the water of bacteria and pathogens (UNEP, 1997). However, boiling water is an energy and time-intensive process and becomes expensive on a large scale system. Distillation is a highly technical process and requires appropriate execution of specific pressures and temperatures required for the system.

2.4.2 Filtration

Water filtration removes contaminants through a filter that traps solid contaminants while purified water flows through (Encyclopaedia Britannica, 2017). A variety of filter media can be used, and each medium targets different contaminants. In a water filtration system, multiple media are typically used in conjunction to produce high-quality drinking water.

Standard filter media include activated carbon, reverse osmosis membranes, sand, gravel, and activated aluminum (Pai, 2020). Activated carbon is highly porous, providing a large surface area to absorb particles as small as 0.5 microns (Johnson, 2015). While extremely effective at removing chlorine and organic chemicals, activated carbon does not perform well for minerals, salt, or inorganic chemicals. Slow filtration methods (i.e., sand and gravel) trap sediments, particulates, and pathogens but are ineffective at desalinating seawater. Reverse osmosis is the preferred filtration method for desalination because it is the most effective at removing contaminants.

2.4.2.1 Reverse Osmosis

Reverse osmosis (RO) membranes are considered hyper-filtration devices and can remove particles larger than 0.1 nm (Voight, Jaeger, & Knorr, 2013). The thin-film composite RO membrane is the most common form of RO membranes in the market due to its high performance. The membrane is a bilayer film (see Figure 8) formed by a two-step process. The first layer is thick, porous, and made from fabric, usually polyester (Peterson, 1993). This first layer provides strength and compression resistance for the membrane. The second layer is a thin barrier layer coated on the top surface and is made from an anisotropic microporous polymer, usually polysulfone. It is responsible for separating the dissolved salt and contaminants from water (Peterson, 1993). The thin barrier layer is semi-permeable and selective. Only water can flow through, and it traps most other solutes. RO membranes are typically wound into a spiral and placed inside a pressure vessel for installation. This system allows for easy membrane replacement and increases the surface area to volume ratio (Bódalo-Santoyo et al., 2004).

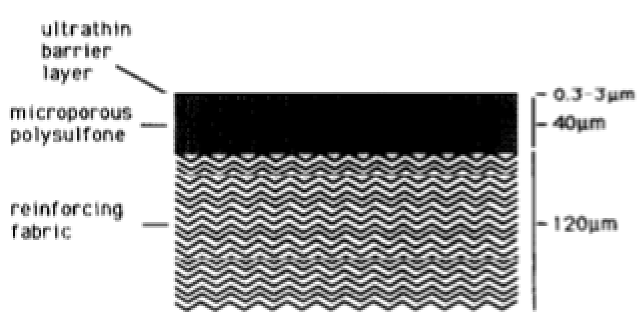


Figure 8. Thin Film Composite Reverse Osmosis Membrane (Peterson, 1993)

In order to separate solutes from the water, pressure above the feed water's osmotic pressure is applied to the filter. Saltwater has a high osmotic pressure; typical RO membranes require 4-7 MPa (580-1015 psi) for seawater (Voight, Jaeger, & Knorr, 2013). In comparison, brackish water filtration requires a pressure of 0.2-1.7 MPa (29-247 psi) (Voight, Jaeger, & Knorr, 2013). Saltwater reverse osmosis systems have a recovery rate (ratio of fresh water outtake to feed water intake) of 35-45% due to the high concentration of solutes, whereas brackish water systems can recover up to 70-97% (Lenntech, n.d.). These recovery rates are due to multi-pass systems where the feed water is passed through multiple (from about 2-3) RO membranes to increase clean water production. Each individual salt water RO membrane filter has a recovery rate from 2-8%, depending on the total membrane surface area (Lenntech, n.d.).

While RO membranes are highly effective, they are also susceptible to pollutant accumulation, known as membrane fouling. Low-pressure membranes tend to have internal fouling when pores clog from solutes. High-pressure membranes tend to accumulate pollutants on their surfaces, which is easier to treat than internal fouling. Fouling leads to increased operating pressure, flux decline, increased need for chemical cleaning, and shorter membrane life. However, steps can be taken to treat and control fouling, such as increased pretreatment, membrane monitoring, foulant removal, membrane cleaning, and surface modification. Pretreating water with other filtration methods to remove sediments, chlorine, and other chemicals is one of the most effective ways to increase the membrane's lifecycle (Jiang, Li, & Laedwig, 2017). With proper care and cleaning, membranes can last up to 5 years (UNEP, 1997). Membrane lifespan is very dependent on system set up and feed water quality.

2.4.3 Limitations and Effects of Desalination

With the increased need for freshwater in diverse settings, many arid regions and coastal areas are looking to desalination (USGS, 2018). On average, humans use 960 cubic miles (1 quadrillion gallons) of freshwater a year (Gleick, 2008). This use of freshwater increases regional scarcity and depletes most freshwater sources. Desalination has been seen as a potential solution to the increasing demand for freshwater.

Desalination meets and exceeds most water standards worldwide because of the tedious filtration processes (Ackerman, 2018). Using desalination systems allows for the need to extract freshwater from endangered and vulnerable habitats and locations to decrease (Ackerman, 2018).

Additionally, desalination provides easy access to water where freshwater is scarce. For example, Saudi Arabia gets 70 percent of its freshwater through desalination (Ackerman, 2018).

However, desalination is energy-intensive and expensive. It can cost over $2 for desalination systems to produce one cubic meter (264 gallons) of freshwater (Gleick, 2008). Meanwhile, an aquifer of freshwater produces the same amount of water at 10-20 cents (Gleick, 2008). Large-scale desalination plants require large amounts of energy to maintain. They can cost up to 2.9 billion dollars to build and operate (Ackerman, 2018).

Water purification systems can harm the local environment due to water intake and waste disposal. Water intake should happen outside of critical biological zones. Additionally, water intake methods should be wildlife-safe to minimize the trapping (entrainment) and killing (impingement) of wildlife. These dead organisms would be disposed of back into their ecosystem at a disproportionate amount, further upsetting the ecosystem's balance (Cooley, Gleick, & Wolff, 2006).

Contaminants leftover from the purification process must also be appropriately disposed of safely. In particular, desalination has highly saline wastewater, also known as brine, containing twice the amount of salt as the intake water. Chemicals used and filtered out, usually in a desalination plant, in the purification process will also be in the brine. During pre-treatment, a number of chemicals are used on the unfiltered water, such as cleaning chemicals, pH adjusters, and antifoaming agents. These substances bind to the impurities so it is easy for them to be removed during desalination (Challener, 2010). Brine is typically discharged back into the ocean; however, this can significantly unbalance the ecosystem and introduce harmful chemicals and substances into the water. Thus, it is essential to minimize, dilute, and distribute the brine discharge (Cooley, Gleick, & Wolff, 2006). Taking into account the effects and limitations of water purification is essential when designing a system.

2.5 Clean Water Standards

Drinking water standards vary across the world because countries develop their codes for water quality. Standards typically include cutoff levels for specific contaminant concentrations along with a protocol for water sampling and testing. The World Health Organization has developed recommendations regarding drinking water quality and supports countries implementing regulations (WHO, 2019b).

2.5.1 Standards in the United States

The United States Environmental Protection Agency (EPA) established the Safe Water Drinking Act (SWDA) to regulate all public water systems. Under the SWDA, the EPA has created regulations for over 90 contaminants (see Table 4). Regulations are created when a contaminant that causes health concerns appears in drinking water supplies. A contaminant's standards are determined by a maximum contaminant level goal (MCLG) and a maximum contaminant level (MCL) or a treatment technique (TT). The maximum contaminant level goal is the ideal level that would guarantee no adverse health effects. The maximum contaminant level is the realistic standard enforced for public water systems (Tiemann, 2017). If there is no MCL, a treatment technique is outlined instead.

Table 4. General Trends in Regulation For Different Contaminants (EPA, 2020)

Contaminant Type	**Contaminant Examples**	**MCLG general trend**	**MCL or TT general trend**
Microorganisms	Enteric Viruses, Cryptosporidium, Coliforms	Zero	TT, identified control levels and protocol *ex:* 99.9% virus removal/inactivation
Disinfectants	Chloramines (Cl_2), Chlorine (Cl_2), Chlorine Dioxide (ClO_2)	Cl_2 = 4 $(mg/L)^2$ ClO_2 = 0.8 $(mg/L)^2$	The same as MCLG
Disinfection Byproducts	Bromate, Chlorite, Haloacetic acids	Zero - 0.8 $(mg/L)^2$ ex: 0.8 $(mg/L)^2$ for Chlorite	Slightly greater than their corresponding MCLG ex: 1 $(mg/L)^2$ for Chlorite
Inorganic Chemicals	Lead, Nitrate, Mercury, Fluoride	Zero - 10 $(mg/L)^2$	This is usually the same as MCLG
Organic Chemicals	Benzene, Glyphosate, 1,1,1-Trichloroethane	Zero - 0.7 $(mg/L)^2$ ex: Zero for Tetrachloroethylene	This is slightly greater than their corresponding MCLG ex: 0.005 $(mg/L)^2$ for Tetrachloroethylene
Radionuclides	Alpha Particles, Radium 226, Uranium	Zero	Varying MCL ex: 30 ug/L for uranium

2.5.2 Standards in the Carribean Sea region

Water standards in the Caribbeans vary per island. For example, the U.S. Virgin Islands follow regulations set by the EPA. Waters in and surrounding the U.S. Virgin Islands are expected to be free of waste products like deposits, debris, turbidity, toxic materials, color, oil, taste, odor-producing substances, and nuisance species (EPA, 2020). Example specifications for pollutants can be seen in Table 5 (EPA, 2020). Standards, for the most part, follow those set by the SWDA.

Table 5. Example of Pollutant Level Criteria for The U.S. Virgin Islands (EPA, 2020)

Pollutant	ug/L
Arsenic	0.018
Copper	1,300
Methylene Chloride	4.6

By contrast, Haiti is still developing its water infrastructure. The Center for Disease Control (CDC) supported Haiti by assessing local water systems and increasing water sanitation (2018). Haiti's priority was to treat the cholera outbreak that started in 2010 by reducing E. coli contamination in water. Chlorination equipment is being installed in cholera outbreaks to improve drinking water safety (CDC, 2018).

2.5.3 Standards During Disaster Situations

Drinking water standards will vary during a disaster situation, especially when there is a limited water supply and a large water contamination probability. Thus, the disinfection of water is crucial. WHO has outlined some considerations to consider during an emergency: water supply reliability, access to water, sources of contamination, long and short-term treatment processes, drinking supply disinfection, and acceptability of water to consumers (2017). Educating consumers about the risk of water contamination and how to minimize transmission is vital so that consumers can be proactive when collecting and transferring water. Routine inspection of water quality from its treatment to collection and distribution is also vital for contamination mitigation. Suppose microbial quality is compromised, the WHO advises boiling water during disaster situations. Another method that can be employed is super chlorination, by increasing the chlorine concentration by 0.5 mg/L (WHO, 2017). For short term water treatment, chemical contaminants may exceed the guidelines as they pose a higher risk after extended exposure (WHO, 2017). The priority is to eliminate microorganisms since microbial contamination poses an enormous health risk during disaster situations.

Hurricane Dorian hit the Bahamas in September 2019, and saltwater flooded into the drinking wells that supplied water for 55,000 people (Rivero, 2020). Water plants were also flooded, including one that supplied 60 percent of the Grand Bahama island with water (Rivero, 2020). A distinct salty taste remained in the drinking water six months after the hurricane (Rivero, 2020). After Hurricane Dorian happened, priorities shifted towards decontamination and desalination of drinking water in the Bahamas.

2.6 Disaster Relief Desalination Devices On The Market

One desalination device currently on the market is the Aquamate solar still (see Figure 9). Aquamate's design uses distillation through solar radiation, which makes it function independently without need for electricity or human maintenance. The device retails for $237.95 and produces 1 to 7.5 cups of drinking water per day (Landfall Navigation, 2021). Operation of the device is simple and intuitive: add water, and wait for solar radiation to evaporate the seawater and condense it into drinking water. The device is compact, with a size of 36 cm x 22 cm x 6 cm (~14 in x 8.7 in x 2.4 in). As mentioned before in section 2.4.1, distillation is inefficient, especially at a small scale like this solar still. 1 to 7.5 cups per day is not adequate for disaster relief usage.

Figure 9. Aquamate Solar Still
(Landfall Navigation, 2021)

Figure 10. Aquifer 200
(Marine Warehouse, 2017)

Another device is the Aquifer 200 (see Figure 10) from Spectra Watermakers which can purify seawater, brackish water, and freshwater. This device produces 8 gallons of drinking water per hour and operates on a reverse osmosis process. The system requires at least 110 Watts of power for the high pressure pump to work. This power can be supplied by solar energy, wind energy, or battery and has a 12V DC input. The Aquifer 200 is slightly larger than the Aquamate device, with dimensions of 31 cm x 15.5 cm x 20.5 cm (~ 12.2 in x 6.1 in x 8.1 in). However, this system is currently very expensive, with a cost estimate of $6,525 (Marine Warehouse, 2017). Additionally, it is still up to the user to decide on, find, and connect a power source.

The Katadyn Survivor 35 (see Figure 11) is a strong candidate for disaster relief desalination. The device can produce up to 35 gallons of drinking water a day with a production rate of 1.2 gph. Water is purified through a reverse osmosis membrane and pressure is provided through a hand pump. The average salt rejection is 98.4%. The device is very compact, spanning 22 in x 3 in x 5 in. However, each unit costs $2,275.25, and its current target audience is the military, sea voyagers, kayakers, and adventurers and intended to be used only by one person. (Katadyn, 2020).

Figure 11. Katadyn Survivor 35 (Katadyn, 2020)

3.0 Design

3.1 Project Scope and Constraints

The team set out to investigate the feasibility of new ways to desalinate water in a post-disaster scenario, and test the feasibility of utilizing human power to provide the energy input needed in desalination. The project objectives are listed in Table 6 below.

Table 6. Project Objectives

Table of Goals	
Objective 1	Investigate different technologies and ways to create a desalination device.
Objective 2	To design a desalination device that operates on clean, green energy.
Objective 3	To design a unique, compact desalination device to allow for easy, inexpensive aid in disaster relief situations within the Caribbean Sea.
Objective 4	To investigate the feasibility of the designed device to reflect a humane way of desalinating water.

3.1.1 Caribbean Terrain

To verify that there was a use-case for the device, the team researched the specific housing located within the Caribbean region. On small islands, housing was often found close to the coastlines. In the Maldives, the entire population lives in a low-lying coastal area (Wilkinson & Stellar, 2018). In Puerto Rico, 15% of the population lives in flood-prone areas, and 61% of the population lives in the island's coastal municipalities (Acevedo & Flores, 2017). From this information, the team understood that people lived along the coastlines in the Caribbean region and could easily travel to the ocean and access seawater. WHO recommended a maximum distance of 500m between a home and the water source (2012). Therefore, the walking distance in most islands in the Caribbean region meets the requirements of WHO.

The team also looked at how disasters affected local topography to determine space, ergonomic constraints, and terrain limitations. Hurricanes proved to deal heavy damage to the environment and infrastructure. During a hurricane, structures and vegetation are often uprooted, leading to many debris and rubble to be scattered across a region (see Figure 12). The team analyzed pictures taken from hurricane disasters to understand disaster situations better. In conclusion, the team determined that even after a hurricane, there could still be stretches of flat land available along the coastline where a device could be set up and used.

Figure 12. A) Before and B) After Hurricane Luis in Nevis (Cambers, 1997)

3.1.2 Water Requirements for Humans During a Disaster

In situations where a steady supply of pure water is unavailable, affected people need to obtain water for drinking. The production of clean water must be a reasonable trade-off with the effort put into producing it. Men require 0.97 gals of water a day, while women require 0.713 to merely survive (Mayo Clinic Staff, 2020). The CDC recommends at least one gallon of drinking water per person per day is needed to meet basic human needs. (CDC, 2020a).

Based on the average household size in the Caribbean region (3.42), the team decided to model the device around the idea that an average of 5 people would be using it daily. This decision means that the device would need to produce at least 5 gallons of clean water daily. The team's goal was to design a device that could meet this requirement and more.

Countries in the Caribbean Region	Average Household Size
Aruba	N/A
Bahamas	3.4
Barbados	2.8
Belize	3.8
Cayman Islands	N/A
Curacao	N/A
Dominican Republic	3.2
Guyana	3.8
Haiti	4.3
Jamaica	3.1
Sint Maarten	N/A
Suriname	3.8
Trinidad & Tobago	3.3
Turks & Caicos	N/A
Puerto Rico	2.7
Average	**3.42**

Figure 13. Average Household Size of The Caribbean Region *(Summarized by MQP team)* (The World Bank, 2020) (PRB, 2020) (U.S. Census, 2019).

With a 4% rate of clean water retention from the Reverse Osmosis membrane selected for the design (discussed in later sections), the device would need to intake about 125 gallons of water to produce 5 gallons of clean water.

The device would also need a flow rate in gallons per minute (gpm) to satisfy the need for water in an efficient amount of time for one day. The group used a similar system, the Katadyn Survivor 35 (market value of $4,295.00), to better understand the device's appropriate flow rate (Katadyn, 2020). This Katadyn Survivor 35 system produces clean water at a flow rate rated as 0.02 gpm (1.2 gallons per hour). The team was careful to keep in mind the mental and physical state of natural disaster survivors; survivors can be susceptible to being weakened. Therefore, the team's goal was to nearly surpass the Katadyn Survivor by having a higher flow rate, higher production rate, and more comfortable use. The team's device would also be ranked higher than other competitive desalination devices for disaster relief.

3.1.3 Energy Availability in The Region

The primary energy source in the Caribbean region is oil. Electricity produced from the oil can be expensive compared to other forms of energy. Imported oil provides 90 percent of the Caribbean region's energy (Schmidt & Sangermano, 2017). Trinidad and Tobago are known for relying on their oil and a natural gas source within the region. Electricity prices in the Caribbean region average $0.34 per kWh and can cost up to $0.50 per kWh (Schmidt & Sangermano, 2017). The price of imported oil heavily impacts the Caribbean Islands' economy because of the heavy dependence on electricity use. Relying on these energy sources are unsustainable during disaster situations (Schmidt & Sangermano, 2017).

During natural disasters, energy infrastructures are vulnerable to damage. Hurricane Irma caused power outages in the Caribbean and the Southeast United States, leaving 17 million people without power (McNamara, 2017). Both power infrastructure and homes were severely damaged. When Hurricane Maria hit Puerto Rico, residents in remote areas were without electricity for nine months after the storm (Irfan, 2018). From this data and research, the team decided that electricity was not a reliable energy source for this project's specifications. Therefore, other sources of energy were explored (see Table 7). The team ultimately decided that either human or solar power for the Caribbean region would be an efficient energy source for the desalination device.

Table 7. Energy Source Considerations

Power	Pro	Con
Human	- Reliable energy source - Eliminates need for external source of power which may be environmentally damaging - Low to zero cost, unless compensating for time, food and water	- Limited energy - Consumers need to be healthy enough both mentally and physically while also having the time and energy to spare that is required to power the device
Electricity	- Pumps are usually configured for electrical power - Can provide sufficient power for a pump to produce the required pressure needed to use a Reverse Osmosis membrane	- In a disaster situation, electricity is limited or unavailable - Some remote areas do not have reliable access to electricity - Different parts of the world have different electricity and power infrastructure (outlet, voltage, etc)

Battery	- Pumps are usually configured for electrical power
	- Can provide sufficient power for a pump to produce the required pressure needed to use a Reverse Osmosis membrane
		- Logistics regarding:
		  - transportation of batteries
		  - recharging of batteries
		  - disposal of batteries

Renewable Energy	- Depending on the source and location, reliable energy source - Solar Energy, Wind Energy, Hydraulic Energy	- Source depends on the local environment - Expensive capital cost - Battery needed to store energy for some cases - Low/inefficient energy conversion
Animal Power	- Reliable source, there is a lot of history in using animals for work - Variety of animals that can be used	- Animals are not necessarily always guaranteed - Cost of upkeep, feeding, and owning an animal can be high especially if it is a large animal such as an ox, horse, mule, etc. - Animal abuse can occur without supervision

The team considered both human power and solar power because of their availability and reliability within the Caribbean region. Battery power was eliminated because it was a finite resource and did not correlate with the team's objective for using a clean energy source. Animal power was eliminated due to the unpredictability of finding an animal during and after a disaster. Human power will be discussed in more detail in the following section, 3.1.4 Human Power. The team highly considered solar power because the Caribbean region has access to long days of intense sunlight, as seen in Figure 14 (CED, 2018). Solar power has also impacted the Caribbean region by providing electrical needs to the islands after severe storms, such as Hurricane Irma and Maria. However, it is essential to note that solar power has mainly been used on these islands as a large-scale source. Lastly, while solar power proves to be inexpensive in the long run, it is significantly expensive for short term use. A solar panel can take up to ten years to fully pay off electrical and maintenance costs. Therefore, solar power was not ideal since this device was meant to be used only for disaster situations that can last from about a couple of days to a couple of months.

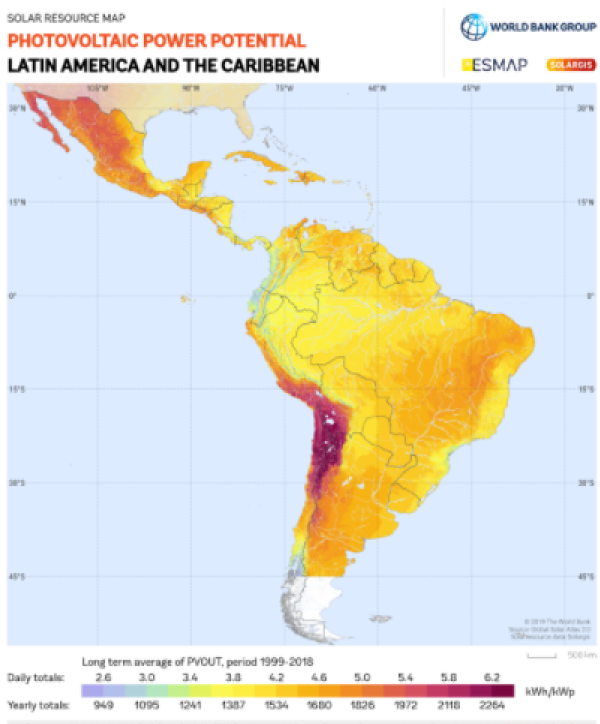


Figure 14. Map Showing Photovoltaic Power Potential For Latin America And The Caribbean (Global Solar Atlas, 2020).

While solar power is a useful energy source, the team reflected on its shortcomings. The initial cost of solar power is inaccessible for most people and is the primary barrier (Roder, 2015). Solar energy also becomes unreliable and inefficient when optimal conditions are not met, i.e., during the night or cloudy days. In a disaster situation, especially in a heavy storm, optimal sunlight is not guaranteed, affecting the energy production rate. Additionally, solar panels take up space, which conflicts with the team's goal of creating a compact desalination device. Approximately 80 square feet of space is needed for solar panels to produce 1 kW. Finally, the team considered solar power's environmental impact. Photovoltaic Cells (PV cells) are made with harmful chemicals such as hydrochloric acid and sulfuric acid (Roder, 2015). With no current regulations for the safe disposal of PV cells, short term use of PV cells would be harmful to the environment due to improper disposal. Based on this analysis of solar power, the team decided to use human power to power the desalination device.

Table 8. Pros and Cons of Solar Energy in The Caribbean

	Pros:	**Cons:**
1.	Lowers energy costs: when used in a wide scale grid system, solar power can lower overall electricity costs	Solar Power initial cost: For a wide scale grid system it takes on average 10 years to pay itself off
2.	Caribbean region has long days of intense sunlight: this makes this region optimal for solar power	Reliability & Efficiency: If optimal conditions aren't met because of cloudy days, the system would require battery storage to maintain efficiency
3.	Creates resilience against severe storms: solar power can be used as backup power and help provide power as rebuilding occurs	Space: 80 sq ft per kW is recommended for solar power systems. Additional space would be required for the inverter, batteries, and related equipment. Space cannot be shaded. Conditions not met would cause lower efficiency
4.		Environmental Impact: No regulation or clear instructions on how to recycle or dispose of PV cells. Chemicals found are hydrochloric acid, sulfuric acid, nitric acid, hydrogen fluoride and more.

3.1.4 Human Power

There are both limitations and benefits to using human energy. Human power requires extra caution when used for extended periods. However, it is a clean energy source that would produce relatively low waste regardless of the time being used. For example, using 1 gallon of gas can produce approximately 19.89 lbs of CO_2 emissions (Palmer, 2009). In contrast, a sedentary human produces 2.3 lbs of CO_2 emissions per day. A human engaging in rigorous activities can produce up to 16 lbs of CO_2 emissions per day (Palmer, 2009). Humans can produce about 0.1 horsepower for an indefinite period and 1.2 horsepower for a brief period (Frank, 2016). Both of these amounts of energy can power the average 60 Watt lightbulb. While humans cannot reach machine power levels, human power can certainly be used for other applications. When used effectively, human power can be harnessed and used as a robust clean energy source.

Ergonomics plays a key role when using human power. The whole human body is powerful, but certain muscle groups are better suited for specific applications. For example, legs are preferred for pushing actions rather than pulling. The pushing movement is also healthier for humans because it requires less involvement of the lower back and utilizes leg power for the forward motion. In contrast, pulling is a full-body movement that can cause the body to twist sideways if the arms are behind the body. This twisting action can strain the lower back muscles and cause injury (Starovoytoya, 2017). When putting energy into a system, it is more useful for a human to push within the "power zone." The power zone extends from the mid-thigh to the mid-chest region and is exhibited in Figure 15. It is ideal for the handles on human operated devices to be located in the "power zone" height to prevent injury and strain. Adhering to the needs of the human body is crucial in ensuring the safety of a human worker.

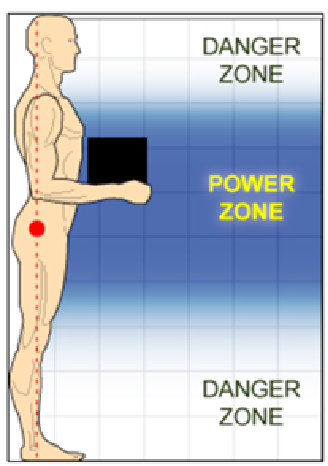


Figure 15. Power Zone For The Human Body When Pushing Heavy Objects (OSHA, 2020a).

While a person can produce energy, it is not humane to expect only one person to produce the energy required to power the project's desalination device. Ideally, people would ethically take turns to avoid fatigue and exhaustion. The Caribbean Sea region has surface water temperatures of about 78 degrees Fahrenheit and island temperatures lower than 81 degrees Fahrenheit before a hurricane strikes (Lindsey, 2012). These warm conditions are also present after hurricanes, making the Caribbean Sea region a relatively warm environment, with temperatures ranging from 68-90 degrees Fahrenheit throughout the year. The United States Department of Labor, OSHA, provided guidelines for heat-related working conditions and how to ensure workers are safe in these conditions; see Figures 16 and 17 below. The team's desalination device was intended for use in the Caribbean sea region, where hot temperatures can sometimes be reached. So, to ensure the safety of those using this desalination device, heat precautions must be taken.

Since multiple people will be required to power this device, they all must remain safe during the device's operating time. One recommendation for doing so is to ensure that proper supplies are at hand while powering the device: water, food, and other basic needs (OSHA, 2020a). Another recommendation for working in hot environments was to ensure people are drinking 4 cups of water for every hour worked. These four extra cups of water would be in addition to the 1 gallon of water per day needed to survive. The team kept this in mind and designed the device to produce more water than consumed during the production stage. This device was recommended to be used during cool hours of the day and under shade. This recommendation was to reduce the possibility of heatstroke. People working in a hot environment need to take frequent breaks in cool shaded areas to avoid passing out and fatigue (OSHA, 2020b).

The team's goal was to design a desalination device after a disaster situation in the Caribbean region. As stated above, the Caribbean region can reach daily temperatures of about 68-90 degrees Fahrenheit. Therefore, the team would need to anticipate the device being used in warmer temperatures. However, as seen in Figure 16 below, 68-90 degrees Fahrenheit is a lower risk range of temperatures and requires basic heat safety. This device must be used appropriately so that all users are kept safe.

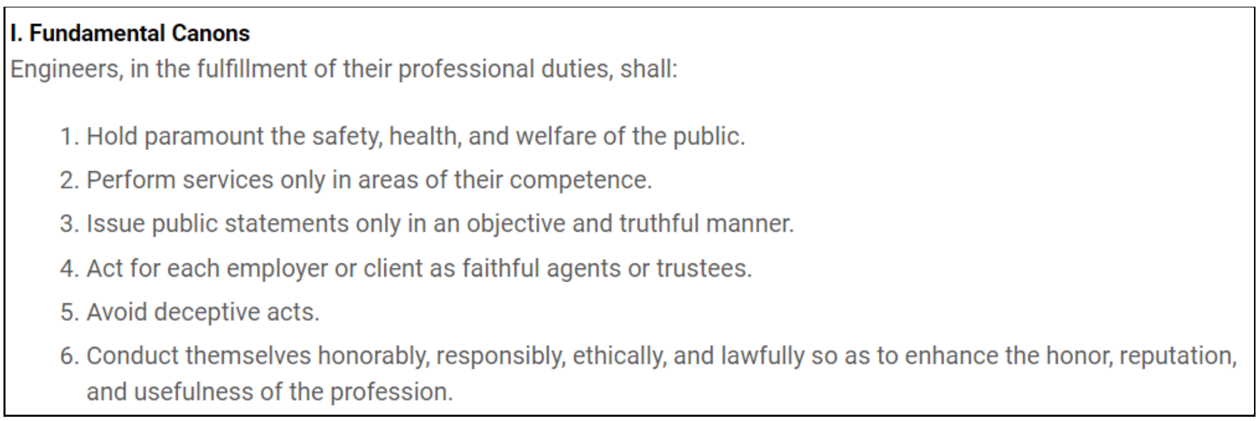
Heat Index	Risk Level	Protective Measures
Less than 91°F	Lower (Caution)	Basic heat safety and planning
91°F to 103°F	Moderate	Implement precautions and heighten awareness
103°F to 115°F	High	Additional precautions to protect workers
Greater than 115°F	Very High to Extreme	Triggers even more aggressive protective measures

Figure 16. Heat Index Table (OSHA, 2020b).

Heat Index	Risk Level	Protective Measures
<91°F	Lower (Caution)	▪ Provide drinking water ▪ Ensure that adequate medical services are available ▪ Plan ahead for times when heat index is higher, including worker heat safety training ▪ Encourage workers to wear sunscreen ▪ Acclimatize workers **If workers must wear heavy protective clothing, perform strenuous activity or work in the direct sun, additional precautions are recommended to protect workers from heat-related illness.***
91°F to 103°F	Moderate	In addition to the steps listed above: ▪ Remind workers to drink water often (about 4 cups/hour)** ▪ Review heat-related illness topics with workers: how to recognize heat-related illness, how to prevent it, and what to do if someone gets sick ▪ Schedule frequent breaks in a cool, shaded area ▪ Acclimatize workers ▪ Set up buddy system/instruct supervisors to watch workers for signs of heat-related illness **If workers must wear heavy protective clothing, perform strenuous activity or work in the direct sun, additional precautions are recommended to protect workers from heat-related illness.*** ▪ **Schedule activities at a time when the heat index is lower** ▪ **Develop work/rest schedules** ▪ **Monitor workers closely**

Figure 17. Plan Of Action For Heat Related Working Conditions (OSHA, 202b)

It was essential to keep engineering ethics in mind when designing, mainly because it involved human power use. The fundamental canons of engineering were stated below in Figure 18. The team ensured that safety was practiced during this project's entirety by providing water and food to those who utilized the prototype device. The team also adhered to all covid policies stated by Worcester Polytechnic Institute to uphold the public's welfare. This project was only used by the project team and therefore did not harm the public's health and welfare. To the best of their engineering knowledge, the team provided sufficient information and data to prove their knowledge on the project topic. The team did not issue any public statements on their project. Finally, the team fully understood these fundamentals and, to the best of their knowledge, implemented these practices in the project while conducting themselves honorably, responsibly, ethically, and lawfully. The design of the device needed to take into consideration the ethics of manual work in a hot environment.


I. Fundamental Canons
Engineers, in the fulfillment of their professional duties, shall:

1. Hold paramount the safety, health, and welfare of the public.
2. Perform services only in areas of their competence.
3. Issue public statements only in an objective and truthful manner.
4. Act for each employer or client as faithful agents or trustees.
5. Avoid deceptive acts.
6. Conduct themselves honorably, responsibly, ethically, and lawfully so as to enhance the honor, reputation, and usefulness of the profession.

Figure 18. Fundamental Canons of Engineering (NSPE, 2020).

3.1.4.1 The Human Body and Exercise

To stay in good health, the body requires fuel, water, and exercise. The Department of Health suggests that the average healthy adult get at least 150 minutes of moderate aerobic exercise or 75 minutes of vigorous aerobic exercise per week (Laskowski, 2019). It is also suggested that the healthy adult do strength training for all muscle groups at least twice a week. Aerobic exercise refers to cardiovascular conditioning; meaning that the heart and lungs are being conditioned during exercise. This includes activities such as swimming, brisk walks, running, or cycling (Chertoff, 2018). Aerobic stands for “with oxygen” meaning that both breathing and heart rate are increased during exercise. This form of exercise helps the heart, lungs, and circulatory system stay healthy.

Strength training is referred to as anaerobic exercise since it requires quick bursts of energy performed at maximum effort for a short amount of time (Chertoff, 2018). Anaerobic is the opposite of aerobic and means “without oxygen”. The major difference between these two exercise types is the method in which the body produces energy. Aerobic exercise utilizes oxygen to produce continuous energy throughout a workout, whereas anaerobic exercise pushes the body to create more energy than the aerobic system produces (Kelly, 2015). Anaerobic relies on the glucose found in muscles, which is called glycolysis. This is also where lactic acid is produced and is the reason behind the sore feeling after intense activity. Anaerobic exercise helps with bone strength and density, metabolism, depression, lowers risk of disease and helps protect joints (Kelly, 2015).

Exercise requires proper aftercare for healthy human bodies. Staying hydrated is key to properly replenishing the body after any workout (Cronkleton, 2020). It is recommended that, after a workout, a person drink 16 ounces of water, or healthy drinks such as coconut water, green or black tea. It is also important to eat healthy foods 45 minutes after completing a workout. By eating healthy foods, the body can properly replenish muscle energy stores and start the recovery process (Cronkleton, 2020). After intense workouts, it is also vital to do light exercise on rest days. Properly cooling down and taking care of the body after a workout is essential to safely exercising.

The human body can produce energy based on the amount of calories burned. Energy can be found by multiplying power by time. Energy is typically in units of Joules, but can be converted into kilocalories by 1 J = 0.000239 kcal (Kaloc, 2020). To put these numbers into perspective: 1 banana is equal to 105 calories (kcal), so a person who burns off 300 calories would need to eat approximately 3 bananas to regain that energy. Below is the basic equation for finding the amount of energy a human produces using calories.

Calculations:
Human Efficiency = 24%
3.6 is the conversion for time in hours $\frac{60\ sec * 60\ min * 1\ cal}{1\ min * 1\ hour * 1000\ kcal} = 3.6$
Humans can sustain 0.1hp indefinitely and 1.2hp briefly
0.1hp = 74.57W
1.2hp = 894.84W

Energy (Joules) = Power (Watts) * Time (Seconds)
1 Joule = 0.000239 kcal

Energy (kcal) = Power (Watts) * Time (Hours) * 3.6

Calories burned doing 0.1hp for 1 hour:
Energy (kcal) = 74.57W * 1 Hour * 3.6 = 268.452 kcal

Calories burned doing 1.2hp for 1 hour:
Energy (kcal) = 894.84W * 1 Hour * 3.6 = 3,221.42 kcal

Figure 19. Human Power in Calories

Humans must eat enough calories to be able to produce energy. Basal metabolic rate (BMR) represents the unique amount of energy that a person needs to function at rest (Thomas, 2019). There are two formulas to be used to calculate BMR for men and women:

Men: 10*Weight(kg) + 6.25*Height(cm) - 5*Age(yrs) + 5 = BMR (calories)
Women: 10*Weight(kg) + 6.25*Height(cm) - 5*Age(yrs) - 161 = BMR (calories)

It is recommended that the daily calorie intake for the average adult male be 2500 and average adult woman be 2000 (Thomas, 2019). The recommended calorie intake can vary based on age, activity level, and other health factors such as diseases. The BMR can be used to estimate the appropriate amount of calorie intake based on age, height, and weight. For humans that are more actively exercising, it is recommended that their BMR be multiplied by a factor of 1.6 to account for extra calories burned (Thomas, 2019).

3.1.5 Device Sizing and Weight Constraints

Transportation is an essential component to delivering the device to the Caribbean region. Essential aspects to consider are accessibility to resources such as trucks, trains, and boats. Since the Caribbean region has a vast area of rural areas, these transportation methods might not be accessible. Additionally, a natural disaster can exacerbate the lack of access by destroying infrastructure. The team chose to design a small and light device to be transported by light-duty vehicles such as pickup trucks or SUVs. Machine-assisted offloading would not be required for unloading this device. The device would be small enough to be unloaded and positioned by hand.

The design parameter for the device's overall size was a standard 48"x40" shipping pallet, with a max height of 72”. Shipping pallets are small and a universal size used across North America (TranPak, 2020). The compact and recognizable size of a shipping pallet would allow producers of the device to easily pack it into large delivery vehicles such as trucks, trains, and boats. An added benefit of packing the device all on one pallet is the possibility of using a helicopter to transport the package to remote communities or communities that were separated by a natural disaster.

The weight of the device must be manageable for people to pick up and move on their own. The CDC recommends a maximum of 51 lb for vertical movement when picking up items (CDC, 2020b). Therefore, it was recommended that at least two people handle the device for maximum safety. The device and pallet combined would not weigh more than 102lbs. Pallets weigh between 30-48 lb, which meant the device would not weigh more than 54 lbs. The device was intended to be used almost immediately after being received. The set up for the device would require positioning the device in a suitable location for use.

3.1.6 Filter Choice

The team chose reverse osmosis as the primary filter because of how effective it was at desalinating water. When considering water desalination methods, the team decided against distillation due to the high electrical input and low production rate. Distillation consumes a considerable amount of energy because of the heat required to boil water over several hours. The production rate can be 4-6 hours for a countertop distiller to produce 1 gallon of clean water (Woodard, 2019). The team considered several filtration methods, but only reverse osmosis could filter out salt content. Sea salt has a size of 0.035-0.5 microns; RO membranes filter up to 0.0001 microns (Engineering Toolbox, 2005; Voight, Jaeger, & Knorr, 2013). In comparison, activated carbon can only filter up to 0.5 microns (Johnson, 2015).

When operating the RO filter, pressure build should be gradual over a 30-60 second timeframe (Lenntech, n.d.). Additionally, it has been recommended that permeate from the first two hours of operation is discarded. This was just for the first time the RO module was in use because the membrane was stored in preservative chemicals that needed to be flushed out. The maximum pressure drop across general reverse osmosis filters was 50 psi, and the free chlorine tolerance was < 0.1 parts per million (Lenntech, n.d.).

The RO membrane was chosen as the primary filtration method for desalination. The team also incorporated additional pretreatment and posttreatment filters for a longer RO membrane lifespan and better drinking water quality. For pretreatment, a sediment filter was chosen to filter large particles from the water. The team also decided that a second pretreatment filter using activated carbon would help prevent RO membrane fouling. This second filter would remove chlorine and additional chemicals, allowing the RO membrane to filter out salt and microorganisms. The posttreatment filter was another carbon filter to improve the taste and quality of the drinking water. This final filter was chosen for remineralization purposes rather than filtration since RO membranes are known to strip water of beneficial minerals for humans.

3.1.7 MQP Cost Constraints

The device was designed to be relatively small and to service the average family of five members. Due to its small size, one device would not be enough to provide clean water for an entire community. This size constraint requires that this device be mass-produced so that many devices can be distributed to households.

A benchmark of $1000 was set for the team to conduct prototyping. However, the device's cost per unit would need to be significantly lower for production and deployment in the field. The team’s overall goal for cost was under $1000 because the device needed to be accessible to families through direct purchase or distribution from a humanitarian organization. The team compared the device's anticipated cost with another emergency desalinator, the Katadyn Survivor 35, which retails at over $2,200 brand new. The Katadyn Survivor 35 is meant for use in emergencies at sea; however, it is on the expensive side and has not been used by humanitarian organizations. It can be used to compare the team's device in terms of flow rate and usability. Although Katadyn is a private company separate from disaster relief organizations, it can be used as a benchmark for an emergency desalination device's flow rate and cost.

In addition to the competitor's prices, the team compared bottled water costs for three months. The team chose a three months timespan because of the unpredictability regarding the lasting effects a hurricane can cause to a country. The team did not anticipate the device being used for more than three months. Four 16.9 ounce water bottles equal the amount of water a human needs per day. Over three months, one person would consume 960 bottles of water, which would mean a family of five would then consume 4800 bottles of water in that period of time. Across the world, the average cost per water bottle is $0.70, meaning an entire family's total cost over three months for drinking bottled water would be $3360 (Kim, 2020). Bulk orders of water bottles could include bulk discounts making the price lower. However, even with a discount, the price for this amount of bottled water still exceeded the team's water purification device's benchmark price of $1000.

The team's Mechanical Water Purification System (MWPS) was also a one-time cost. Unlike other models of saltwater purification systems, the MWPS was a one-time purchase and did not rely on external energy sources. It could be difficult to find gasoline, diesel, or an electric power source in the wake of a natural disaster. The use of the MWPS relied solely on human power and did not need additional purchases for fuel sources as it was used.

3.1.8 Summary of Design Constraints

Identifying these design constraints helped the team when moving forward in creating and finalizing design ideas. The constraints in Table 9 were referenced throughout the design process to ensure that the system would meet the project objectives.

Table 9. Summary of Project Constraints and Criteria

Constraint	Criteria
Size	< 48” x 40” x 72” (LxWxH)
Weight	< 54 lb
Filtration	< 0.035 micron
RO Water Pressure	600-1000 psi
RO Free Chlorine Tolerance	< 0.1 ppm
RO pH Range	2-11
RO Max Temperature	113 F
Human Work	360 kJ
Human Energy	0.1 hp
Temperature Range	70-90 Degrees Fahrenheit * < 91 Degrees Fahrenheit is considered a lower risk level for humans to work in. This is recommended for the use of this device. *Device is not recommended to be used in temperatures > 97 degrees Fahrenheit
Human Basic Heat Safety Constraints	-4 cups of water for every hour working in high risk temperature conditions -Have food and medical supplies available -Work in shade or cooler times of the day and take frequent breaks as needed
Daily Water Production Rate For A Family	5 gallons per day + 4 cups per hour of operation per person
Daily Seawater Intake	About 125 gallons per day *168.75 gallons taking into consideration the extra 4 cups per hour
Microorganisms in Drinking Water	0, focus on eliminating enteric viruses
Drinking Water Total Dissolved Solids (TDS)	< 900 mg/L
Cost of Device	MQP project constraint = $1000 Final Device would realistically cost less than the leading competitor, the Katadyn Survivor, which retails for about $2000. The final device would also cost less than the amount of bottled water a family of five needs for three months = $3360
Complexity of Design	The device must be simple enough for any person, regardless of engineering knowledge, to be able to effectively use and operate. The device would need to be in a ready to use state and require minimal set up.

3.2 Preliminary Design

The team brainstormed using the platform Miro, an online whiteboard, to collectively input ideas, concepts, and visions for this project. The team began by visualizing what processes and components were needed for a successful water purification system; methods revolved around pressurizing, powering, and maintaining the system. The team also discussed whether the system would be permanent or portable and the overall housing design that would best suit the application. In this section, the team decomposed the brainstorming process with sketches and calculations supporting the team's design decisions.

3.2.1 Brainstorm Ideas

First, the team conceptualized which critical components were needed for a reverse osmosis device. First, the team created a concept map for some working mechanisms within the device and then brainstormed ideas for how each component could be modified or improved. Below is the first concept map created by the team, shown in Figure 20. This map showed the need for a high-pressure pump to intake the seawater feed and create the pressure required to flow into the Reverse Osmosis Membrane. Then the Reverse Osmosis membrane would produce clean water and discharge the seawater. Figure 20 shows a necessary representation of what a reverse osmosis system requires. A reverse osmosis membrane requires 700-1000 psi of pressure to function correctly when purifying salt water at 35ppt (AMI, 2019).

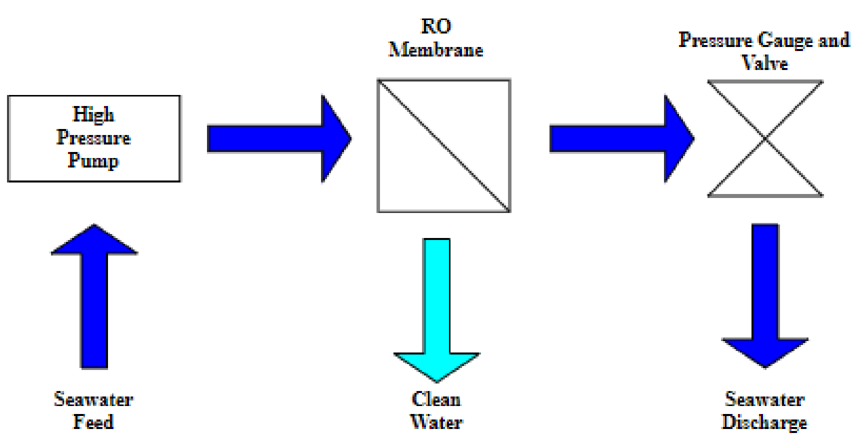


Figure 20. Basic Functioning of a Reverse Osmosis Desalination Device Concept Sketch

3.2.1.1 Permanent vs. Semi-Permanent vs. Portable

To begin designing a device, the team needed to decide on a permanent, semi-permanent, or portable device. Permanent devices would require a permanent structure for long term use, which could be expensive, labor-intensive, and cause problems for local people in the area. The team decided not to pursue a permanent device because of the envisioned device's desired applications and accessibility. The team's goal was to provide a device that would be easy to set up, take down, and use during a disaster situation in the Caribbean Sea region. Having a permanent device would not align with the team's vision. Instead, the team further discussed semi-permanent and portable devices.

The team created a rough design of a portable desalination device as a cart, shown in Figures 22 and 23. The cart would move on wheels and be either pushed or pulled by a person. As the person pushed or pulled the cart, the wheels would turn and move the pistons inside the cart. The pistons would then create a sufficient water flow and pressure for the water to pass through the Reverse Osmosis filter and pre/post filters. The team did not move forward with this design because of discussions surrounding weight, road or ground conditions, discharge of seawater, and the device's stability. The team discussed scenarios where debris, sand, or water would be flooding the disaster situation. Therefore a cart would not be able to be pushed or pulled in the area. The team also discussed that the cart would be required to weigh an exceptional amount since a reverse osmosis filter produces only 4% of clean water from the total intake seawater. The team also discussed storage for the reverse osmosis filter's discharged seawater and the safety concerns of disposing of the wastewater within a community. Lastly, the team discussed possible stability issues with the cart because of the water's weight, as seen in Figure 21. The cart was not intended to have a steady supply of water introduced into the system, so when seawater in the intake tank runs out, that causes an imbalance in the system.

Calculations:

$1\ person\ needs\ 1\ gal/day.\ \ A\ family\ of\ 5\ would\ need\ 5\ gallons\ per\ day.$

$4\%\ rate\!:\ 5\ gals\ clean\ water\ *\ 0.04\ =\ 125\ gallons\ of\ seawater\ required$

$1\ gallon\ =\ 8.3\ lbs$

$125\ gallons\ *\ 8.3\ lbs\ =\ 1075\ lbs$ **This is only for water weight, the whole system would weigh more, but this is still too heavy for the average human to push/pull.*

**The average person can push/pull 225 N, which is 50.582 lb*f*

Figure 21. Calculations For Water Weight

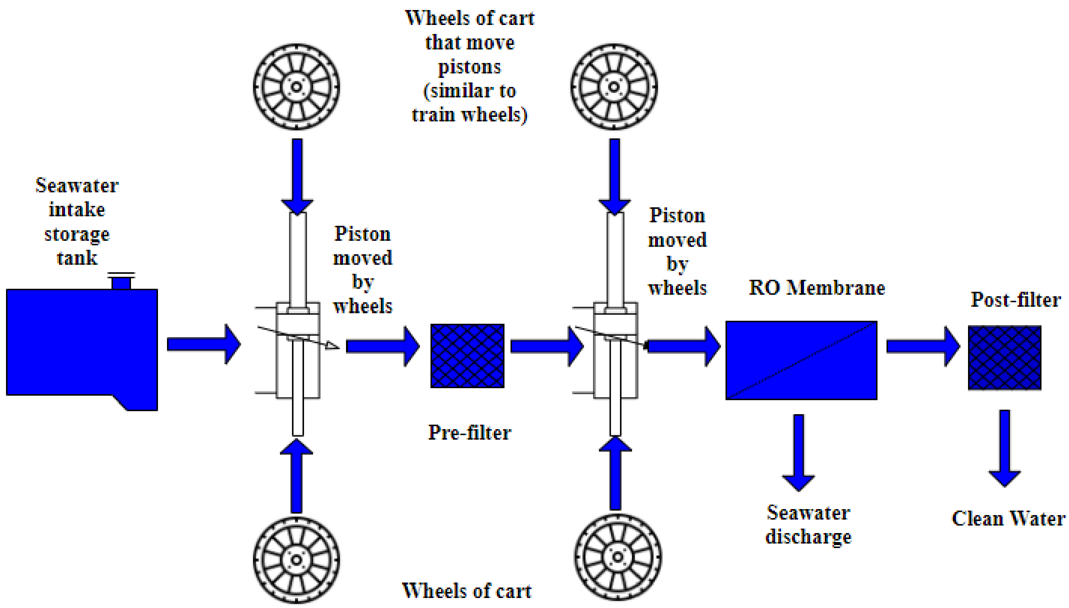


Figure 22. Concept Map of a Portable Desalination Device. *Wheels move the pistons as the cart is pushed/pulled. This idea was inspired by a train.*

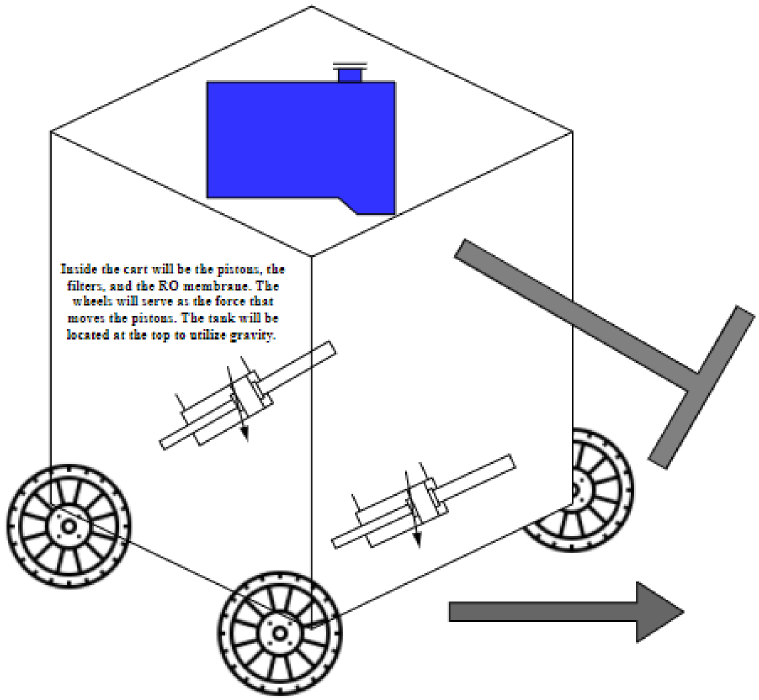


Figure 23. Sketch of The Portable Cart Design. *A person would either push or pull the cart using the T handle.*

The team ruled out a permanent and a fully portable device, and a semi-permanent design was sketched out and analyzed. The team utilized a similar cart design. However, instead of being fully moveable, the cart would stay in place and be moved around a singular point and pushed or pulled by a human using a bar. As shown in Figure 24, the cart would also sit on a platform with grooves to allow the cart's wheels to move smoothly and efficiently. This idea was inspired by discussions about road and ground conditions after a disaster relief situation. A platform was introduced to the design because the team did not want the device hindered by uneven terrain. There were concerns with this design's feasibility, so the team further discussed powering the device in the next section, Section 3.2.1.2, to better understand how to optimize the idea.

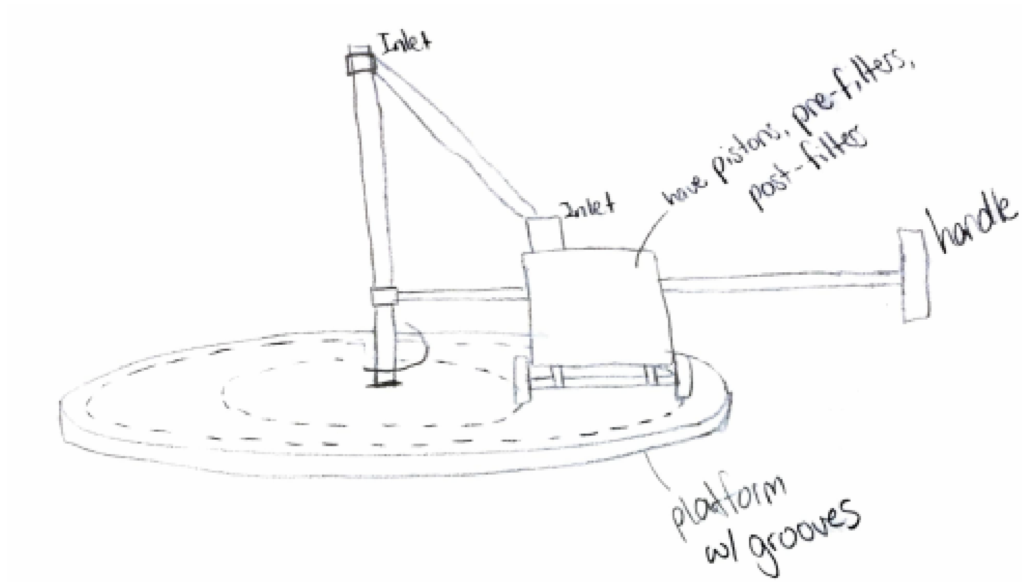


Figure 24. Rough Sketch of a Semi-Permanent Desalination Device. *Similar to the previous cart design, but semi-permanent.*

3.2.1.2 Powering the Device

The team brainstormed ideas on how to power the reverse osmosis device mechanically. Initial ideas included using batteries, solar power, turbines, or animals. However, as discussed in section 3.1.3 Energy Availability in The Region, the team decided to only focus on using human power. This decision was made by reasoning that human power was accessible during a disaster situation and would benefit the environment. Human energy eliminated the need for external power sources like electricity and fuel (Partridge & Bucknall, 2016). In turn, this reduced the environmental impact of the device. The average human can exert a maximum of 1 horsepower and maintain 0.1 horsepower indefinitely (Partridge & Bucknall, 2016). By utilizing human power, the team had a limitation on the available amount of energy used. The team planned for the device to provide one gallon of clean water from every hour worked. Since the average person is known to exert 0.1 horsepower indefinitely, the team found that at least 6 hour of work must be done per day to achieve the 5 gallons of drinking water. The normal working day is 8 hours, and in the wake of a disaster there is a lot for families to deal with. Because of these reasons, the effort needed to operate the device, based on initial calculations, was too high. The team needed to come up with ways to make the device more time efficient, such as examining different gear ratios and different ways to input energy.

The team explored using rotational movements and hand cranks on a semi-permanent device, as previously discussed in section 3.2.1.1. The team decided that the housing for the filters, pump, and reverse osmosis membrane would be stationary. Meanwhile, the input of human power would be generated using some form of human movement.

The team considered using a crank mechanism to power a high-pressure pump. The concept map below demonstrates human power going into the system through a crank mechanism. The crank would then turn a gearbox that would optimize the torque created by the human pushing or pulling the crank. The crank would power the high-pressure pump and create the desired pressure and flow rate for the system. The team first looked at utilizing a regular hand crank to make a rotational motion by a human. This system was also tied to using an Archimedes screw for pumping seawater into the system. The team did not go forward with this idea because it would need to be located by the shore and be positioned at a sufficient height for the Archimedes screw to function correctly. Having a device elevated on the shore was not ideal for the team because of the unknown elevation found on a shore after a disaster situation. The team then considered a design that would utilize a longer crank that could be pushed or pulled with the whole human body and would not need an Archimedes screw.

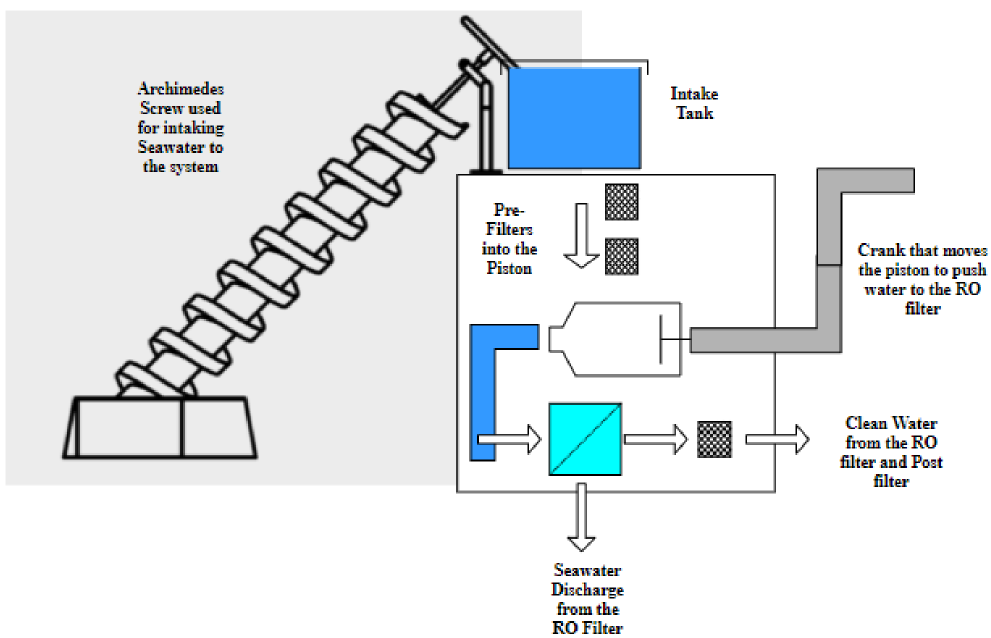


Figure 25. Sketch of a Desalination System Using An Archimedes Screw. *The screw was for intaking seawater into the system. Powering this device would be a hand crank that moved the piston.*

The team decided that a longer crank would allow a person to create a more significant torque required to power the high-pressure pump. The RPM created from a human pushing a crank is not very high (1.73 RPM to 7 RPM). The lower limit was calculated based on the recommended load of 50lb and the upper limit was calculated from the average walking pace of a person with no load, which can be seen in Figure 27. The team decided that a gearbox would be needed to provide a sufficient RPM required to power a high-pressure pump. The team brainstormed on this crank idea and drew inspiration from a circular horse walker because of the rotational motion about a shaft in the middle of the walker (Figure 26). Having a human push with their whole body and walk in a circular motion would increase the torque required to power a high-pressure pump.

Figure 26. Circular Horse Walker. (Marques, 2018)

In Figure 27, the team calculated how a push/pull crank would work for the system. The calculations demonstrated that a torque of 411.75 N could be achieved. During this stage of design, the team was exploring high torque options in order to provide the force necessary to compress piston cylinders. The team was still considering the use of a small number of large pistons to pressurize water to at least 800psi. Due to this design decision, a long lever arm pushed by a person's whole body was seen as optimal since gears and links would be attached to a drive shaft to oscillate a piston.

Calculations:

$Torque = F * d = 225N * 1.83m = 411.75\ N * m$ (303.69 ft*lb)

$Power = \frac{\tau * RPM}{5252}$ *Humans can create 0.1 hp indefinitely, and 1.2 hp briefly*

RPM = $\frac{P*5252}{\tau} = \frac{(0.1hp)(5252)}{303.69ft*lb}$ = **1.73 RPM** *For a human creating hp indefinitely*

RPM = $\frac{P*5252}{\tau} = \frac{(1.2hp)(5252)}{303.69ft*lb}$ = **20.75 RPM** *For a human creating hp briefly*

RPM with no load = Average walking pace for a person revolving around a 6' radius

RPM with no load = 3mph * $\frac{5280\ ft}{1\ Mile} * \frac{1\ hr}{60\ min} * \frac{1\ revolution}{37.7\ ft}$ = 7 RPM

Where:

*Torque is in ft*lb*

RPM is Revolutions Per Minute

Power is in horsepower

Figure 27. Calculations for Torque, Power, and RPM

Through the crank, the human mechanical power would power a gearbox that would optimize the RPM and torque to power a high-pressure pump. Of the positive displacement pumps that the team was investigating, the average displacement per revolution was 1 in^3. Using this metric and the 800 psi needed in the system, the team calculated the torque needed to turn the driveshaft of a given pump which can be seen below in Figure 28. The team used 800 psi because the membrane that was chosen was rated for typical usage at that pressure. The membrane had a maximum operating pressure of 1000 psi, but it was specified that 800 psi was sufficient to filter salt water. The resulting torque gave the team the ratio between the torque that the pump needed and the torque that a person could generate using a six-foot lever arm. That ratio determined the gear ratio in the gearbox that the team needed to create smooth power transmission from the motion of the lever arm to the pump. This high-pressure pump would pump water from the pre-filters into the RO membrane, and the water from the RO membrane would be filtered through a post-filter that would, in turn, discharge clean water.

Calculations

$$\text{Torque} = \frac{\text{Pressure} * \text{Pump Displacement per Revolution}}{2*\pi}$$

Where:
*Torque is in lbf*in*
Pressure is in PSI
Displacement is in cubic inches
Values were taken from the pump specifications sheet (A. (n.d.). Hydraulic Gear Pump APQ-20 [PDF]. Anfield.)

$$T = \frac{800psi * 1in3}{6.28} = 127.39 \text{ lbf*in} = 14.39\text{N*m}$$

Figure 28. Calculations for Torque Required to Turn Pump at 800 psi

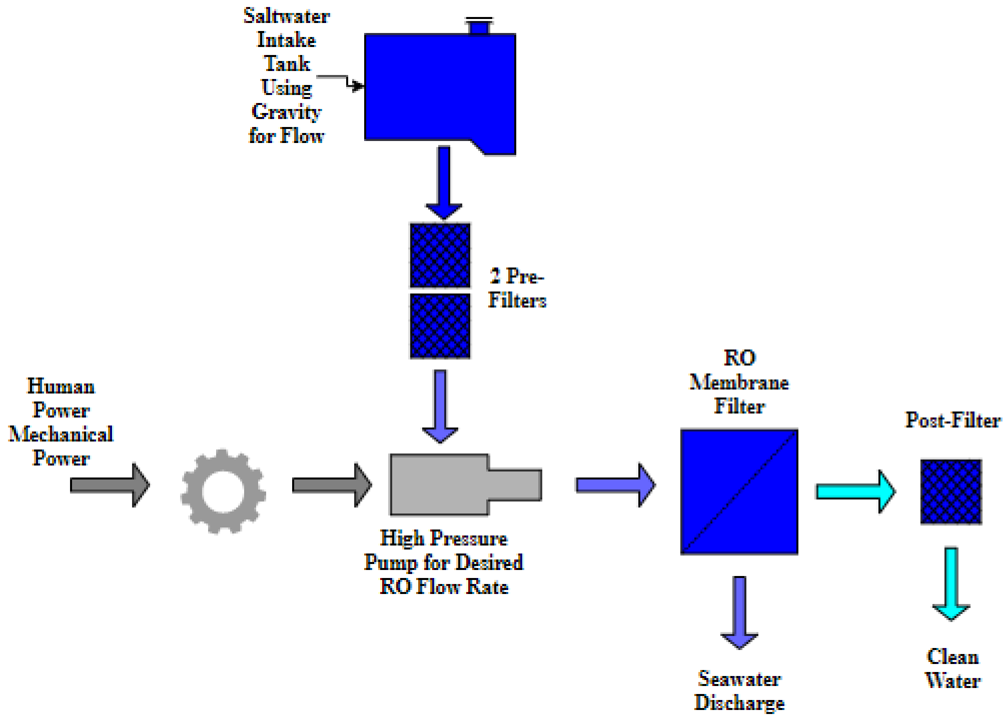


Figure 29. Sketch of a Desalination System Using Human Power. *Humans would power a high pressure pump to move water through an RO membrane.*

The team explored various options for powering the device using human power, such as using a hand crank and pushing a lever. The team also explored using pedal power. Figure 30 demonstrates the functioning mechanism for a pedal-powered system. Pedals would create RPMs necessary to turn sprockets connected to a drive shaft on a high-pressure pump. This pump would, in turn, pump water from an intake tank into the Reverse Osmosis membrane. The pump would also create the pressure required by the reverse osmosis membrane to produce desalinated water. The team made preliminary calculations for pedal power, found in Figure 43. It was determined that pedal power could only produce about 15.91 N*m of torque and 60 RPM (Frank, 2016). So, while pedals provided a decent amount of RPMs, the torque created was relatively low.

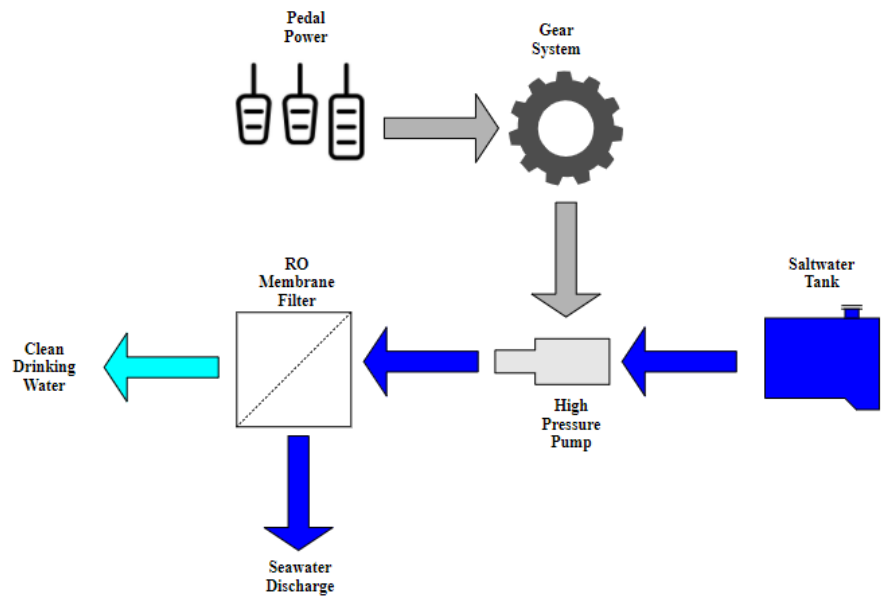


Figure 30. Sketch of Pedal Power Layout For Desalination.

The team was left with two viable options for powering the desalination device: using a long crank or pedal power. While the six foot crank provided a higher torque than pedal power, the RPM was significantly less. The team decided to move forward with using the long crank for the preliminary device, but understood that a design change could result in using the pedal power idea instead.

Table 10. Calculation Comparisons

Metric	**Six-foot Crank**	**Pedals**
RPM	1.73	60
Torque	411.75N*m	15.91N*m
Space Taken	6-foot radius circle	Less than 2 square feet of additional space for the pedals

3.2.1.3 Different Pump Options

The team identified three potential pumps that could be useful for the device: piston pumps, gear pumps, and centrifugal pumps. Piston pumps are composed of two valves, a chamber and a piston. This pump moves the piston into the chamber which, in turn, compresses the fluid inside. When the fluid pressure becomes higher than the outlet valve spring, the fluid goes through the outlet valve. When the piston comes back up, the outlet valve closes, and the inlet valve opens. Their pressure rating can be as high as 10,000 psi (Thomas, n.d.). Piston pumps have an efficiency up to 95% (Kent, 2008).

On the other hand, gear pumps operate by catching fluids between the teeth of two rotating gears that mesh together. A shaft is connected to one gear. This driven gear turns the other gear. When the teeth of the gears pull apart, a partial vacuum is created. The fluid goes into this area and is transported between the housing and the gear. The fluid comes out when the teeth mesh again. There is an uneven load on the gears and their bearings due to the pump's outlet (Mobley, 2000). Additionally, gear pumps have efficiencies of 80% at best but become less efficient over time (Kent, 2008).

Another pump that is often used with the transfer of fluids is the centrifugal pump. This pump uses an impeller that rotates and moves fluids by centrifugal force. This type of pump is often used in agriculture, wastewater plants, petroleum industries, and much more. The centrifugal pump can move considerable quantities of fluids, which in turn produces high flow rates. These pumps are designed to handle low viscosity fluids, like water and some types of oils. Higher viscosity fluids require more power to work (Power Zone Equipment, Inc., n.d.).

Table 11. Comparison of Centrifugal And Positive Displacement Pumps. (Castle Pumps, n.d.)

Factor	**Centrifugal**	**Positive Displacement (Piston and Gear Pump)**
Mechanics	Impellers pass on velocity from the motor to the liquid which helps move the fluid to the discharge port (produces flow by creating pressure).	Traps confined amounts of liquid and forces it from the suction to the discharge port (produces pressure by creating flow).
Performance	Flow rate varies with a change in pressure.	Flow rate remains constant with a change in pressure.
Viscosity	Flow rate rapidly decreases as velocity increases, which is due to frictional losses inside the pump.	Due to internal clearances, high viscosities are handled easily and flow rate increases as velocity increases.
Efficiency	Efficiency peaks at a specific pressure; any variations decrease efficiency dramatically.	Efficiency is less affected by pressure, but if anything tends to increase as pressure increases. Can be run at any point on their curve without damage or efficiency loss.
Suction Lift	Standard models cannot create suction lift, although self-priming designs are available and manometric suction lift is possible through a non return valve on the suction line.	Create a vacuum on the inlet side, making them capable of creating suction lift.
Shearing	High speed motors lead to shearing of liquids. Not good for shear sensitive mediums (such as seawater)	Low internal velocity means little shear is applied to the pumped medium. Ideal for shear sensitive fluids (such as seawater)

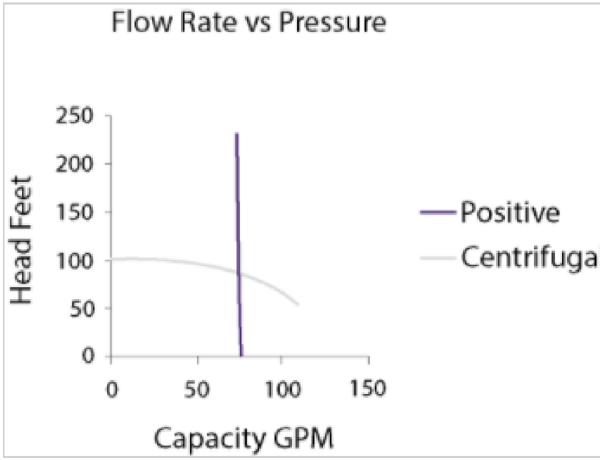


Figure 31. Flow Rate vs. Pressure Graph (Castle Pumps, n.d.)

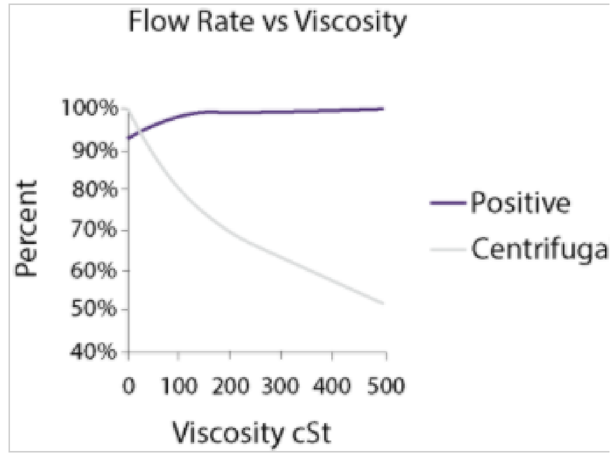


Figure 32. Percent Flow Rate vs. Viscosity Graph (Castle Pumps, n.d.)

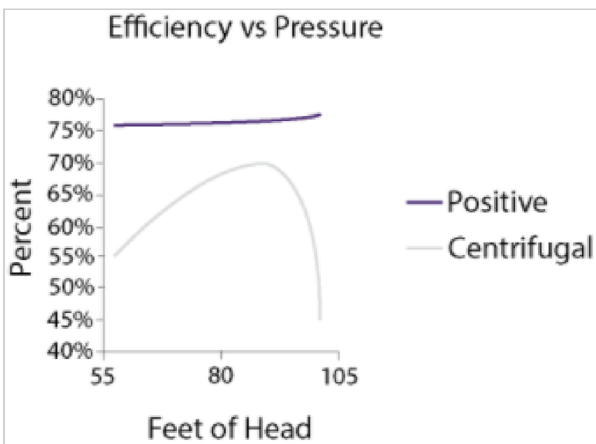


Figure 33. Efficiency vs. Pressure Graph (Castle Pumps, n.d.)

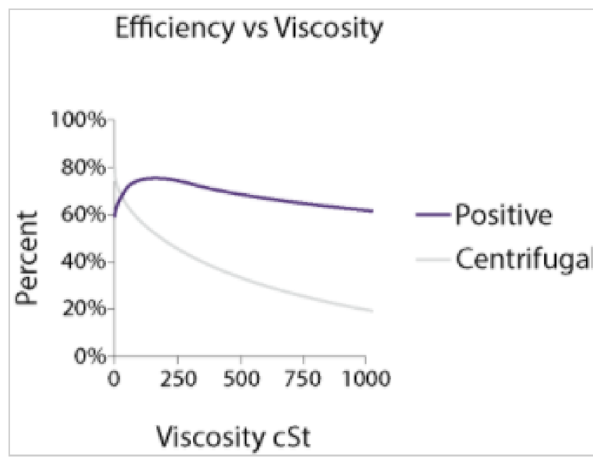


Figure 34. Efficiency vs. Viscosity Graph (Castle Pumps, n.d.)

Table 12. Quantitative Pump Comparison (PumpScout Staff, 2019).

Quantitative Pump Comparison			
Type of Pump	Flow Rate Ranges	Total Head Pressure Ratings	Horsepower Ranges
Centrifugal Pumps	5-200,000 GPM	10-7,500 ft	0.125-5,000 hp
Piston Pumps	5-7,000 GPM	50-50,00 psi	1-500 hp
Gear Pumps	1-1,500 GPM	10-2,500 psi	0.5-2,000 hp

A piston pump and a gear pump are considered positive displacement pumps. As seen in Table 12 and Figures 31-34, positive displacement pumps appear to be better suited for the team's application. Figures 31-34 contain general data for positive displacement and centrifugal pumps. Since the team was designing for contaminated saltwater, there would most likely be varying degrees of viscosity. Positive displacement pumps can handle higher viscosity fluids. Also, these pumps can have a constant efficiency versus pressure graph, as shown in Figure 33. Continuity in pressure was preferred as a reverse osmosis filter requires constant pressure (Castle Pumps, n.d.).

The team was left with two pump choices: the gear pump and the piston pump. The team initially decided to go forward with a piston pump for the preliminary design, as shown in Figure 35. The team wanted to maximize the amount of water that came out of the system. The desired pump would need a high horsepower and efficiency (Gannon, 2017). Since the piston pump had a higher pressure range, as shown in Table 12, it would pump water to the reverse osmosis filter successfully (PumpScout Staff, 2019). The more significant water pressure entering the RO membrane, the cleaner the water produced would be. (Gannon, 2017). However, due to budget restraints, the team decided to go forward with gear pumps for the final design, as shown in later figures. Gear pumps are similar to piston pumps but significantly cheaper and easier to find.

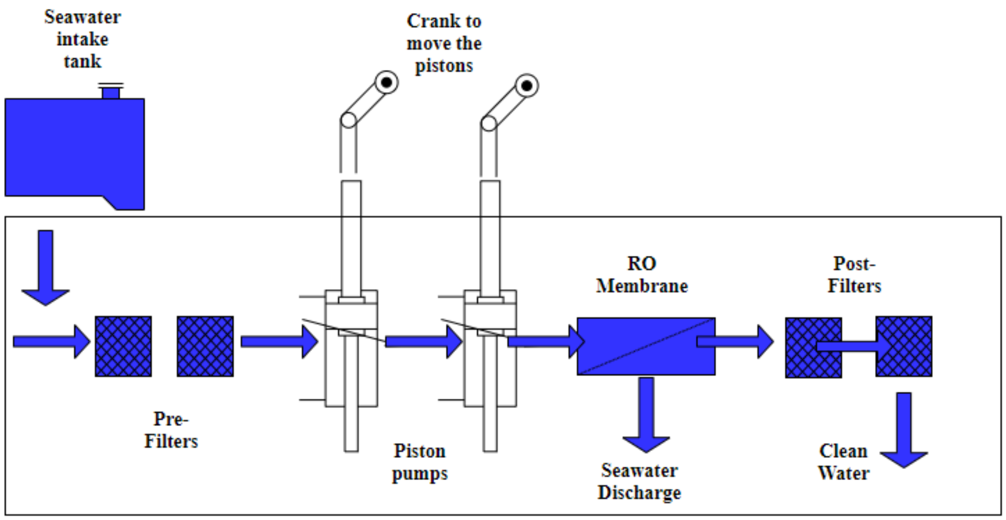


Figure 35. Sketch of a Piston Configuration For The Desalination Device. *Pistons would be moved using a human powered crank.*

3.2.2 Key Components of Preliminary Design

For the first preliminary design, the team decided to create a semi-permanent structure that utilized a long crank and crankshaft to be pushed or pulled with the whole body to power the system. The design included a solid outer housing made of wood or plastic (shown as clear in the design below), an intake tank for water, pre and post filters, a gearbox, a high-pressure pump, and a crank with crankshaft and handles. For this system, the crank would be pushed in a circular motion around the device using the handles. Doing this would turn the gearbox gears and optimize the torque and RPM required by the high-pressure pump. The pump would then move pressurized water from the pre-filters to the reverse osmosis membrane to produce clean water. The critical components of the device were described below.

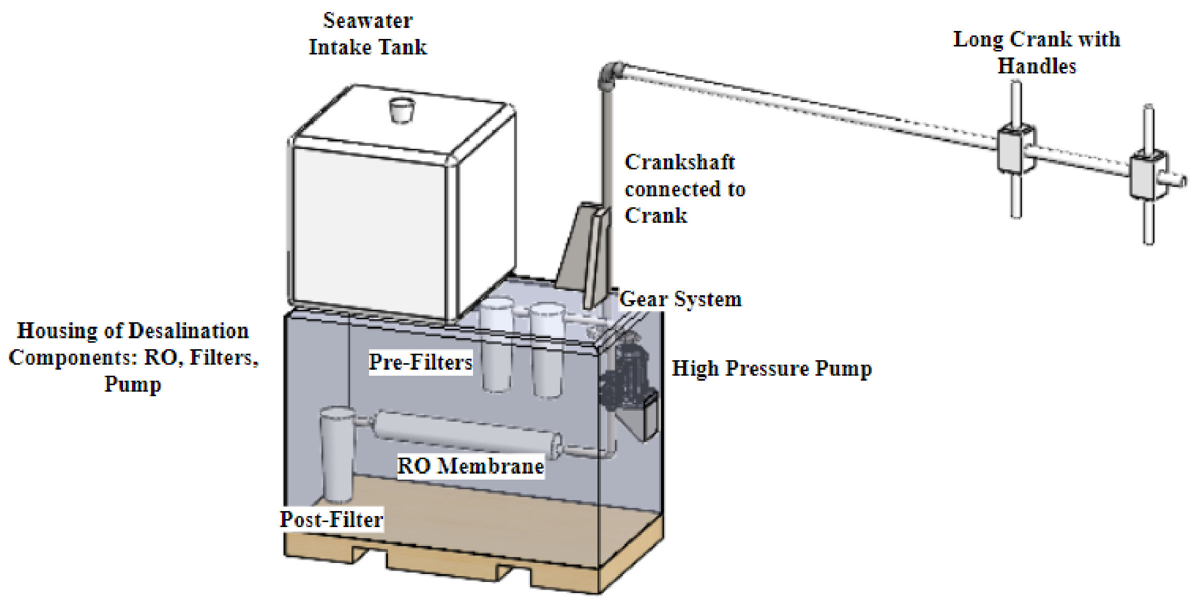


Figure 36. First Solidworks Draft of Preliminary Design

3.2.2.1 Crank and Handles

The team decided to use a regular PVC pipe as the device's crank and utilize vertical handles for comfort. The team decided to use a standard length of 6 feet for the crank. By using this length, the torque produced would be 411.75 N*m. The crank itself would be attached to a crankshaft connected to the gearbox. The crank would be attached to the crankshaft using a 90 degree PVC Pipe elbow. The crankshaft would be at chest height for the average adult so that a person could use their whole body to push the crank. The force required to push the crank would be too large for a child as the CDC recommendation for 225N (50lb) of sustainable horizontal force targets adult workers. There are two handles for the crank, designed to give optimal comfort for a person pushing with both arms. The vertical handles also allow people of different heights to access the most comfortable position to apply force. As discussed in previous sections, a vertical handle allows the user to utilize their power zone. The handles were also designed based on the average barbell grip diameter and hand length (Home Gym Resource, n.d.).

Calculations:

Amount of Force a Human can push standing: 225 N

Crank Length: 6 feet = 1.83m

Torque = F * d = 225N * 1.83m

Torque **= 411.75 N*m (303.69 ft*lb)**

**Torque created by a human and a 6 foot crank*

Figure 37. Calculations for Torque

3.2.2.2 Gearbox

Calculations:

RPM and Torque Affected by Gear Ratio:

Gear 1: 40 teeth

Gear 2: 10 teeth

Gear Ratio = 1:4

RPM into the pump = RPM from human*Gear Ratio

RPM into the pump = 1.73 * 4 = 6.92 RPM **For a human creating hp indefinitely*

RPM into the pump = 20.75 * 4 = 83 RPM **For a human creating hp briefly*

Where RPM from human is calculated in ***Section 3.2.2.3***

TorqueOut = TorqueIn * Ratio * η

η= Efficiency

TorqueOut = (TorqueIn: 411.75 N*m)*(Gear Ratio: $\frac{1}{4}$) * 0.98=100.87 N*m

Horsepower from Torque into Pump:

Torque In = 100.87 N*m (74.40 ft*lb)

HP = $\frac{Torque * RPM}{5252}$

HorsepowerIn = (TorqueIn*RPM)/5252 = $\frac{(74.40\ ft*lb)(6.92\ RPM)}{5252}$ = 0.1 HP **For hp indefinitely*

HorsepowerIn = (TorqueIn*RPM)/5252 = $\frac{(74.40\ ft*lb)(83\ RPM)}{5252}$ = 1.18 HP **For hp briefly*

Figure 38. Calculations for The Gearbox

The gearbox for the system would be composed of two gears. The team decided to utilize a gearbox to optimize the RPM and torque introduced to the system (Budimir, 2017). The team began with preliminary calculations to show how the system's torque and RPM would be affected by using a gear ratio of 1:4. The team continued to explore gear ratios, depending on the pump requirements.

3.2.2.3 Piston Pump

The team wanted to create a unique piston pump configuration. So, a list of requirements for the desired pump was created. The preferred operating pressure was between 800-1000 psi. The inlet and outlet pipes needed to be a standard pipe diameter to fit with standard tubing. The driveshaft of the pistons would need to connect to a gearbox to receive power. The team also needed to make sure that the pump could be secured and attached to the housing. Additionally, an anti-corrosive material, such as stainless steel, was used for the pump because of its saltwater application.

Hypothetical calculations for various piston pump configurations

Maximum Force exerted from human for brief amount of time: 225 Newtons
Will use a crank of 6 feet or 1.183 m

Torque = Fd = (225)(1.83) = 411.75 Nm → torque generated from a human with a 6 ft shaft

The torque was going to be transmitted into a gear with a link attached to it. The link would have been connected to a piston's tie bar and oscillate with the rotation of the gear. The force that the link exerted onto the piston was directly related to the torque generated and the distance between the joint connecting the link and the center of the gear.
Upon our research, we found piston pumps to have a range of diameters for the pistons. Below the team has done some calculation on what the force will look like if an "X" diameter piston is used.

Force to get 1000 psi:

- 1.0" diameter piston*
    - F = P*A
      $F = pi*(1000\ psi)*(6894.76\ Pa / 1\ psi)*(0.5*(0.0254\ m / 1\ in))^2$
      F = 3493.63 N*m
- 2.0" diameter piston*
    - F = P*A
      $F = pi*(1000\ psi)*(6894.76\ Pa / 1\ psi)*(1*(0.0254\ m / 1\ in))^2$
      F = 13993.78 N*m
- 3.0' diameter piston*
    - F = P*A
      $F = pi*(1000\ psi)*(6894.76\ Pa / 1\ psi)*(1.5*(0.0254\ m / 1\ in))^2$
      F = 31442.63 N*m

T = 411.74 N*m = (411.74 N*m) * (1 lb(f) / 1.36 N*m) = 302.76 ft*lb(f)

Power from a human: 0.1 hp
$Power_{Hp}$ = (T*S)/5252
S = (P*5252)/T = (0.1 * 5252)/302.76 = **1.73 RPM** → *generated by a human*

Figure 39. Calculations for a Pump

The pistons needed a specific force to apply pressure to the mechanism. This force depended on the diameter of the piston that was chosen.

Important Equations to Calculate Desired Pump Specifications:

Note: Values can be found from a pump's data sheet. The equations were used to determine what values the team wanted and then finding a pump with similar values. Numbers used below are arbitrary and not from a specific data sheet.

Flow Rate:

$$Q = \frac{\frac{D_P^2}{4} \times L \times n \times N \times \pi}{231} = \frac{D_P^2 \times L \times n \times N \times \pi}{924}$$

Q = Flow Rate (GPM)
D_P = Plunger/Piston Diameter in inches
L = Stroke Length in inches
n = Number of Plungers/Pistons
N = Speed of pump in revolutions per minute
π = 3.14159
Conversion Factor: 231in^3 per gallon

Brake Horsepower:

$BHP = Q \times P / (1714 \times \eta)$

BHP = Brake Horsepower (Hp)
Q = Flow rate (GPM)
P = Pressure (psi)
η = Efficiency (in decimals)

Maximum Operating Pressure:

$P_{MAX} = F_{RL} \times 4 / (D^2_P \times \pi)$

P_{MAX} = Maximum Operating Pressure (psi)
F_{RL} = Rated Maximum Rod Load (lbs)
D_P = Plunger Diameter (in)
π = 3.14159

Maximum Plunger Size:

$D_P = 2 \times \sqrt{\{FL / (P \times \pi)\}}$

D_P = Maximum Diameter of Plunger in inches
F_L = Rod Load Rating in pounds
P = Operating Pressure in pounds per square inch
π = 3.14159

Figure 40. Calculations Needed to Verify Pump Specifications (Power Zone Equipment, Inc., n.d.).

3.2.2.4 Reverse Osmosis Membrane

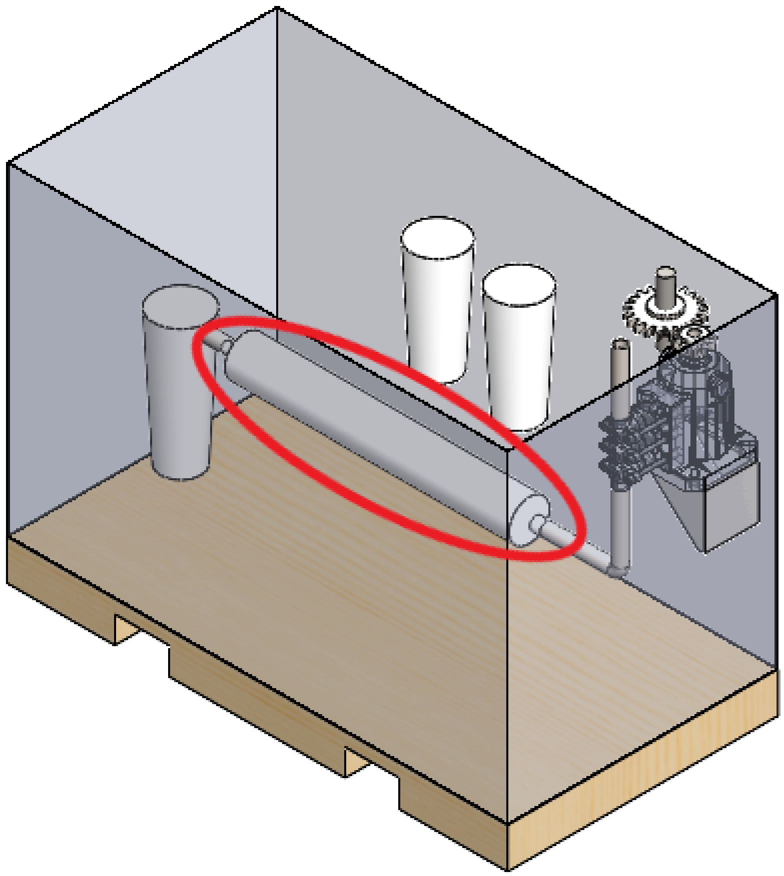


Figure 41. RO Filter Location

The team chose reverse osmosis to be the primary method of purifying the water. Reverse osmosis required a high-pressure range, 500-1000 psi, for the water to pass through the membrane. The team aimed to reach the upper threshold of the range to maximize the amount of clean water produced. The team chose an RO filter with an operating pressure of 700-800 psi. This RO membrane produced a 4% retention rate, meaning that only 4% of the input water would be suitable for drinking. This filter would be placed right after the pump to utilize the pressure created from the pump.

3.2.2.5 Pre- and Post-Filtration

Before becoming clean drinking water, the seawater would travel through a series of processes. First, the seawater would be filtered by prefilters before going through the reverse osmosis membrane. Once the water passed through the membrane, it would be filtered by a post-filter before being ready to drink. These filters were used to take out solids and similar debris from the water. The pre-filtration process occurred within the intake water tank. Water first went through sediment filtration to separate particles and substances found after a natural disaster (see Figure 42) (Budimir, 2017). Sediment filtration was achieved using a 100-micron mesh filter to filter out sediments the size of beach sand and larger.

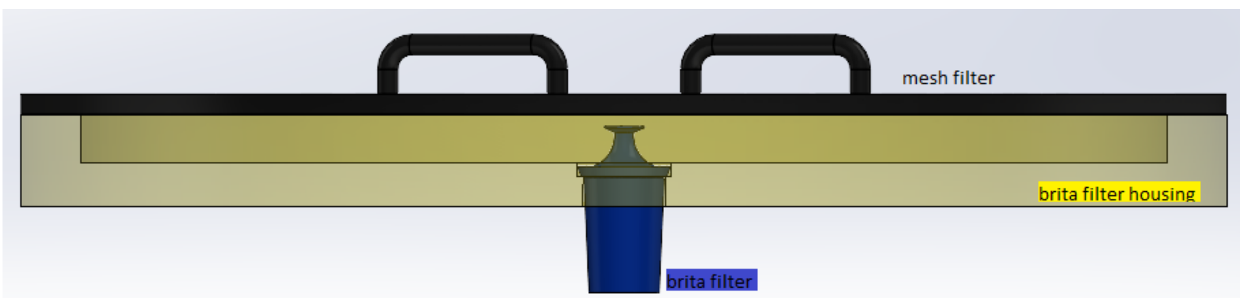


Figure 42. Pre-Filter Set Up

The other filter used was a carbon filter. For simplicity, this carbon filter took the form of a Brita filter. Along with removing sediment, it "also removes chlorine, volatile organic compounds (VOCs), odors, and unpleasant tastes" (Budimir, 2017). This filter utilized activated carbon to filter out unwanted substances. As water flowed through this filter, contaminants and substances became chemically bonded to the carbon and filtered out of the water. Carbon filtration was used to remove chlorine and improve water taste and quality. This filter was placed after the sediment filter and after the RO membrane. The pre-and post-filters chosen relied on gravity for water flow and did not require any additional pump pressure.

3.2.2.6 Water Intake, Rejected, and Output tanks

This device included an intake tank, output tank, and method for rejected water within the device. The intake tank would be placed on top of the mechanism and would hold the unfiltered seawater. Polypropylene plastic was considered for the intake tank material; however, this plastic would require a UV-resistant coat of paint to protect against degradation from the sun's UV rays (Brostow et al., 2020). The team also planned to make the intake tank under 22" in height to allow space for the crank to pass above it. Similarly, the output tank would be made of polypropylene plastic. This output tank would be located inside the device housing and be no longer than 35". This length was chosen based on the housing dimensions. The team wanted the output tank inside the housing away from contaminants such as sand, bugs, and rainwater. A faucet would be attached to allow the user to access the filtered water easily. Lastly, the rejected brine water from the RO filter would be routed back to the sea through a hose.

3.2.3 Preliminary Design Revisions and Changes

As the team moved forward with their design, discussions and scenarios were brought up, making the team rethink the overall design components. The team continued to revise their preliminary design based on advice, critiques, and newfound research. This process included revisions on the power source, framing, and pump choices.

3.2.3.1 Pedal Power vs. Hand Crank

Initially, the team considered using a hand crank because of the increase in torque provided by the long lever arm. However, when analyzing the preliminary design, the team realized several other metrics affected the system. These metrics included RPM and gravity. The team had initial reservations about using pedal power because of the lower torque produced. As seen in Figure 43, the team did preliminary calculations, using hypothetical numbers to understand how pedal power would affect the system. The team discovered that while pedaling provided higher RPM, the torque produced was relatively low and would affect the pump's power. Ultimately, pedals were deemed viable because despite the lower torque, the higher RPMs resulted in a higher flow rate. The pump displaces a certain volume of water per revolution, so maximizing the RPMs would maximize the amount of water pumped. A hand crank was more suited to the slower, high-torque application of compressing a small number of pistons, whereas a gear pump displaced a small amount of fluid per revolution and required higher RPMs to get the flow rate needed to move enough water through the RO module. To apply the hand crank for use on a gear pump would have required a high gear ratio involving a gear train of multiple gears. The team realized that more gears would reduce the mechanical efficiency and needed a way to reduce the number of gears. Given the higher initial RPM available from pedalling, the gear ratio needed was smaller, and required fewer gears. The pedals would function by rotating a series of sprockets connected to the shaft of a high-pressure pump. Pedal power was found to be viable because the high initial RPM allowed the team to design a transfer of power to the pump shaft with a lower gear ratio than using a hand crank and still provide the needed torque to pressurize the water.

Calculations for Bike Pedaling

Torque produced from person pedalling

Avg Adult = 100 to 320 W, for bike pedaling

$$Power = \frac{\tau * RPM}{9.5488}$$

$$Torque = \frac{Power * 9.5488}{RPM} = \frac{0.10\ kW * 9.5488}{60} = 15.91\ N*m$$

**The above equation shows torque provided from a person at 60 RPM, and 0.10kW of pedaling power. This torque is relatively low.*

The torque needed to operate the pump at 800 psi is 14.39 N*m, referenced in Figure 28. Since the torque provided by a person is higher than the required torque, pedal power is shown to be viable.

Figure 43. Calculations for Bike Pedaling

Thus, the team compared human power from hand-cranking against foot pedaling. This comparison is summarized in Table 13. From this comparison, the team decided on using pedal power because it was more user-friendly and provided the power and RPM needed for the system.

Table 13. Pedal Power vs. Hand Crank Pros and Cons

Design	Pros	Cons
Pedal Power	● More compact and level user space ● Pedaling uses a good muscle group that is more energy efficient ● Higher RPMs than the crank, which can increase flow rate even at high pressure ● More ergonomic	● Taking into account rough terrain after a storm, the ground could be uneven and unstable for a biking set up ● After a storm, the weather might not be ideal for exercise ● Lower torque
Hand Crank	● Stronger force from pushing motion ● Increased torque	● Uneven center of gravity due to large lever arm constantly changing positions ● Requires a 6 foot radius around the system for human to crank ● Crank positioning is optimized for specific height range

3.2.3.2 Bike Frame Discussion

Pedal power came from the idea of using a bike to generate energy. The team needed to discuss whether the desalination device would require an entire bike frame or only the pedal assembly. To easily do this, a decision table was made with pros and cons for each design idea. As the team discussed these options, it became evident that only using a pedal assembly without the full bike frame would be more feasible. This decision would allow for greater flexibility, ease of transportation, cost reduction, and more benefits. A couple of downsides to not having a bike frame are stability issues and requiring external seating. In the end, the team decided that no bike frame would give the user of the desalination device the best experience.

Table 14. Decision on the Bike Frame.

Design	Pros	Cons
Bike Frame	• Standardized parts • Adjustable seat and handles • Rigid frame for consistent power transmission • Ability to use full body weight on pedals	• Adds space • Adds weight • Not as adjustable and personalized as "no frame" • Adds cost of materials
No Bike Frame	• Easy to transport • Light • Seating can be variable (someone can use their own chair, some debris, a couch, etc) • Takes away from cost of materials • Since seating is variable, more people can use it (child, adult, larger person with longer legs, shorter person with shorter legs) • Could use arm movement instead	• Stability (requires a strong frame) • External seat required, instead of built in

3.2.3.3 Pump Choice

The team initially planned to use a piston pump for the device to generate very high pressure for fluids: up to 4,000 psi (Panagon Systems, 2020). The Reverse Osmosis Membrane's operating pressure was approximately 800 psi. Since this was a low-pressure rating compared to high-pressure pumps, the team felt it was unnecessary to obtain a top-shelf industrial pump. The 800 psi was a minimum pressure since reverse osmosis filters would not effectively filter saltwater at lower pressures. Additionally, piston pumps are often used in industrial settings and not small scale settings such as the team's desalination device. The piston pump's price also deterred the team from purchasing them: piston pumps cost $800 to more than $2000. Piston pumps exceeded the team's budget and were unrealistic in producing an accessible desalination device for disaster relief.

The team then researched other pumps and realized gear pumps were a more viable option. Although gear pumps have a low maximum pressure rating (3000 psi), it meets the team's psi requirement (Panagon Systems, 2020). Gear pumps are also inexpensive compared to piston pumps, ranging from $106-$300. Purchasing a gear pump was more accessible with the team's budget. It also made more sense for use within disaster relief situations.

3.3 Final Design

In this section, the components of the final design are discussed. These components were either changed, improved, or updated from the preliminary design in the previous section. As discussed in section 3.2.3 Preliminary Design Revisions and Change, the team implemented changes to create the desalination device's final design.

3.3.1 Pedals, Sprockets, Fixtures

The final design of this project utilizes human power from biking pedals. This biking set-up was preferred over the crank design because of better spacing, ergonomics, center of gravity, and RPM. The average adult produces 100 Watts when biking (Frank, 2016). This human power is translated to the gear pump through chains and sprockets. The pedal gear assembly (see Figure 44) increases the RPM of the driven sprocket. By adjusting the gear ratio, the team can either increase power or RPM to the gear pump.

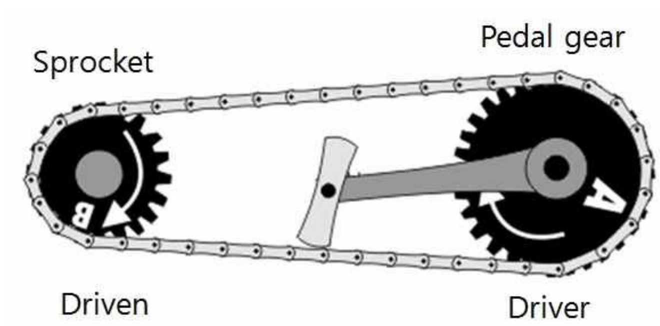


Figure 44. Pedal Gear Assembly (Woo, 2020)

Because a bike frame was rejected, the team created a compacted, sturdy stand for the bike pedals that allows the user to adjust according to their size and preference. A handle was also attached to the system for the user to stabilize themselves. The user would pedal seated from a chair, rock, or whatever seat is most convenient at the location.

Calculations for torque from pedaling:
An average adult biking produces 100 W = 0.1 kW = 0.134 hp
Without a gear ratio, average RPM produced from biking is 60 RPM
Power = $\frac{\tau \cdot RPM}{9.5488}$
0.1 kW = $\frac{\tau \cdot 60}{9.5488}$
$\tau = 15.91\ N \cdot m$

Calculating flow rate from Gear Pump based on pedaling RPM:
Flow Rate (Desired) = RPM (Desired) * $\frac{Flow\ Rate\ (Rated)}{RPM\ (Rated)}$
= 60 RPM * $\frac{9.51\ GPM}{1800\ RPM}$ = 0.317 GPM (19 Gal per hour)

Calculating Sprocket RPM:
Sprocket Ratio = $\frac{\#\ teeth\ driving\ sprocket}{\#\ teeth\ driven\ sprocket}$
Driving is the gear attached to pedals, usually largest
RPM Ratio = Driving RPM*$\frac{T1}{T2}$= Driven RPM
For a sprocket with 28 teeth that fits the gear pump and a sprocket with 48 teeth at the pedals
$\frac{48}{28}$* 60 RPM = Driven RPM
Driven RPM = 102.86 RPM

Figure 45. Calculations for Pedal Power

3.3.2 Gear Pump

To provide high-pressure flow into the RO module, the team decided to use a gear pump. Gear pumps are positive displacement pumps that utilize the meshing of gears to create a seal. These pumps can be broken down into groups, including external gear, concentric gear, and two stage pumps. The team implemented an external gear pump due to its simplicity, ability to provide fluid flow at high pressure, and simplicity to operate. An external gear pump consists of two meshed gears inside a high-pressure container, as shown in Figure 46.

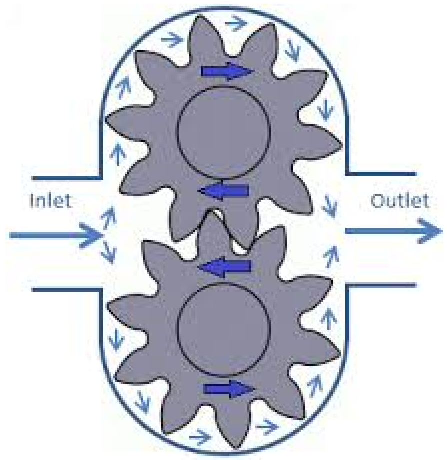


Figure 46. External Gear Pump (Michael Smith Engineers, 2020)

One gear is known as the "drive gear," and the other is known as the "idler gear." The drive gear is run by a drive shaft that extends outside of the pump shell. The driveshafts are keyed, allowing users to attach a chain, a pulley, or a gear directly from a motor (Michael Smith Engineers, 2020). The pump can be face mounted using two SAE-A2 bolt mounts, securely bolted to the frame.

The average person can produce about 0.1 kW of energy per hour (Partridge & Bucknall, 2016). Using this, the team calculated the gallons per minute that could be produced, knowing the amount of horsepower and pressure requirements for the system: A reverse osmosis system requires a pressure of a minimum of 725 psi for filtering salt water (Oram, n.d.). Using the hydraulic horsepower formula, the team calculated the device's approximate flow rate to be about 0.317 GPM. The expected time required to produce 5 gallons of clean water was about 7 hours from this calculation. However, the team took into account 4 cups of added water every hour a person was powering the device. This additional amount of water led to calculating the device being used for approximately 8 hours. This time frame correlates with about 1 gallon of clean water for every hour worked, which is approximately the same rate as the Katadyn Survivor device.

Flow Rate Calculations

HHP = $\frac{P * Q}{1714}$

HHP = Hydraulic Horsepower

P = Pressure in psi

Q = Flow Rate in GPM

1714 = Conversion factor necessary to yield hydraulic horsepower in terms of horsepower

0.1 kW = 0.134102 hp

HHP = $\frac{P * Q}{1714}$, so GPM =$\frac{HHP * 1714}{PSI}$= $\frac{0.13402\ hp * 1714}{725\ psi}$= 0.317 gpm (19 gallons per hour)

Expected Time for required water production:

Flow Rate = (GPM) = 0.317 GPM (19 gallons per hour)

5 gallons needed, with a 4% retention rate that means that 125 gallons are needed to produce 5 gallons of water

$$125\ gallons\ \ * \frac{1\ minute}{0.317\ gallons}\ \ =\ 394.32\ minutes\ (6.57\ hours)$$

Based on these calculations, our device will produce 5 gallons of clean water within a 7 hour time span. This means that the system will intake 125 gallons of water and at the end of a 7 hour period, produce 5 gallons of clean water. However, the above calculations do not include the 4 cups of water each person operating the device would also require.

4 cups of water = 0.25 gallons

7 hours of work = 1.75 additional gallons of water

6.75 gallons of clean water are required per day meaning that with a 4% retention rate that means that 168.75 gallons are needed to produce the clean water.

$$168.75\ gallons\ \ * \frac{1\ minute}{0.317\ gallons}\ \ =\ 532.33\ minutes\ (8.87\ hours)$$

Based on these calculations, in order to meet the requirements of providing clean water safely to 5 people, our device will need to be operated for approximately 8.87 hours per day.

Figure 47. Flow Rate Calculations (Drilling Formulas, 2009).

3.3.3 The Human Body and The Final Design

Since the device required the usage of human power, it was important that all safety precautions were followed. The team recommended that at least two people take turns pedaling the device on any given day. It was imperative that each person who used the device be properly hydrated and nourished. Pedaling would be conducted at a comfortable pace and would be sustained for no more than 45 minutes at a time to avoid exhaustion and fatigue (Kaloc, 2020). Below was a breakdown of the calories burned throughout the day by each person when used during certain situations. A hypothetical BMR and human profile was used to be able to compare the amount of calories burned by a sedentary person and the amount of calories that would be burned by a person using this device. As shown below, a person using the device for 4.435 hours would need to consume an extra 1190.58 kcal to remain healthy. The amount of calories was found to be too high of an extra load on food intake (equivalent to 12 mangos) for a disaster scenario. Indeed, the intent of the project was not to create a device on which people would need to pedal for over 6 hours a day under high intensity workout conditions to get water. These calculations show that the design was not viable for use in the field, and the team needed to use a prototype to investigate how to make the design more efficient.

Calculations:
Time required to produce 5 gallons = 6.57 hours
Time required to produce 6.75 gallons = 8.87 hours
Human power indefinitely = 0.1 hp = 74.57 W
*Energy (kcal) = Power (Watts) * Time (Hours) * 3.6*

Hypothetical Person: male, 165 lb, 5'10", 30 yrs old
Hypothetical BMR of each person = 1714.25 (number of calories a human burns at rest)

Scenario 1 Example:
Two people are taking equal turns to pedal. It is a relatively hot day, so they need extra water. They take 8.87 hours to use the device, so each person pedals for 4.435 hours. They are pedaling at power relative to 0.1 hp.

Energy (kcal) = 74.57 W * 4.435 Hours * 3.6 = 1,190.58 kcal
Each person will burn 1,190.58 calories pedaling the device for pedalling half of the day each

Questions	Scenario 1	Scenario 2
Number of people pedaling	2	2
Extra water?	Yes	No
Time Required (per person)	4.435 Hours	3.285 Hours
Power Required	0.1 hp	0.1 hp
How many calories does each person burn from the device?	1,190.58 kcal	881.86 kcal
Total calories burned during use	1507.36 kcal	1116.5 kcal

Calculations for Total Calories Burned During Use:
(Calories burned during hours worked) + $(\frac{BMR}{24})$(4.435 hours)*

Figure 48. Human Calories Burned During Different Scenarios.

3.3.4 Tanks

The system included a water tank before and after the pump and RO module. A sizable 55-gallon tank was used to hold unfiltered water and transferred water to the pump using gravity. The team chose a 500lb capacity tool stand to raise the tank above the ground. The tank's bottom is slightly higher than the pump to provide water flow without using auxiliary pumps. The RO membrane is rated at a 4% recovery rate, meaning to purify the 5 gallons needed by a family of five, the operator would need to pump a total of 125 gallons through the membrane, plus an additional 4 cups of water for every hour worked. However, the size of tanks large enough to fit more than 125 gallons would be unfeasible to implement in the system. The team decided to use a smaller tank and expected the system to be used in batches. The tank was required to sit at least

24 inches off the ground to maintain gravitational potential energy from the intake tank to the pump. Therefore, a large tank would pose safety hazards, especially in high winds. The tool stand would need to be anchored to the ground via cables and pegs driven into the ground to mitigate the risk of tipping over. The cables were meant to increase the resistance to lateral forces applied to the tank, such as high winds or people accidentally knocking into it.

3.3.5 Final Model

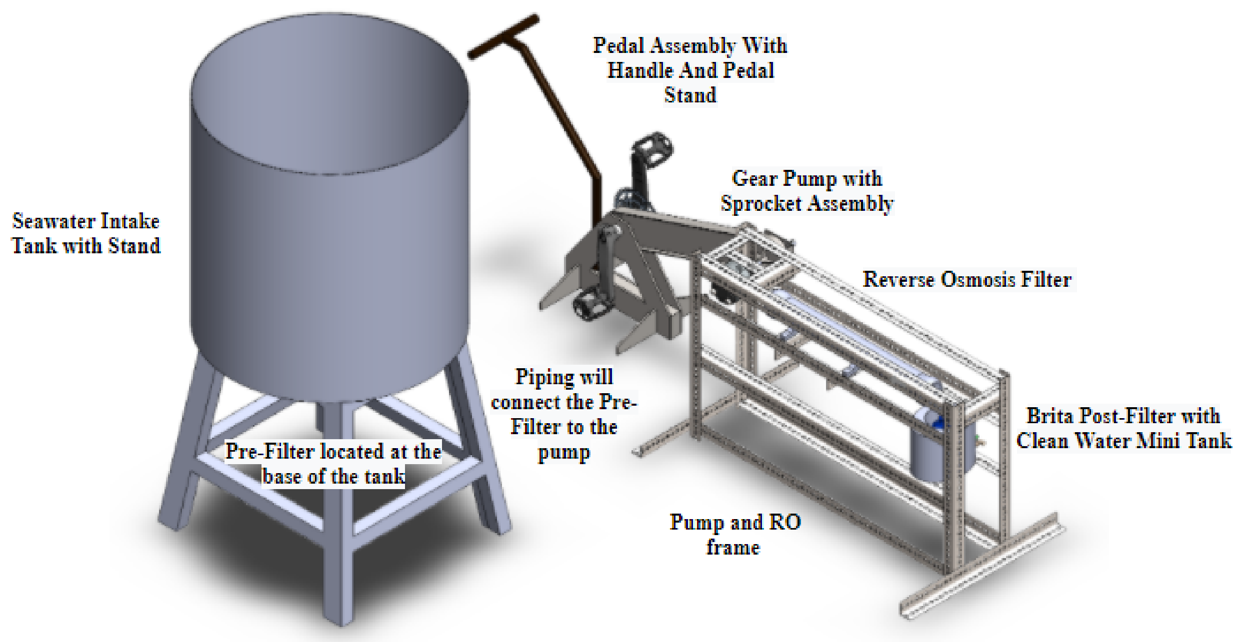


Figure 49. Final Model Assembly

The final design was the product of many iterations of models and changes, shown in Figure 49. The assembly was broken down into three sub-assemblies. The table below shows the dimensions of the footprint of each sub-assembly on the ground.

Table 15. Model Dimensions

Sub-Assembly	Footprint (L*W, inches)	Height (inches)
Intake Tank Stand	26”x24”	26”
Pedal Assembly	2.5”x16”	14”
Overall Frame	24”x40”	24”

3.3.5.1 Intake Tank Sub-assembly

The first sub-assembly included the intake tank. The intake tank was a 55-gallon tank with an integrated sediment filter and a Brita filter to pretreat the water before going through the pump. The sediment filter was a fine mesh held in with a bracket that fit the tank’s contour. A Brita filter was fed by gravity, after which the water flowed to the pump through flexible tubing. Prefiltration was necessary to remove large particles from the water before going into the pump. In addition to protecting the pump from wear, removing large particles protects the RO module from unnecessary fouling; fouling reduces the membrane’s efficiency.

The tank was set 26 inches off the ground by a metal tool stand to provide the gravitational potential to feed the pump. The stand was rated for 1000lb, which was sufficient to hold 55 gallons of seawater at 8.6lb/gal. The tool stand was also anchored to the ground with cables and pegs to provide extra stability. The total weight of 55 gallons of seawater was 473lb. The MQP team determined that even though more than 125 gallons of saltwater were necessary to yield 5 gallons of fresh water at a 4% recovery rate, a 125-gallon tank, or larger, was too big to be used. A tank large enough to hold that amount of water would pose several problems. A full tank would weigh more than 1075lb. Holding it 26 inches from the ground would require additional support, which would take up more space and increase the risk of collapsing or tipping in a high wind situation. Although device operators were not required nor recommended to carry all gallons at once, the safety concerns warranted a reduction in intake tank size.

Additionally, the device had a size constraint of a shipping pallet. The tank alone would take up the entire pallet. Thus, the device was intended for batch use, from which a 55-gallon tank would yield 2.2 gallons of clean water. This tank was not intended to be carried around, but instead would stay in place while people filled it up using smaller containers.

3.3.5.2 Pedal Sub-assembly

The next sub-assembly was the pedal and chain assembly, shown in Figure 50 below. The pedals were held off the ground by a small triangular frame. This frame was designed to be made from strips of steel because it was easy to weld together and drill holes for bolts. Additionally, steel would provide durability and weight to the subassembly to ensure it stayed on the ground and did not move around while being pedaled. The steel was painted to mitigate rusting and corrosion.

Figure 50. Pedal Sub-assembly

The bike pedals already contained integrated ball bearings, which allowed them to be secured onto the triangular frame without additional components to reduce friction. The frame did not contain a seat. The MQP team determined that the operator would provide personal seating to ensure individual comfort and accommodate various heights. The operator would sit in front of the pedals instead of directly above, as seen in traditional bicycle setups. A handle was added to the frame to allow the operator to steady themselves as they pedaled. The handle was constructed simply by using a 1-inch diameter steel pipe with a wooden handlebar. In hot, sunny conditions, a steel handlebar would absorb heat energy and transfer it to the operator, potentially causing an uncomfortable experience. The MQP team concluded that a wooden handlebar would provide a more comfortable experience for the user since it would retain and conduct less heat than a steel bar.

The sprockets were held at a uniform distance and aligned to prevent the chain from slipping off. To achieve these parameters, a rigid steel arm, designed by the team, was added to hold the sprockets in alignment, as shown in Figure 51. Since the arm acted merely as a spacer between the sprockets and was not a load-bearing component, it was designed out of thin gauge steel to reduce weight.

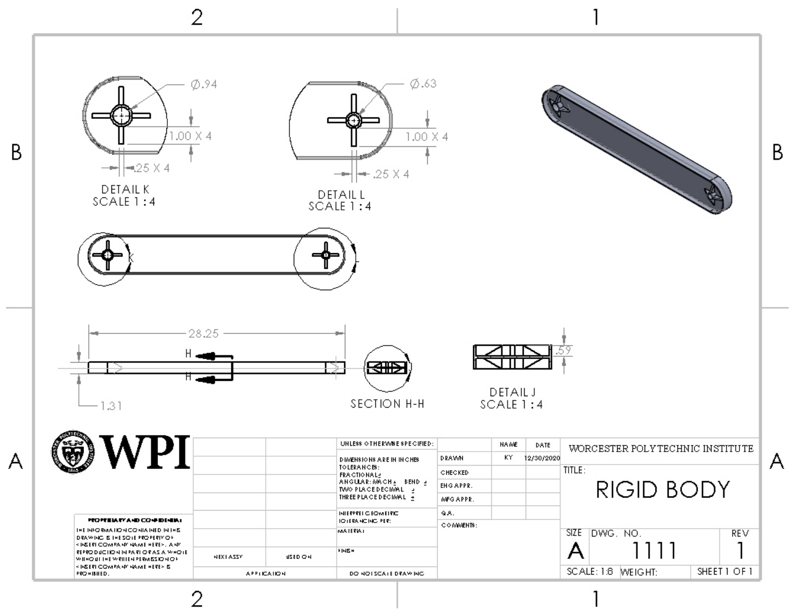


Figure 51. Solidworks Drawing of the Steel Arm

The steel arm was limited to rotation in the vertical plane. Its fulcrums of movement aligned concentrically to the sprockets. This rotation allowed the pedal frame to move vertically, independent of the rest of the system. This movement benefited the users because the pedal frame could sit at a different height than the rest of the system on uneven ground. The steel arm was designed to be made from 1/8-inch steel sheets. The component's perimeter was tack-welded to a strip of the same steel sheet to act as a strong-back and increase rigidity.

At the steel arm's end, a bracket held a keyed shaft to transfer power to the pump. This keyed shaft held the sprocket in place and rotated the driveshaft of the pump. The steel arm and sprocket were held in place by a steel bracket bolted onto the frame containing the pump. Slots and holes were cut into the bracket to match the frame's slotted angle iron to ensure alignment.

3.3.5.3 Overall Frame

The final sub-assembly was the overall frame. The frame contained the pump, RO module, and post-filter at a level at which people could lay a container underneath the post-filter to collect the water. The back view of the frame is shown in Figure 52. The right hand side of the image shows the arm holding the sprocket and chain onto the pump.

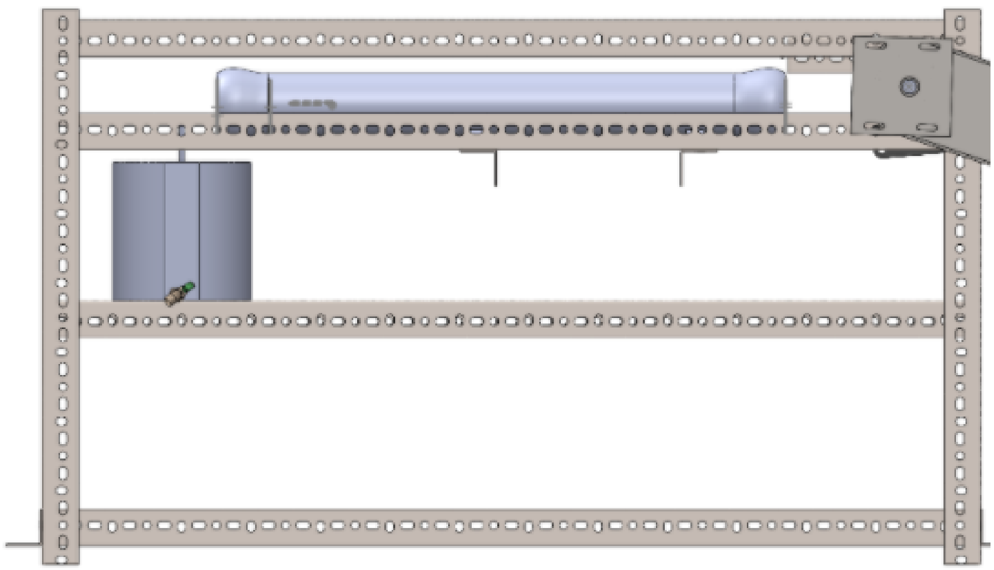


Figure 52. Back View of Overall Frame

The frame was constructed from 14-gauge slotted angle iron, an example section of which can be seen in Figure 53.

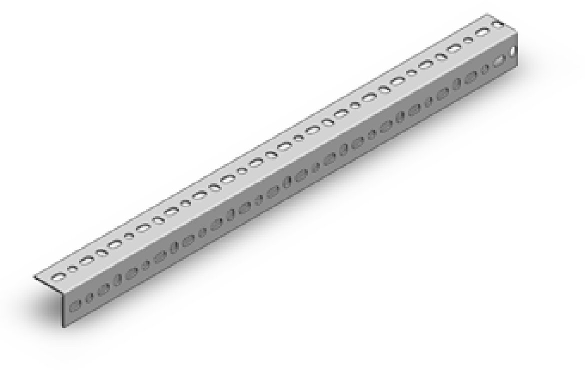


Figure 53. Example Slotted Angle Iron

The slotted angle iron was chosen due to its strength and convenience. The slots in the angle iron allowed the frame to be bolted together and proved to weigh less than regular angle iron. Since the intake tank's height was 26 inches, the frame's height was set to 24 inches. This height difference allowed the pump to be positioned lower than the intake tank so gravitational potential could feed water into the pump. The pump, RO module, and post-filter were all bolted to the frame using smaller pieces of the slotted angle bars as shelves and brackets.

The pump and RO module's size and thread type were different and needed several adapters to make the connection. To connect the 7/8" diameter pump outlet to the ¼" National Pipe Thread (NPT) fitting in the RO system, the team used adapters to reduce the pipe's diameter. A 7/8 Unified National Fine Thread (UNF) male thread to ¼" NPT female thread was inserted into the pump's outlet port. The ¼" NPT was then connected to a male ¼" NPT nipple. Another ¼" NPT nipple was threaded into the feed inlet of the RO pressure vessel. A female threaded union connector was inserted between the pump nipple and the RO nipple to connect them.

After the clean water flowed out of the RO module, a Brita filter acted as a post filter to improve the water's flavor. The Brita filter was set inside a small holding tank with a spigot on the bottom. The spigot's height was set such that users could place a clean water container below and collect the water as it was filtered.

3.3.6 Manufacturing

Manufacturing would be a key component in mass-producing the device. Using bulk orders for materials and components could reduce individual costs through mass production. If the team's device were to be used for natural disaster relief, multiple copies of the device would need to be made accessible. Machining parts with Computer Numerical Control machining (CNC) was considered for the team's final design to accommodate unique parts that cannot be bought from retailers. By nature, CNC machining can also be called subtractive manufacturing. Subtractive manufacturing means that a blank workpiece would be cut away into the shape of the final product. The waste produced by excess material adds to the overhead costs of CNC machining. Due to the high cost of CNC machining, the team chose parts and designs that would not need to be machined. Most of the assembly could be bought in bulk and assembled for mass production. For example, the frame was made from slotted angle iron, meaning low skilled laborers could bolt it together with minimal experience. The pump and RO module could be purchased from manufacturers in bulk to reduce the overall cost when mass producing this device.

3.3.7 CAD Model Analysis

For the CAD model analysis, the team conducted five separate analyses of the intake tank stand. These analyses were done to ensure the model functioned as intended before the building process occurred. The team analyzed the toolstand to ensure stability for this application.

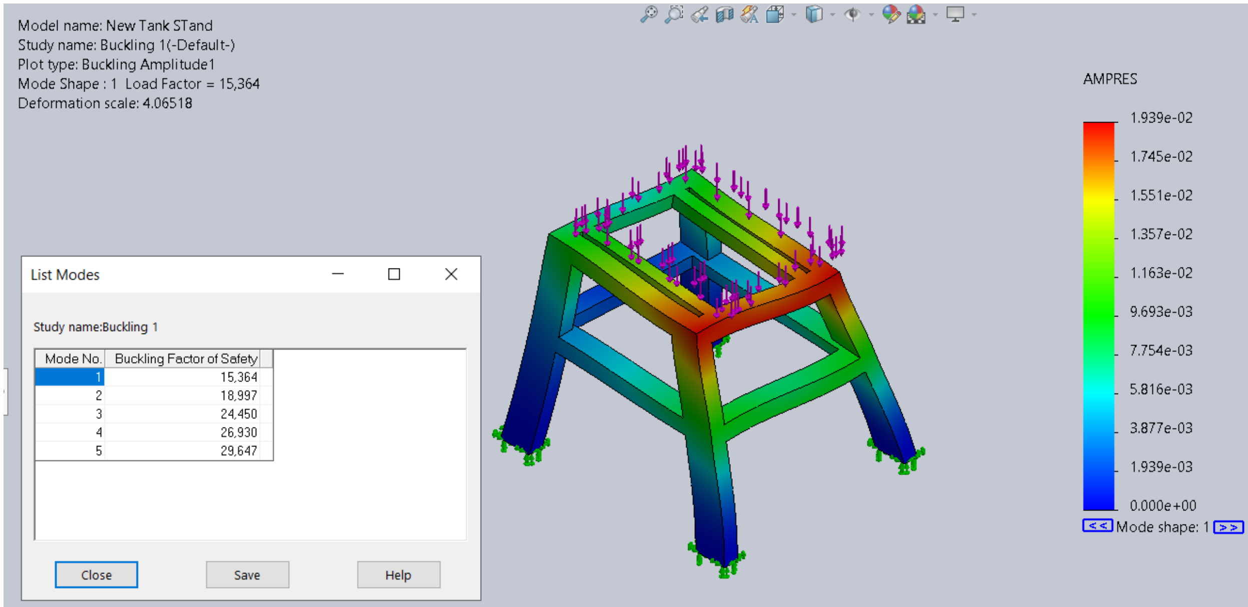


Figure 54. Buckling Analysis of the Tank Stand

In Figure 54 above, the team found a stand made of AISI 304 steel. For the buckling analysis, an external load was applied. The team decided that 55 gallons of water would be placed on the stand. As can be seen in the List Modes pop up in Figure 54, the stand had a factor of safety of 15.364. This meant that the stand would buckle under a load that was 15.364 times the initial load of 1680 N applied. It was expected that if a larger tank was needed for this device, then users would be able to comfortably use it with this safety factor.

Calculations for load on stand:

$$55\ gal\ *\ \frac{8.3454\ lb}{1\ gal} = 458.997\ lb \simeq 459\ lb$$

$$459\ lb\ *\ \frac{0.82286\ lbf}{1\ lb} = 377.69\ lbf$$

$$377.69\ lbf\ *\ \frac{4.448\ N}{1\ lbf} = 1679.97\ N \simeq 1680\ N$$

Figure 55. Force Applied on Tank Stand Calculations.

The highest temperature recorded during the average summer in the Caribbean region was usually a few degrees above 90 F (Bateman, 2021). For the thermal analysis, the team decided to test the stand at 95 F, as seen in Figure 56. The device was intended to be used outside during the daytime. In the legend, the color red indicated where there was maximum temperature affects and the blue indicated the minimum temperature effects on the stand. The stand resulted in being almost completely blue. This analysis illustrated that even if the stand was in the sun all day at 95 F, it would experience little to no thermal effects. This was helpful since the Caribbean region can reach temperatures up to 90 F during the summer, especially during the hurricane months in late summer.

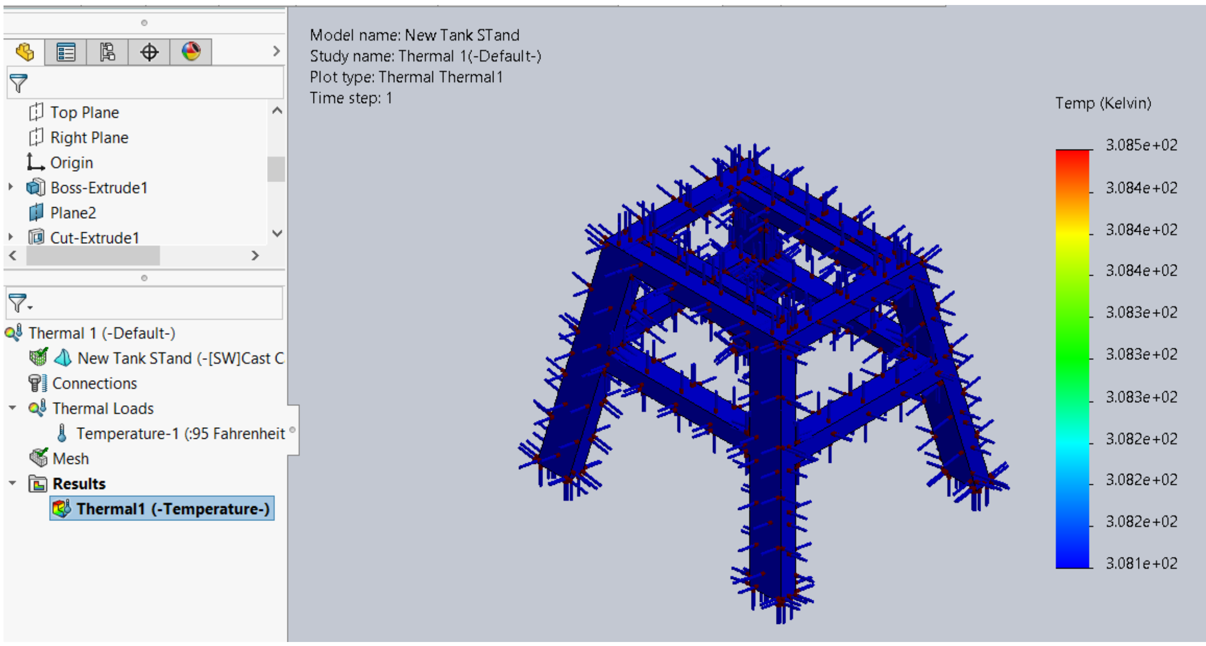


Figure 56. Thermal Analysis of Tank Stand

A static analysis was conducted for the stand, as seen in Figure 57. Most of the stand resulted in being blue, which meant there was not a large amount of stress being put on the stand. The legs of the stand appeared to absorb most of the stress caused by the tank's load. This data proved that AISI 304 steel was capable of holding the amount of stress that a 55 gallon tank can cause on a surface. Therefore, it was assumed that the stand would not break or tip over if the full weight of a tank was placed upon it. This reassured the team about the safety of the stand with the weight of the tank upon it.

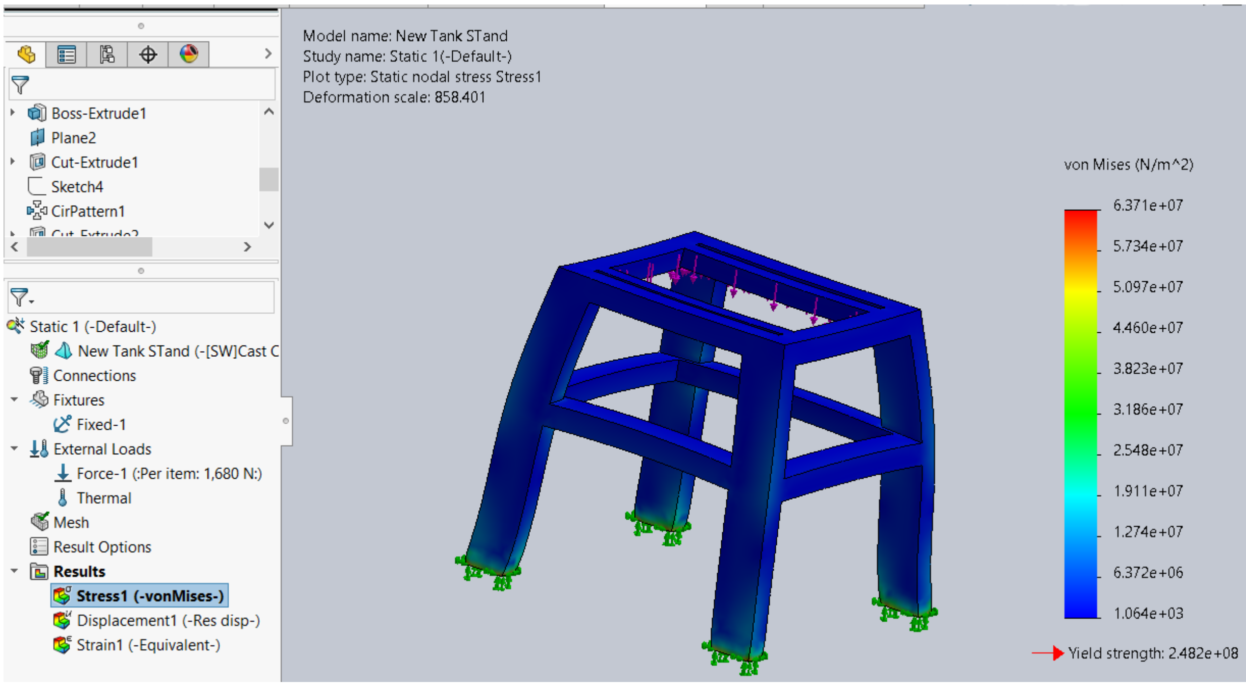


Figure 57. Static Analysis of Tank Stand: Stress

A static analysis for displacement was conducted on the stand, as seen in Figure 58. According to the analysis, the larger amounts of displacement would take place towards the top of the stand since this is where the tank would be located. Less displacement would occur towards the bottom of the stand since the load from the tank would be evenly distributed across the four stand legs. This also meant that the stand would be relatively stable with the load of the tank placed on top.

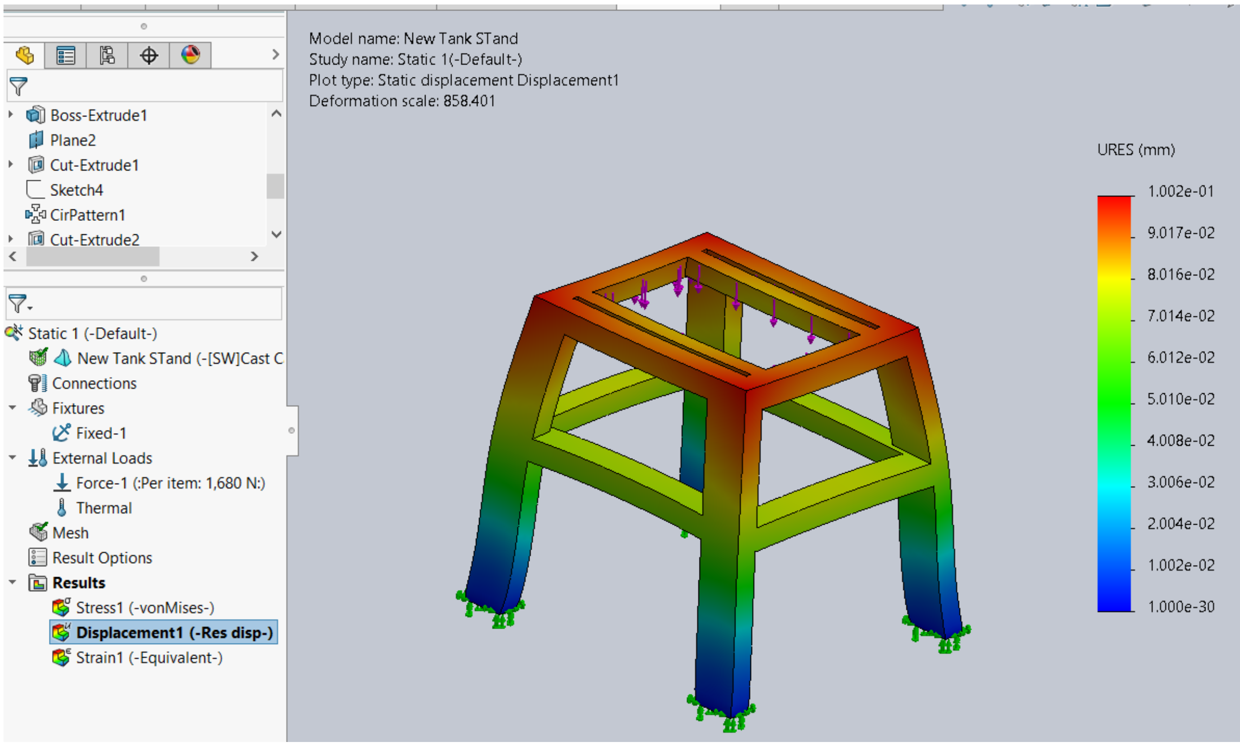


Figure 58. Static Analysis of Tank Stand: Displacement

The stand was also tested for forces of strain, as shown in Figure 59. The strain experienced by the stand was concentrated at the top, which is demonstrated by the figure above, showing the equivalent displacement given the 1680 N load. Red on the stand would indicate the maximum amount of strain on the stand, however the analysis showed that the stand did not have large amounts of strain. This meant that the stand was capable of withstanding the load from a full intake tank. As seen in Figure 59, the stand did demonstrate some forms of strain along the bottom of the legs and middle of the stand bars. The team noted these areas as possible strain points on the stand, and ensured to take this into consideration when testing the device.

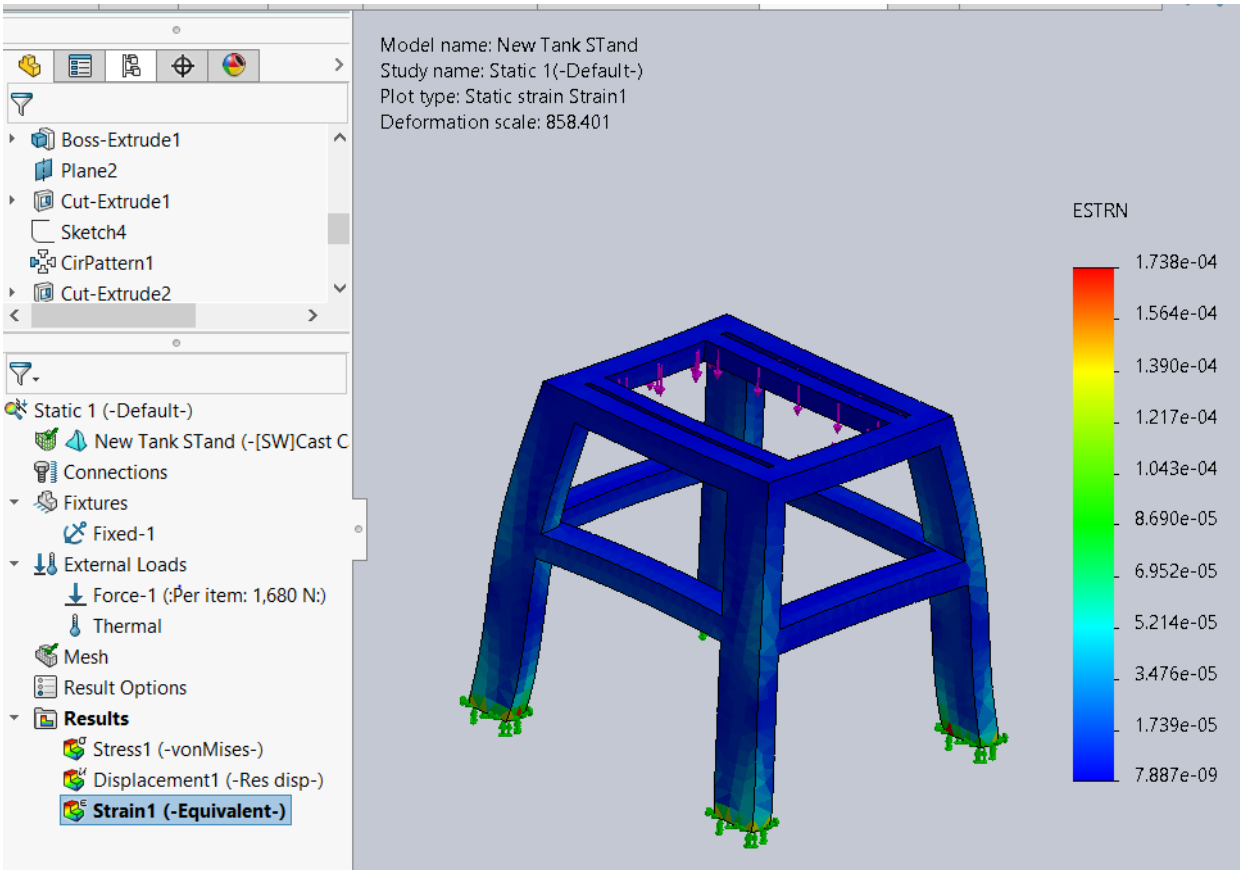


Figure 59. Static Analysis of Tank Stand: Strain

4.0 Prototype Building

4.1 Full Scale vs. Scaled-Down Model Decisions

The team faced the choice of either prototyping a scaled-down model or building a full-scale model. Scaling down the model referred to building a model half the size of the intended model or smaller. This model would be beneficial in terms of lower cost and ease of mobility and testing. A downside to scaling down the model was that testing would not necessarily be accurate for a full-sized model. Testing results would need to be scaled up, providing artificial results for a full-sized model. The team analyzed costs, ease of building, and accessibility of the full-scale model vs. the scaled-down model. It was determined that building a full-scale model would be feasible, so the team chose this option.

4.2 Prototype Materials

The majority of prototyping materials and tools were available through the team's resources or local stores. The pedals and sprockets were taken from an old bike found by the team. Tubing, tube fittings, wood, and appropriate fixtures were bought at a local Home Depot. Wood was chosen as the framing material for the bike pedals and the reverse osmosis module due to its low cost and high strength. 3D printing was used to customize housing for the Brita Filter due to its unique shape. The team provided a strainer (for prefiltration) and containers (as water tanks).

Three items were critical for the team to purchase for prototype building: Reverse Osmosis Membrane, Membrane Housing, and the Gear Pump. These three critical components were the most expensive materials and critical materials for the team to attain. The cost was broken down in Table 16, including the necessary tubing to connect the pump to the RO module, which totaled about $675.

Table 16. Cost Breakdown of Purchased Materials for Prototype Building

Part Description	Quantity	Price/Part	Total Cost
Gear Pump	1	$118.21	$118.21
RO Membrane	1	$169.99	$211
RO Housing	1	$299.99	$299.99
Pump and RO Tubing	1	$45.50	$45.50

4.3 Building Methods

The team planned to split the whole assembly into four subassemblies and build them individually because of COVID restrictions. However, because of increased covid restrictions on campus, the team was unable to do this. The team finished the prototype building during the winter break to have more time to build separately and have the complete prototype ready before C Term. The components were made out of standard dimensional lumber and salvaged slotted angle iron. Wood was chosen as a building material as it is readily available, easy to work with, and quickly purchased within the team's budget.

4.3.1 Pedal Sub-Assembly

The pedal assembly consisted of a wooden base with holes for the pedals to be attached. The available bicycle used in the prototype had pedals that did not align with the team's CAD model, so modifications to the base were made. Fortunately, the pedals contained ball bearings that reduced friction between pedals, so the team did not purchase extra ball bearings. During construction, the team determined that the chain was too short, so the team had to raise the pedal stand off the ground by 6 inches to create an angle that would satisfy the length of the chain. In addition, the rigid spacer arm designed to prevent wobbling and chain slippage could not be made with the precision needed. The hub on the pump shaft did not have the thickness needed to create a stable fixture to negate bending moments as the chain was tensioned. Instead, a spacer was fitted between the vertical face of the pedal stand to the vertical face of the overall frame with a bevel in it. As the spacer was pushed into its slot, the bevel acted as an inclined plane and pushed the pedal stand outward from the frame. This movement tensioned the chain and prevented the chain from jumping. This first iteration of the pedal stand is shown in Figure 60. However, the connection between the pedals and their stand became strained from wear, and eventually started to wobble. This caused the chain to slip off the sprockets as they became out of line. To fix the problem of wobbling between the pedal stand and the pedals, the team replaced the wooden pedal stand with a fully intact bicycle frame, as shown in Figure 61. Although it didn't conform to the design's specifications, it alleviated all movement and wobbling between the sprockets and chain which negated the chain jumping altogether. The length of the pedals were also increased by welding pieces from another set onto the ends. The increase in length improved torque and comfort.

Figure 60. Pedal Stand Iteration 1

Figure 61. Pedal Stand Assembly Final Iteration

4.3.2 Intake Tank Stand Sub-Assembly

The intake tank stand, pictured below, was constructed from a slotted angle iron base with a wooden top, shown in Figure 62. In contrast with the CAD version, the prototype was bolted together with wood and angle iron. This decision was made in order to save money on the prototype. The team also understood that testing the prototype would not cause as much wear and tear as the device's actual application. Therefore, the tank stand would not need to withstand a 55-gallon tank's total weight on top of it. This reasoning came from anticipating smaller amounts of water being tested, such as using 25 gallons of water at a time instead of 55.

Figure 62. Prototype Intake Tank Stand

4.3.3 Reverse Osmosis Membrane Setup

The frame assembly, shown in Figure 63, was also made of wood and salvaged angle iron. The wooden braces emulated the function of slotted angle iron that would be used in the manufactured version. The slots in the angle iron enabled the team to adjust the pump and RO module height during testing to find optimal performance height. When the team had access to appropriate metal-cutting tools, modifications were made to ensure stability. During the building process, piping between the pump and the RO module was not installed to protect the pump's inside from the workshop's dust and debris. Therefore, piping was not shown in the prototyping building pictures. In the picture below, the gear pump is hidden behind the grey sprocket on the left hand side of the frame.

Figure 63. Overall Frame

4.4 Instructions For Using MWPS

Below are the procedures for using the Mechanical Water Purification System (MWPS).

Figure 64. Full Set-Up of Device

Step 1: Set up the device in the desired location on the beach. Ensure that the device is far enough from the shore to avoid high and low tide.

a. Ensure that the pedaler has a proper seat and is set up at a comfortable distance from the pedals.
b. Ensure that the intake tank is set up next to the device and piping is properly placed so that it flows into the pump without air bubbles.
c. Ensure that the outtake tank is properly stationed below the RO membrane and stable.

Step 2: Once everything is properly placed, fill the intake tank with the desired sea water amount. To do this, it is recommended that two people carry water from the ocean and fill the tank.

Step 3. Once the intake tank is being filled, wait until the intake tubing is completely filled with water and there are no air bubbles before the pedaler begins pedaling.

Step 4: Once there are no air bubbles in the intake tubing, start pedaling at a comfortable pace. It is recommended to maintain a comfortable pace without too much exertion.

Step 5: Make sure to switch pedalers after 45 minutes to prevent exhaustion.

Step 6: Enjoy clean water!

4.5 Comparison With Leading Small-Scale Desalination Devices

As mentioned in section 2.6, there are several small-scale desalination devices in the market that serve as competitions to the team's proposed design. The team has compared their device against the Katadyn Survivor and Aquamate to determine the strengths and weaknesses of the system, as seen in Table 17. The team determined that the MWPS's main competitor is the Katadayn Survivor in terms of the desired daily drinking water output, since the Aquamate has such a low flow rate. MWPS is cheaper than the Survivor but has a slower water production rate. Ergonomics of both devices are comparable and up to user preference but it can be argued that a bike pedal motion is more intuitive and can be sustained longer than a hand pump. In order to compete with the Katadyn Survivor and be viable for humanitarian purposes, the MWPS will need a higher production rate.

Table 17. Small Scale Desalination Device Comparison Chart

Criteria	MWPS	Katadyn Survivor	Aquamate
Cost	Under $1000	$2,275.25	$237.95
How To Use Device	Fill the intake tank of Seawater. Pedal to produce water	Pump water through the RO device using a hand crank. Place tube in water.	Uses distillation.
Flow Rate of Device	0.76 gallons per hour	1.2 gallons per hour	0.019 gallons per hour
Intended User of The Device	Disaster Survivors	Sailors, single person	Sailors
Intended Situation The Device Should Be Used For	Disaster in the Caribbean Sea region	Survival at sea on a boat where there is no auxiliary power	Survival at sea or in places where there is contaminated water
Time Requirement To Produce 5 Gallons of Water	About 6.57 hours	About 5 hours	About 263.15 hours
Extra Steps Or Features	N/A	N/A	Reservoir that can be held up

5.0 Testing and Analysis

5.1 Replicating a Caribbean Disaster Environment

The basis of this project revolved around designing and creating a device suitable to produce clean water for people during a disaster relief situation. It was ideal that the team test the prototype in the intended environment which was the Caribbean Sea. The Caribbean Sea region environment included a tropical climate with temperatures ranging from 68-90 degrees Fahrenheit. The anticipated environment also included sandy beaches, debris, flooding, and uneven terrain. Since this project was completed in Worcester, Massachusetts, and prototyped and tested during January through March, this replication of the environment proved tricky.

The team embraced the difficult task at hand and sought out to do as much as covid restrictions and weather allowed. For example, the team asked WPI’s CERT team for permission to travel to Massachusetts' beaches to gather ocean water suitable for replicating water found in the Caribbean Sea. Luckily, the team was approved and followed all covid regulations such as riding in separate cars, wearing masks, and maintaining 6 feet of distance where possible. The team also had an option to replicate their seawater but found that testing real seawater would be more beneficial for this project's purpose.

Another obstacle the team intended to overcome was temperature replications. During the testing periods, Massachusetts' temperatures were cold enough for multiple snow days, ranging from 20 to 40 degrees Fahrenheit. Replicating the environmental temperature that the device was intended to be used proved to be difficult. The weather in Worcester, Massachusetts remained cold and snowy for the duration of the project. Testing outdoors resulted in being the best option for the team, however it was cold and the team bundled up as best as they could and traveled to the beach on days that were warmer. Below are pictures taken outside a team member’s apartment where the team did preliminary testing with tap water to find and fix prototype failures. These failures will be discussed in section 5.4 Discussion.

Figure 65. Team's Preliminary Testing Environment

Figure 66. Setting Up for Preliminary Testing

Figure 67. Preliminary Testing

Testing was primarily conducted locally as the team continuously revised and improved the prototype. Seawater was gathered from a local beach and transported back for batch testing. The team also conducted testing at a local beach to replicate the beach environment. The team set up the device on the edge of high tide, and managed to test before the scheduled high tide at 4:20 PM. The beach's shore was relatively sandy with lots of shells washed up across the shore. By testing the device on the beach, the team was able to determine that it was feasible to transport and set-up in a sandy environment. There were no issues regarding stability and the sand could be used to help stabilize the device if the terrain was a little uneven.

Figure 68. Beach Testing Environment

5.2 Methodology for Testing

The team identified and justified testing procedures to ensure that enough qualitative and quantitative data was gathered to analyze and evaluate the prototyped device properly. With COVID restrictions, the team needed to form a testing plan to collect as much data possible in limited testing sessions. Testing was split into three categories: production rate, water quality, and device usability.

5.2.1 Production Rate Testing

Gathering data regarding the device's production rate allowed the team to understand how efficient the device was and how it compared to competitors. To calculate the production rate, the team measured the time duration the device was used, and how much drinking water was produced in that time.

5.2.2 Water Quality Testing

The team researched methods for testing the experimental water using appropriate measures and devices to achieve this goal. The team compiled a list of four items that helped with the testing process. These devices and tests included: a TDS checker, a refractometer, a free chlorine test, and a total chlorine test.

A TDS meter determined the Total Dissolved Solids (TDS). TDS are inorganic salts and tiny amounts of organic matter that can be found in water. These substances could be sodium, calcium, magnesium, potassium cations and carbonate, chloride, hydrogencarbonate, sulfate, nitrate anions, pesticides, and pollutants (WHO, 2003). This instrument approximated a TDS reading by examining the conductivity in a liquid caused by how much ionized solids, like salt and minerals, were in the water (Lawrence, 2020). The water was tested with this device before and after it went through the filtration process.

A refractometer was also used to measure the change in salinity of the water. As the concentration increases, so does the light refraction index indicated by the device. Some parameters that affect this refraction index include salinity, sugar content, coolant (such as antifreeze and battery acid), urine, serum album, a protein found in blood, and density of the liquid in relation to water (Grainger Editorial Staff, 2020).

Additionally, the team used chlorine test strips on the unfiltered and filtered water. The strip operates like a pH litmus test but tests for free chlorine and total chlorine. When chlorine is added to water, it dissolves and produces hypochlorous acid (HOCL). This acid can be mixed with oxygen and further dissociated in water to become hypochlorite (CLO), which is found in bleach. These two substances make free chlorine. If there is ammonia or nitrogen in the water, it will oxidize with the free chlorine and produce combined chlorine. The sum of the amount of free chlorine and combined chlorine in water is total chlorine. It is crucial for there to be a higher amount of free chlorine than combined chlorine in water (Giovanisci, 2020). Therefore, chlorine test strips were utilized to ensure the water the team produced was sufficiently filtered.

5.2.3 Usability of Device Testing

The device's usability is an important metric since users would be expected to operate this device for hours. The team needed to investigate the usability of the device to determine where redesigns were necessary. The prototype differed slightly from the final design in dimensions and weight because the team mainly used wood to build. Using wood increased the prototype's weight since extra material was required to provide the desired structural integrity. The prototype provided a close enough approximation of the device to reliably test the usability.

Determining the usability required testing overall experience of using the device, experience setting up the device, experience using the pedals, experience collecting water and filling the intake tank, and experience collecting the clean water. The usability was tested accurately since the team was permitted to travel to a beach to conduct testing. The team timed how long it took to carry the device and assemble the system at a suitable location. A Fitbit was used to track heart rate and the calories burned during pedaling. The user's heart rate was measured before, during, and after the operation to give baseline measurements and compare the energy usage to health standards.

5.3 Analysis of Overall Results

The team gathered data from multiple testing trials and analyzed the findings. This data gave the team a better understanding of the functionality of their device.

5.3.1 Production Rate

As the team tested the device on the beach, it quickly became apparent that there were factors at play that prevented the device from working as intended. Unanticipated leaks occurred during testing as well as pressure loss from piping and defective pedals. At the beach, the team was unable to produce clean water, however there was rejected water coming out of the membrane. This rejected water signaled that the membrane was being flushed out and water was moving through the system, however clean water was not being filtered out.

The mechanism the team used to pressurize the water was to restrict the flow of water coming out of the system by using a needle valve attached to the reject water outlet on the RO pressure vessel. A needle valve contains a plunger that can be moved up and down normally to the direction of the water flow. Moving the plunger down reduces the diameter of the pipe, restricting the water flow. As the flow was restricted, the pressure of the water coming from the pump towards the valve increased. The water pressure increased steadily until water started moving through the RO membrane. Since there was water flowing through the membrane, the pressure of the fluid around it, pressurized by the restriction at the needle valve, was limited to the osmotic pressure of the water in the system. This is why the pressure measured on the gauge was determined by the concentration of the fluid being tested at the time, as seen in Table 19.

For production rate testing, the team measured the amount of drinking water produced from diluted seawater for a certain duration of pedaling. To do this, the team mixed seawater with regular tap water and measured the percent salinity using the refractometer. The percent salinity was first measured before the trial was run. The timing began when clean water was produced and ended when the pedaling stopped. In the table below, the team measured these two factors for seawater diluted with tap water, and determined that the calculated flow rate was achieved with a lower salinity percentage. Seawater was rated as approximately 35ppt salinity, so the team extrapolated this data to predict the flow rate at 35ppt salinity.

Table 18. Water Production Over Time

Water Production			
Salinity in parts per thousand	**Clean Water Production Time (min)**	**Drinking Water Produced (cups)**	**Calculated Volume (Gallons per hour)**
6	2	1.25	2.34
10	1	0.5	1.875
14	1	0.5	1.875
15	2	0.666	1.25
18	1	0.5	1.875

Using the calculated volume of water production and salinity of the water used in testing, the team created a graph from the data to get a better understanding of the correlation between these two factors. Using a trendline obtained from a linear regression, the team was able to calculate the percentage of salinity that the device would be able to handle given this data. The trendline was created using the linear regression feature on the graph from google sheets. Using the trendline equation, $y = -0.0524 * x + 2.5$, the team calculated that with $x = 35$ppt, the flow rate that could potentially be achieved would be approximately 0.67 gallons per hour. This was not the 1 gallon per hour that the team expected to achieve, but the results showed promise for future improvements.

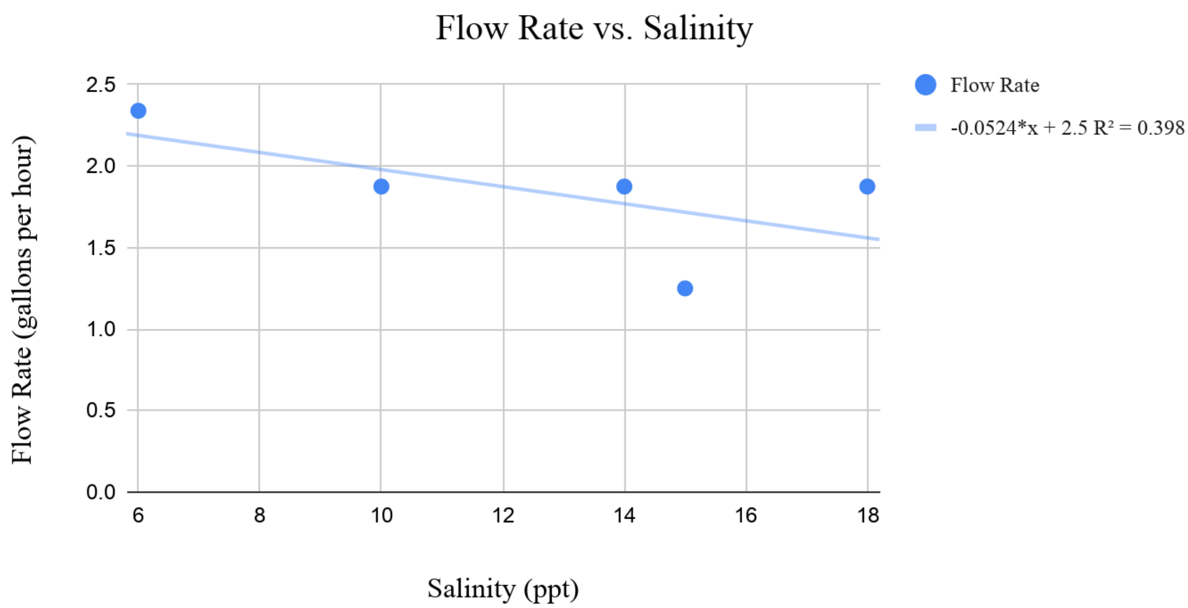


Figure 69. Graph for Flow Rate vs. Salinity in ppt

During testing, the team was able to record a couple pressure readings from the device. However, the team ran into complications on not being able to fully record all pressure readings for every salinity percentage. So, using the data available, the team created an extrapolation from a linear regression to be able to predict the pressure reading for a given salinity percentage. Using the equation obtained from this linear regression, 26.7*x + 8.36 = y, the team calculated that for a salinity of 35ppt, which is that of seawater, the pressure the device would require would be 942.86 psi. This pressure reading falls within the reverse osmosis's desired pressure of 700-1000 psi, therefore the team was confident that the device would be able to produce the desired pressure in order to filter out clean water from seawater.

Table 19. Pressure Reached During Testing

Salinity in ppt	Pressure Reached (psi)
0	10
14	375
18	495

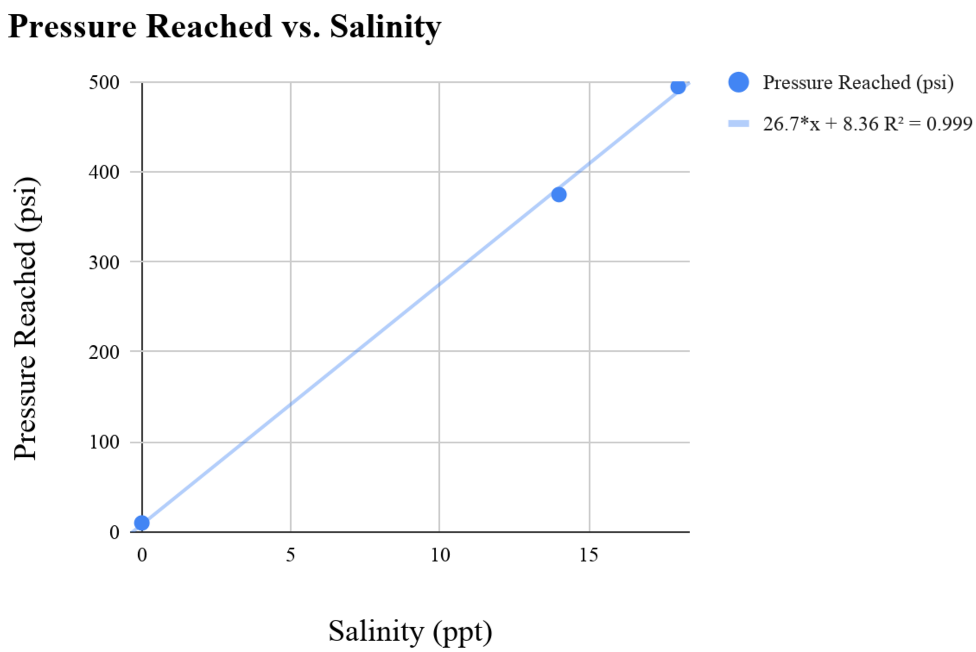


Figure 70. Graph of Pressure Reached vs. Salinity in ppt

5.3.2 Water Quality

The team found seawater easy to work with as the beach water was fairly clean apart from high TDS levels. Seawater gathered had no distinct color or odor to raise health concerns. A chlorine test revealed that there was no chlorine to worry about in both the seawater and the filtered device water. Because the reverse osmosis membrane would be damaged by chlorine, this was good news. The team conducted several trials to measure the refraction and TDS of the water before and after going through the device. As shown in Table 19, the seawater concentration increased, the seawater refraction index and TDS concentration increased. Above 15ppt salinity, the TDS concentration was out of range (OOR, greater than 9990 ppm).

General trends showed that the purified water produced by the device had no refraction, which indicated that the solution concentration greatly decreased. TDS also noticeably decreased. Purified water from the device had similar refraction (0 SG) and TDS (400-500 ppm) across the different seawater concentrations. These numbers are expected, as reverse osmosis is known to filter out at least 90% of dissolved solids, shown in the before and after measurements in Tables 20 and 21 below. This shows that the device can reliably produce clean drinking water so long as the pressure requirement is met.

Table 20. Before and After Comparison of Water Quality Session 1

Water Quality Testing						
Concentration	**6ppt Salinity**		**10ppt Salinity**		**14ppt Salinity**	
Test Type	**Before**	**After**	**Before**	**After**	**Before**	**After**
Refractometer (SG)	1.005	0	1.008	0	1.011	0
TDS meter (ppm)	3450	431	9110	489	14619	492

Table 21. Before and After Comparison of Water Quality Session 2

Water Quality Testing								
Concentration	**0ppt Salinity (Tap Water)**		**6ppt Salinity**		**15ppt Salinity**		**18ppt Salinity**	
Test Type	**Before**	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Refractometer (SG)	1.001	0	1.005	0	1.011	0	1.014	0
TDS meter (ppm)	185	690	8670	584	OOR	294	OOR	425

The team noticed that when testing tap water, TDS actually increased when water went through the system (see Table 20). The team hypothesized that the water may actually be flushing out the membrane due to tap water's low osmotic pressure. This is a device limitation and outlier that will require more research in the future and discussions with the membrane manufacturers. From the results of the refractometer and TDS meter, it is clear that the RO module effectively filtered out the specified salt content, rated at a minimum salt removal of 99.2% by the manufacturer (AMI, 2019). Of course there was no initial salt content in the tap water, but the rise in TDS detected after it went through the RO module shows the flushing of the preservatives that the membrane was stored in. The packaging specified that all product water gained in the first two hours of operation should be discarded because the membrane was in a sealed container with preservatives such as formaldehyde. It was unlikely that the RO module would have made a significant difference in the TDS for tap water under ideal conditions, and that it was specified that chemicals would enter the filtered water for the first time it was in operation hypothesized that the rise in TDS was due to those chemicals.

5.3.3 Usability of Device

Setting up and packing up the device on the beach was simple. With 5 people working together, it took 7 minutes and 50 seconds to move and set-up the device onto the beach. Packing up the device took 5 minutes and 25 seconds. When setting up and packing up the device in Worcester, it could also be done by 1-2 people. In terms of set-up, the most challenging aspect for the team was the seawater collection.

The team recorded data to determine the usability of the device. The team measured heart rate and calories burned using fitbit and apple watch devices. The individual trials each lasted approximately 4 minutes. The heart rates of each individual person varied according to age, gender, BMR, and athletic ability. This information was withheld for privacy reasons. However, as seen in the table below, each person burned approximately the same amount of calories and achieved similar horsepower while using the device. Each person's heart rate increased above their resting heart rate when pedalling. This indicates that there was physical effort involved in operating the device. The team found that when the intake water's salinity increased, pedalling took more effort.

However, the device was still safe to operate. According to the American Heart Association (AHA), the maximum advised heart rate for a person is 220 BPM minus their age (Smith, 2019). Testing data was gathered by users in their 20s; for this age range, the maximum heart rate is 200 BPM. AHA recommended that users have a target heart rate of 50%-80% of their maximum heart rate during exercise. Thus, the target heart rate for users in their 20s is 100-170 BPM (Smith, 2019). Data gathered shows that the testing heart rates were safe within the exercise range.

Table 22. Testing Data For Usability

Usability Testing				
Trial (person testing)	**1**	**2**	**3**	**4**
Initial Heart rate (BPM)	80	86	89	86
Testing Heart rate (BPM)	120	148	134	140
Final Heart rate (BPM)	90	117	145	118
Calories burned	18	21	19	20
HP Achieved	0.11	0.13	0.12	0.11

Equation for Horsepower:

Energy Equation: Energy = Power * Hours * 3.6

Rewritten: Power (Watts) = $\frac{Energy\ (calories)}{Hours * 3.6}$

1 Watt = 0.00134 HP

Figure 71. Horsepower Calculations

5.4 Discussion and Future Considerations

The team has learned a lot through this project. Developing a solution for the ongoing clean water crisis to improve human health was a priority for the team. This reinforced the aspect of making an applicable device that could be humanely used and attained by the average person. The team envisions that with further improvements to the device, it will actually be used by natural disaster victims suffering from a lack of clean water. This section will go into each obstacle that the team faced during this project.

5.4.1 Discussion of Results

The ultimate goal of the prototype was to develop a feasible design that would accurately bring the team’s calculations and design considerations into a working scale model. The basic shape and functionality of the device was correctly applied to the prototype. The team was able to create a scale model of the device by saving money on parts that did not need to be purchased from manufacturers. The pump, reverse osmosis module, and piping needed to be purchased, but the team was able to salvage wood and some spare angle iron to construct the rest of the device. In doing so, the team succeeded in creating a prototype that pre-filtered water, pressurized the water to up to about 500 psi, and purified up to 18ppt salinity. The team was hoping for the prototype to purify 35ppt salt water, at a rate of 0.76 gallons per hour, but certain design flaws prevented this from happening.

The pump's efficiency and potential defects had not been fully considered when calculating the flow rate at the desired pressure. For example, the flow rate was determined based on 60 RPM, at a 1:1 ratio between the RPM of the pedals to the RPM of the pump. However, during testing the team discovered that pump efficiency increased as the RPM increased. Positive displacement pumps inexorably experience some degree of slip, the phenomenon where tolerances in the pump mechanisms allow a small amount of fluid to slip around the gear teeth and flow back. Since slip does not change with flow rate, it follows that the higher the pump RPM, the higher the volumetric efficiency, as a smaller proportion of the fluid is slipping per each increase in flow rate. At higher RPMS, the flow rate proportionally increased, so during testing operations, the team maximized the amount of water flowing through the needle valve at the end. The amount of slippage had not increased, so a greater proportion of the water was restricted at the needle valve, building up higher pressure than at lower RPMs. In addition, the pipes and fittings leading from the pump to the RO module were filled with friction and minor losses which lead to a reduced flow rate and inability to maintain high pressure.

The team then replaced the sprocket on the pump with a smaller sprocket to make a 48:28 sprocket tooth ratio. The increase in sprocket ratios allowed the pump to run at a higher RPM which allowed it to pressurize water at up to about 500 psi, enough to purify water at 18ppt salinity. Because the pump was unable to purify salt water at first, the team decided to test dilutions starting at 0% salt (tap water), up to 18ppt of salt. The resistance built up in the pump showed that a higher concentration would require pressures that would have been unsustainable to maintain. With each increase in salinity, the osmotic pressure of the fluid increases, meaning the pressure required to succeed in reverse osmosis rises with it. Above 18ppt, the resistance to rotation from the pump resulting from the backpressure was too high for a user to pedal for hours in a day.

The prototype was evaluated based on the initial constraints and requirements of the project. The team found that the design could be easily transported and stored. This metric was difficult to measure because the prototype differed in dimensions and weight from the final design. This was due to material differences and lack of access to specialized tools. However, the device was light enough to be carried by two individuals from a vehicle to its testing spot, an important criteria which negated the need for heavy lifting vehicles. The team was also able to make a full scale prototype on the $1000 budget they were given. For a manufactured model, mass production and bulk orders are known to lower the costs per unit. In addition, the device was designed to allow low-skilled workers to assemble it, reducing the labor cost as well. The prototype showed that it was possible to filter 18ppt salinity at a calculated flow rate of 1.875 gallons per hour, and projected the flow rate of clean water from filtering seawater at 35ppt salinity would have produced 0.67 gallons per hour. The team's goal was to investigate the feasibility for a fast working, easy to use, and humane water filtration device, however the team fell short and was unable to meet certain goals.

Primarily the calculated time needed to produce 5 gallons of fresh drinking water was too high, at a minimum calculated value of 6.57 hours. During a disaster, people may have lower energy, nutrition, and free time. Spending an entire work day filtering water was not a viable time and expectation for people during a disaster. Additionally, during testing, the team found that the effort needed to pressurize the water was comparable to an intense exercise session. Expecting a person to commit to a high-intensity cardio workout in the hot Caribbean environment everyday in a disaster scenario proved to go against the humanitarian goals of the project. To be fully viable for use in the hot Caribbean environment, the design needed to go through some improvements that would maximize the efficiency and flow rate of clean water, which will be discussed in Section 5.4.3.

5.4.2 Prototype Improvements

For this project, the MQP team faced many challenges. The first and obvious challenge faced was the pandemic and COVID-19. Due to the pandemic, the team was unable to meet in person for most of the project. This meant that the team met everyday virtually and worked individually on the report, CAD, and prototyping. Towards the end of the project, the team was able to meet socially distanced to perform testing, however this was also challenging. Testing had to be done outside during the cold winter months of January, February, and March. This hindered the team's ability to comfortably test a device meant for warmer weather. Future considerations for these challenges would be for future teams to begin testing during the warmer months of the year, and also once the nation was more stable with COVID-19.

During the prototype testing period, the team faced many failures due to leakage within the system. The team initially connected all piping without adding a sealant to the fixtures. This resulted in mass leakage that affected the pressure within the system. To fix this, the team initially added temporary teflon tape to all of the fixtures in the system. By adding the tape, the leakage problem was solved. However, the team also experienced leakage and air bubbles from the inlet pump tubing. The team fixed this by adding a temporary PVC elbow and sealing the tube with silicone sealant. The team's future recommendations were to use an epoxy sealant for a more permanent hold on the fixtures, and to also brainstorm a more effective way for the pump inlet to be properly sealed while also being fixed at a proper height to prevent bubbles from building up in the tubing.

Unfortunately, the team was unable to create a stable structure for the pedal assembly and was limited on time and supplies. The pedal assembly became increasingly wobbly and unstable after multiple uses. The chain of the pedal assembly also kept jumping out of place. Due to the pandemic and campus restrictions, the team made the pedal assembly with the tools they had readily available and because of this, the team was unable to create a more stable and professional assembly. At the last minute, the team decided to attach an actual bike to the assembly to help with stability. Doing this allowed the team to have a sturdier assembly, however it made the device harder to transport and set up. The team's future recommendations were for a pedal assembly to be manufactured and bolted together instead of being made from wood, as the prototype was. Using metal would help the pedal assembly keep its structural integrity and make it more of a permanent addition to the overall device.

While the team decided to utilize human power, they understand that other forms of power could also be harvested to power this desalination device. Human power is a readily available and clean energy source, however it does face many limitations. The team's device is well suited to being adapted for a motor that could be powered using a different form of clean energy. Future ideas for powering this device would be using solar power and batteries, wind power, or wave power.

This device did not have a permanent method for collecting seawater from the ocean. During testing, the team carried a 5 gallon bucket back and forth from the sea to their device.

While this method worked, it was not the most efficient way of transporting the water. The team had discussed using a pump or piping for collecting the seawater, but due to time and money constraints were unable to pursue the idea further. For future considerations, the team recommends a more effective way of intaking the sea water. This can be done by utilizing another pump or perhaps finding a way to create a more effective system where one pump can do all the required actions.

Lastly, the team was unable to create a more aesthetically and compact design because of limitations on available materials. The team used wood, tools, and supplies found at home to create the device and utilized the $1000 budget for purchasing the pump, RO membrane and housing, and piping. Due to covid restrictions, the team did not have proper consistent access for workshops on campus throughout the duration of the project. Due to this, the team made do with what they had and could find, so they created a rough first prototype. For future considerations, the team recommends refining the prototype to be more polished and structurally sound.

5.4.3 Future Design Improvements

After the design and prototype had been built, the team kept brainstorming for making the device more efficient in the future. The calculations for expended calories per hour of use led the team to think of ways to reduce this requirement. The solution that came to mind was to add a second set of pedals so that another person could pedal. The design would emulate the concept of a tandem bicycle where two or more people could power a single bicycle frame. Including a second set of pedals provided the possibilities to either decrease the effort required to spin the pump's drive shaft at pressure, or to increase the RPM at which the pump's drive shaft spun at the same effort from both users.

Using two pairs of bicycle pedals could allow for multiple arrangements methods of synchronization: in phase and out of phase. In phase synchronization refers to the arrangement of pedals such that both pairs of pedals are always at the same angle relative to the ground. Keeping the pedals in phase meant that the effort required to spin the pump shaft would decrease. The team found that for 800 psi, the pump shaft required a torque of 15.91 N*m. As both users would be applying torque at the same angles, the torque to turn the pump shaft would be effectively halved. Decreasing the torque would either allow users to pedal for a longer duration of time, or allow them to pedal faster, thereby increasing the flowrate of the pump.

The other arrangement for the two pairs of pedals was called “out of phase”, where the pedals were offset in an angle relative to each other. The offset was calculated by the number of teeth on the drive sprocket that the pedals were set at. Ideally, the two pairs of pedals would be offset by 90 degrees for the team’s application. This meant that when one pair of pedals was horizontal, the other pair was vertical. This offset allowed each user to put their full strength into the downward motion of the pedals, including standing on the pedal to apply their whole body weight. As one person completed this power cycle, the other person would be just starting theirs. This arrangement would allow people of different strengths to pedal at the same time without concern for desynchronizing. Additionally, since the maximum torque output from both users was at their max, the sprocket ratio between the pedals and the pump’s drive shaft could be increased. The increase of this ratio would maximize the RPM that the drive shaft would spin, increasing the flow rate and pump efficiency.

The team decided that pedals arranged in “in-phase” would maximize the RPM acted on the pump. The configuration of each set of pedals in the new design would be the same as the original design; the only area that would change would be the sprocket size connected to the pump and an additional bracket for mounting extra sets of pedals. The bracket could be designed in such a way that additional pedal assemblies could be attached after setup. Increasing the number of people operating the pump would reduce the strain on each individual user which would maximize endurance.

6.0 Conclusion

The Mechanical Water Purification System was designed to filter seawater through reverse osmosis using human pedaling power. A compact and portable system was designed and conceptualized through 3D CAD models. The entire full-scale device fits within a 40”x24”x24” enclosure. Calculations predicted that the device could produce 0.76 gallons of clean drinking water per hour under ideal conditions. The device is estimated to take 8.87 hours to produce enough drinking water for a family of five. To do this, the device would need to be operated consistently during the 8 hours, be located somewhere with warm temperatures, and have constant power from the pedals. While this production rate is not sustainable for humanitarian efforts, the team wanted to test the feasibility of a human powered reverse osmosis desalination system.

A small-scale prototype was built as a proof of concept and to gather production rate data. The prototype showed that pressure was needed to filter pure seawater, as the device was only capable of filtering diluted seawater (up to 18ppt salinity, whereas seawater has 35ppt salinity). Testing the prototype showed that the flow rate was lower than anticipated. Extrapolating the test data, the team estimated that, provided enough pressure is supplied, the prototype device is capable of producing 0.67 gallons of clean drinking water per hour. Future improvements, such as eliminating leakage, improving stability, and having two people pedal, can help improve this flow rate. However, the prototype proved that filtering saline water is possible through reverse osmosis and human pedal power. Refractometer measurements showed that solution concentration was reduced to 0 in the acquired drinking water. The TDS meter indicated that TDS concentration decreased to an average around 400 ppm (with prior concentration ranging above 3000-9990 ppm).

Because the device is fully human powered, it is sustainable, with little impact on the surrounding environment. Energy does not need to be sourced from an electrical grid or from a battery, which can both have negative environmental consequences. With an estimated cost under $1000, the device is affordable. However, the current production rate is not sustainable in terms of human effort. Thus, the current design is not recommended for use in disaster relief aid. Further design improvements will need to be incorporated to make the device easier to operate and produce water at a faster rate.

7.0 Special Thanks

The team would like to thank Professor Levey for all her advice and guidance throughout this project. Although covid messed up a lot of the plans the team had made, Professor Levey never failed to assure us that things could still work out.

The team would also like to thank friends and family who supported the team members throughout this project. Friends and family contributed by helping with travel, testing, and casual feedback. We would also like to thank friends and family members who helped provide materials and tools for building the prototype.

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