Utilizing Hydrogels for Energy Efficient Desalination

Saltans - Team 1

BENG 493 - Senior Advanced Design Project 1 - Dr. Shani Ross
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05/03/2024

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Executive Summary

Access to uncontaminated and desalinated water is a growing need throughout the world. Current solutions are costly, require energy, and are sometimes challenging to set up. A solution for this problem would require it to be user- and eco-friendly, reliable, energy-efficient, affordable, and generate drinkable water. Our design utilizes a hydrogel filter composed of Chitosan, Poly-Vinyl Alcohol (PVA), and Polypyrrole (PPy), heated by sunlight to evaporate water. This water then condenses and falls into our water reservoir. Our design does not use electricity, so that it can be used in areas without access to power. Hydrogel makeup is also relatively affordable compared to other solutions. The design can be scaled up to accept more extensive filters to filter more water. It meets environmental safety standards by using materials safe for the environment, such as 316 stainless steel. Although it requires sunlight to evaporate the water, it can reliably convert salty or unclean water into fresh, drinkable water. After using water testing strips, we found the filtered water meets water safety metrics.

Additional tests include Long-term hydration in salt water, swell ratio, rheology, and scanning electron microscopy (SEM). Each test evaluates a specific aspect of the hydrogel and its performance, and it is also about a particular requirement that the hydrogel must meet. The long-term hydration in salt water test evaluates two significant aspects of our hydrogel: does the hydrogel retain salt water, what salinities, and how long can the hydrogel last in certain salinities before undergoing noticeable change or degradation? The swell ratio testing evaluates the maximum amount of water the hydrogel can retain. Rheology was used to assess the mechanical properties of the hydrogel. SEM was utilized to determine the pore sizes of the hydrogel. Our desalination and purification device could desalinate/purify roughly 3-4 liters of water per hour per square meter. The desalinated water had zero parts per million (ppm) for the tested impurities, such as copper, lead, iron, and salt. Another key finding was that our hydrogel filters could last at least three months in 3.5% salinity salt water, showing promising results for our primary goal of six to twelve months. Our design met our critical requirements of purifying water and could meet the 4 to 6 liters per hour mark when scaled up to a larger size of a one square meter surface area hydrogel.

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Problem Statement

The demand for pure, uncontaminated water is escalating unprecedentedly in our rapidly evolving world. This need is most acute in rapidly expanding urban areas, particularly in regions like Africa, the Middle East, China, and India. Here, the quest for a reliable water source is not just urgent but critical. While effective in specific contexts, current methods to purify and desalinate water need to be improved in others. Their shortcomings are multifaceted: a need for more versatility to meet the diverse needs of various terrains and population densities, a detrimental environmental impact through excessive waste and energy consumption, and economic inaccessibility for a substantial segment of the global populace.

Furthermore, the existing desalination devices need more user experience. They often come in large, complex machines requiring multiple operational steps. This complexity persists even in smaller, supposedly more portable devices, making the desalination process tedious and user-unfriendly.

Delving deeper into the core of the problem, we see a glaring discrepancy between the escalating demand for pure water and our capacity to provide it sustainably and affordably. As urban areas grow and populations skyrocket, the chasm between water necessities and their fulfillment expands. This shortfall is not just a logistical hurdle but a profound ethical dilemma. Access to clean water, a fundamental human right, remains elusive for many, underscoring a stark inequality in global resources.

In light of the complex and multifaceted causes of water scarcity, our project aims to tackle a more immediate and attainable objective within the timeframe of our senior capstone year. Our primary goal is to design and develop a functional prototype of a water desalination system. This system will demonstrate the feasibility of our innovative approach to water desalination and lay the groundwork for future advancements in this field. We intend to create a compact, efficient, and user-friendly device that can effectively desalinate water, reducing contaminants and making it safe for consumption.

Background and Relevance

Overview of the Project

Our initiative tackles the pressing demand for pure water in areas of Africa, the Middle East, China, and India that have many people. These places are growing fast, and changes in climate badly affect the amount of clean water there. Our project goes beyond usual ways to make dirty water clean by creating solutions that can grow big without spending too much money or harming nature. They save energy and don't produce a lot of waste, either.

We concentrate on ensuring our product is cost-effective and simple to operate so that it's within reach for people whether they live in city flats or countryside homes. Our initiative works towards making pure water available to everyone; this effort helps enhance community health and life standards while also trying to lessen the gaps between different social and economic groups. This represents a meaningful move into an era where clean water is considered a fundamental right for all.

Relevant Background and Market Research

The worldwide water scarcity is worsening, and more than two billion individuals live in areas with high water stress. Climate change worsens This situation, resulting in increased droughts and freshwater pollution. These factors have led to a rise in the need for water purification technologies for safe drinking water and fulfilling agricultural and industrial requirements. Our market research shows an absence of current solutions that are either expensive large-scale systems unsuitable for individual use or small-scale filters that are less effective when dealing with dense populations. Our goal is to fill this space using a low-cost and resource-oriented product, satisfying the needs of urban areas while tapping into the latest technology for widespread, long-term water availability.

Market Research and Current Solutions

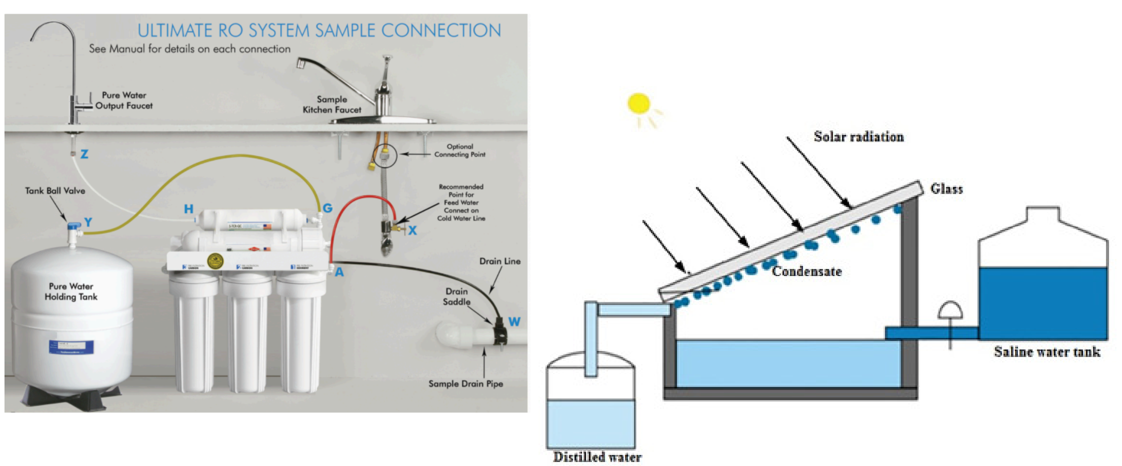

Figure 1: Reverse Osmosis and Solar Stills System Examples

The standard methods of purifying water, reverse osmosis systems, solar stills, and chemical treatments have limitations. Reverse osmosis is very good at getting rid of impurities but needs a lot of energy and setup, making it not practical for portable purposes. Solar stills do not harm the environment but work slowly and cannot produce significant amounts quickly, so they are unsuitable when there is high demand or an urgent need for purified water. Chemicals may work to eliminate harmful microorganisms but could also cause a strange taste. Moreover, these methods might only partially remove all chemical impurities. The difficulties show why having a water purifier that you can carry around is essential. It uses little energy and is easy for anyone to operate, regardless of the environment's changing conditions.

Potential Impacts of Our Design:

Our design's effect on water purification is far-reaching. In terms of society, it holds the potential to improve public health by giving a consistent supply of clean water and lowering diseases caused by contaminated water. Environmentally, our design emphasizes energy effectiveness and materials sustainability - this means it could be viewed as an eco-friendly option compared to usual methods. Economically, this idea helps people who cannot afford to buy clean water because it makes the technology to purify water less costly. On a worldwide level, the project supports sustainability aspirations about crucial matters of limited water supply and health.

Gaps in Current Solutions

Our system is designed to integrate both desalination and water purification processes, effectively removing salts and other impurities to produce clean, purified water. By focusing on these correlated techniques, we aim to ensure that even water from saline sources can be transformed into safe, drinkable water through efficient and sustainable methods.

Target Market and Stakeholders

Our market targets over 600 million people living in coastal areas globally, with a device priced to be affordable for large-scale deployment by governments and nonprofits, supported by stakeholders including health and environmental agencies, investors, regulatory bodies, and NGOs to ensure widespread adoption and regulatory compliance.

Requirements, Specifications, Metrics, and Standards

Requirements

Our water purification device is designed to rigorously meet or exceed global drinking water standards set by the Environmental Protection Agency (EPA) and the World Health Organization (WHO), targeting the removal of contaminants like heavy metals, pathogens, and chemical pollutants through thorough testing and certification processes. We must adhere to stringent budget constraints and maintain cost-effectiveness without sacrificing quality, which requires regular financial reviews and innovative design adjustments to stay within the university and sponsor funding limits. A cornerstone of our project is energy efficiency, with our device aiming to revolutionize standards by utilizing direct solar heating for desalination. This approach is expected to purify water at rates competitive with or better than traditional methods, typically requiring 20 watt-hours per liter for 0.3 liters per hour, but without relying on established power grids. Additionally, our device incorporates a novel, cost-effective hydrogel-based filter that enhances heating efficiency and offers environmental benefits, aligning with our goal of sustainable, accessible water purification technology.

Our water purification device effectively treats saline and contaminated water sources by integrating desalination with purification, ensuring clear, safe drinking water. This dual-function system is essential for adapting to various environmental conditions and maintaining high efficiency in the desalination and filtration processes. We aim to achieve measurable success in reducing Total Dissolved Solids (TDS) and other contaminants through regular testing that verifies consistent adherence to established standards for water quality.

Our design prioritizes user-friendliness and accessibility. The device will have a straightforward interface with clear instructions, making it easy for anyone to use. Minimal maintenance is required. We also focus on optimizing the evaporation rate to accelerate water purification cycles while enhancing efficiency without increasing energy consumption. We prioritize durability and use high-quality materials such as robust metal housing and a hydrogel-based filter that is being evaluated against industry standards. This filter has a potential lifespan of 2-3 months. Our ongoing developments and evaluations ensure that our device exceeds functionality, quality, and user experience expectations.

Specifications

Our water purification device meets EPA and WHO standards for water quality by effectively removing harmful substances such as microorganisms, chemicals, and radionuclides. The hydrogel filter eradicates up to 99% of lead, reduces chlorine taste and odors by 92-95%, and filters out significant pollutants with a pore size of 0.1-2 nanometers. It is designed to withstand coastal environments, including wave impacts, saltwater erosion, and temperature fluctuations. It efficiently meets daily water needs with a productivity rate of 4-6 liters per hour per square meter of hydrogel. The device is compact, lightweight, and easy to carry, with convenient dimensions for filter replacement and uninterrupted access to safe drinking water.

Metrics

Our device must adhere to the strict legal standards set by the EPA's National Primary Drinking Water Regulations (NPDWR) to ensure the safety and quality of the water, performing tests on minerals to keep necessary ones at safe levels: aluminum between 0.05 and 0.2 mg/mL, chloride up to 250 mg/L, copper not more than 1.0 mg/L, along with fluoride, substances that create foam in water and iron content. The machine also monitors elements other than minerals like how clear the water is (not beyond 15 color units), its acidity or alkalinity within a range of pH from 6.5 to 8.5, and ensuring total solids dissolved in it do not exceed 500 mg per liter so that the water stays non-corrosive and suitable for drinking. Our thorough testing ensures that the water from our device is safe and keeps good minerals for people's health.

The performance measures for our device aim to check how useful and long-lasting it is when used in very tough situations. We test the hydrogel filter, which is a crucial part of our system, to see how well it can last when facing very hot or cold temperatures and also when there's a lot of salt present, like up to 50% salt content—more than what you find in the most salty waters naturally occurring on Earth. The device can clean 8-10 liters of water every hour, and the hydrogel plus housing should last between 2 to 3 months and one year each. We also check that its weight stays below 50 pounds and it has a size that makes carrying and moving it not difficult. It has parts you can remove and a design that is easy to use, so taking out water quickly and changing the hydrogel cartridge is efficient for one person or a group.

Standards

Our project for water purification and desalination abides by a rigorous set of worldwide and domestic criteria to guarantee excellence, security, and ecological integrity. This incorporates ISO 23044:2020, serving as a framework for the softening and desalinating industrial effluent, which is integral in improving our filtration design utilizing hydrogel for broader uses. Moreover, WHO-HSE-WSH-11.03 guarantees that our system proficiently handles chemical and microbial hazards, which is critical in ensuring the purity of drinking water. We adhere to NSF/ANSI regulations, with NSF/ANSI 61 and 62 explicitly influencing the material safety of our product and enhancing the efficacy of distillation processes. Additionally, following ANSI/AWWA B100-16 guidelines, specifically regarding incorporating activated charcoal as a granular filter material, guarantees that our system is effective and safe.

Final Design

Our current design has gone through many improvements to reach the point where it is currently. The developed prototype has a height of two feet and a diameter of five inches. Regarding the physical design, different materials were used to make the other device parts. The bottom half, the inner tube, and the coupler are all made of ABS for our final prototype (figure 1). ABS was chosen due to it being environmentally friendly and food safe. ABS also has a heat resistance range of -20 °C to 80 °C and won't soften or deform in our testing [4]. The top outer layer is made of acrylic and clear resin to let in as much light as possible (figure 1). Allowing as much light as possible allows for further heating, ogle heating, and chamber heating greenhouse gas effect. Acrylic was chosen since it is durable and safe to use in the environment and for food-based applications. The resin was used mainly because we could fabricate the shape we wanted. It can be safe to touch water that will be contaminated after being fully cured and safe for the environment.

We attach the pool noodle as our floatation device to the main body using four wood rods. We also wanted to include a GPS unit composed of an AVR-IoT cellular mini and a GPS FeatherWing, which a mini solar panel would have powered. When it came time to test our GPS unit, the provided code by the company needed to be fixed. Due to this issue, we could not incorporate this into our device. Some of our Senior Design Day advisors recommended using an Apple Airtag. The problem with this would be that only some have an Apple device to track the Airtag. In the future, we would like to do a more rigorous search for a GPS unit to add to our device.

It is important to note that these materials were chosen for the prototype; for the full-scale design, 316 Stainless Steel would ideally be used instead of ABS, and the lens would also be made of acrylic rather than resin. The design can also be scaled up to increase the water filtration rate by increasing the diameter of the device. Irving a hydrogel filter with a surface area of at least one square meter would be best. To meet this surface area, the final dimensions of our design should be 1.5 meters in diameter and about 0.750 meters tall in total.

Hydrogels were a mandatory part of our stakeholder's end product requirements. The porosity of hydrogels in combination with a heat transfer material, like carbon nanoparticles or PPy, can increase the efficiency of heating the water to evaporation. Using a hydrogel also allows our device to be as energy efficient as possible since water can travel up the whole of the gel with basic capillary movement. Since the hydrogel helps with heating efficiency, we can achieve our goal of requiring no electricity to use our device. Hydrogels are also cheap and straightforward, making them a suitable medium for large-scale manufacturing. We use a hydrogel comprising 2% w/v chitosan, 10% w/v PVA, 0.5% glutaraldehyde, and 0.5% PPy. This gel was chosen since it was the best performing at the price of the components. Chitosan and PVA hydrogels chemically crosslinked via glutaraldehyde have demonstrated their resilience to wide temperature ranges, long-term water hydrations, and physical disturbances [1, 2, 3]. This is a good composition since our device and hydrogel will be subjugated to these intense factors. This non-toxic gel can handle high temperatures, long-term saltwater hydration, and cost. The PPy was chosen because it has no patents associated with heat transduction. It will increase the heat absorption of the gel and transfer heat to the water in the pores [1, 2, 3].

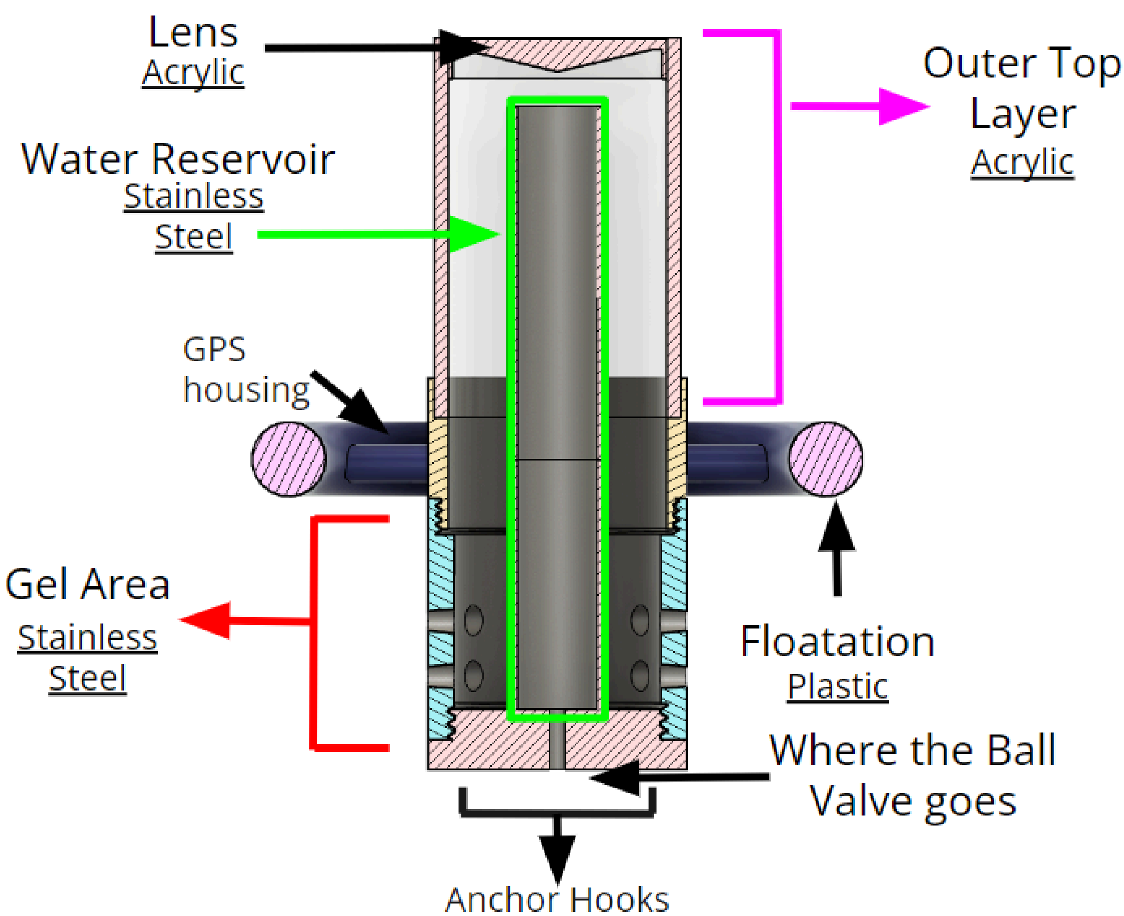

Figure 2: Side View of CAD Model

This device first allows the salt water to enter through the holes on the side of the device where the hydrogel is located. Once the water has entered the device, the water gets absorbed by the hydrogel through the process of capillary action. As the water continues to be absorbed by the gel, the sun hits the lens of the device, causing it to heat up. While the gel heats up, the water absorbed by the gel begins to evaporate out of the gel while salt and other contaminants remain. Water vapor begins to build up and then condenses on the lens. Once the water condenses, the droplets begin to fall within the water reservoir, and at the end of the process, the freshwater can be taken from the valve. Additionally, the floatation device surrounding the filter prevents the device from sinking in the water while the anchor keeps it in place.

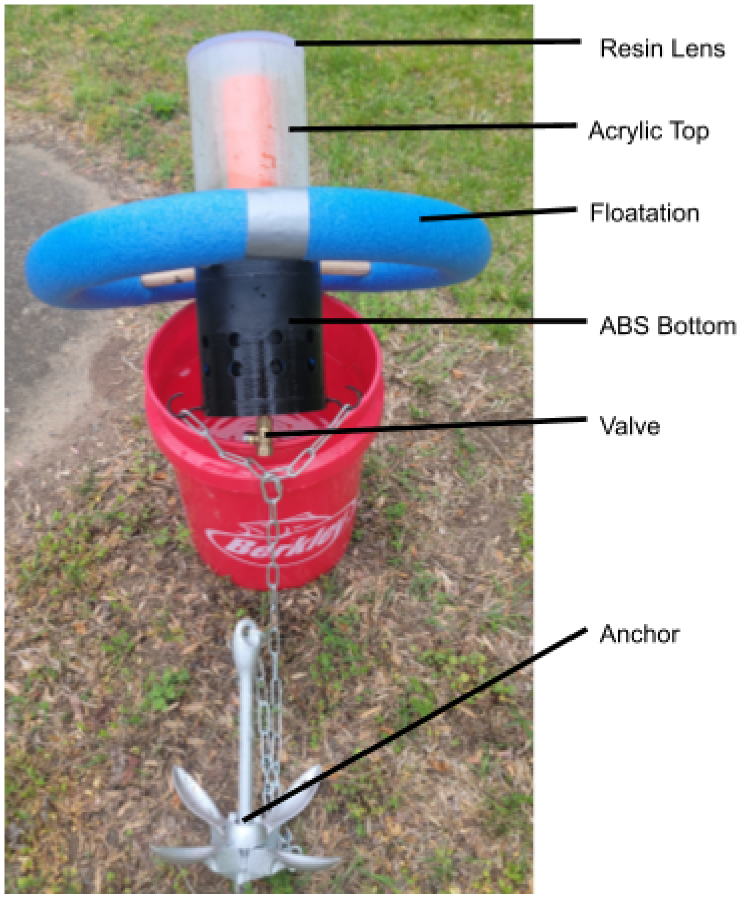

Figure 3: Final Prototype

Figure 4: Final Prototype floating in water

Verification and Validation of Design

Test #1: Long-Term Hydration in Salt Water

Methods:

a. Materials/Equipment

i. An 80 to 100 mL sample of our current prototype hydrogel. The sample was a scaled-down version of the gel that would eventually go into our device.

ii. Three salt water solutions at varying salinity are used to test the durability of different salt concentrations. One solution at an average ocean salinity of 3.5%, a solution at 7% salinity, and one at 43.3% salinity, which is the salinity of the saltiest body of water. These concentrations allowed us to test the hydrogel at a working salt concentration, which wasn't too high to encompass the natural change in salinity in bodies of water, and finally, one to test the end.

iii. The hydrogels will be contained in a cartridge that is a sixth of the version of the cartridge in our final prototype.

iv. A 500 mL beaker was used to make sure there was enough water at all times.

b. Procedure

i. We filled three 500 mL beakers with 250 mL of one of each concentration of low, medium, and high salinity waters.

ii. Place the cartridges into the beakers and take note of the time placed.

iii. The beakers were then moved into a fume hood to prevent the hydrogels from being disturbed. They were also covered to ensure that the water would not evaporate.

iv. Replace water as needed.

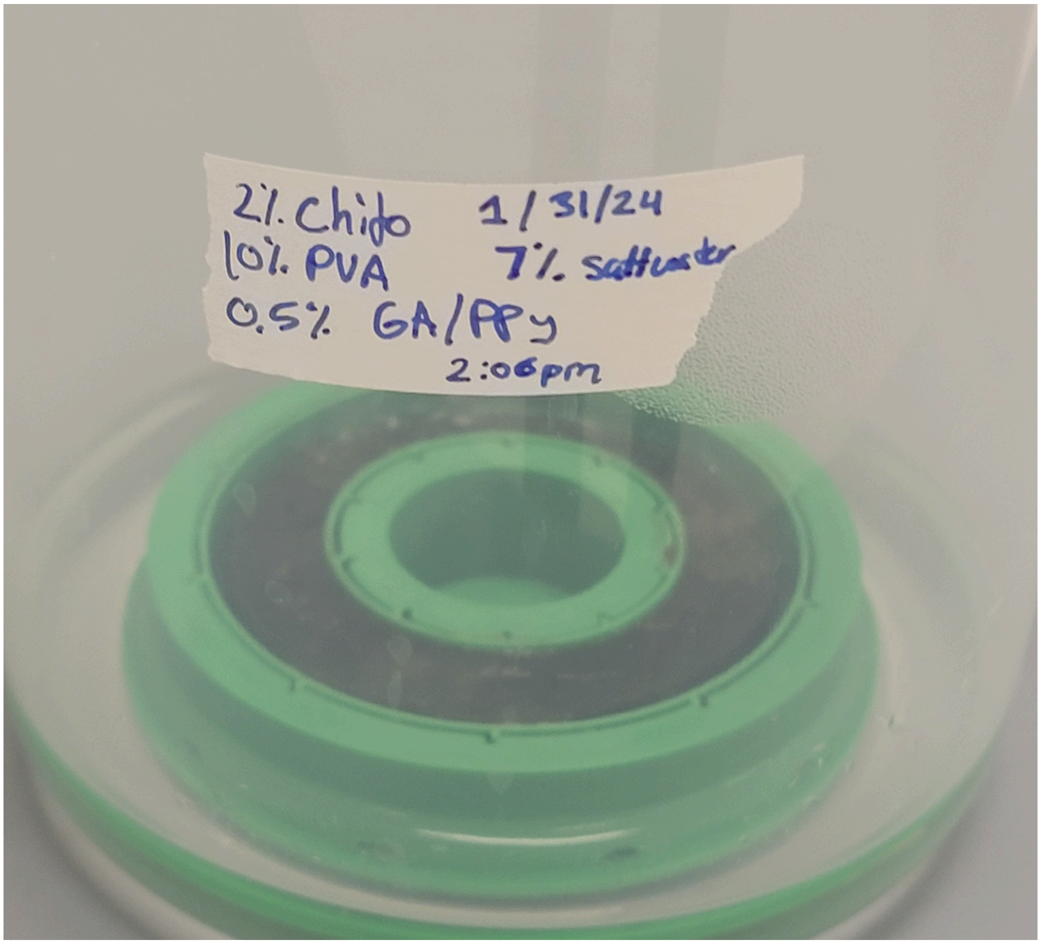

Figure 5: Setup of hydration test

Results:

The 3.5% has been in the water for 90 days, and the only significant differences that can be qualitatively assessed are the gel's stiffness and size. The hydrogel shrank by about 2% of its original size (determined using the percent change formula with the old and new diameter). It has relatively the same stiffness as when the gel was first made, showing that the hydrogel does not break down too quickly. Another aspect that could be a potential sign of hydrogel disintegration was goopier water surrounding the hydrogel. This was not seen in the 3.5%, another example of maintaining its structure. The gel is still resilient and bounces back after being pressed using the back of the scalpel. The 7% gel has been in the water for 90 days and is showing signs that it may be degrading. When poked with the back of a scalpel blade, imprints can be left behind that does not bounce back. The gel also shrunk by roughly 7%. The chitosan is more apparent in this gel, which could mean it was not mixed well when we made it. This could be why it performs much worse than the other hydrogels. Finally, the 43% gel has also been in the salt water for 90 days, but it has the most evident change. The gel is much firmer than the other two gels, almost rubbery. On top of being rubbery, the gel has also shrunk by about 50% of its original size.

Another critical difference between this gel and the other two is the dense water between the gel and the outer shell.

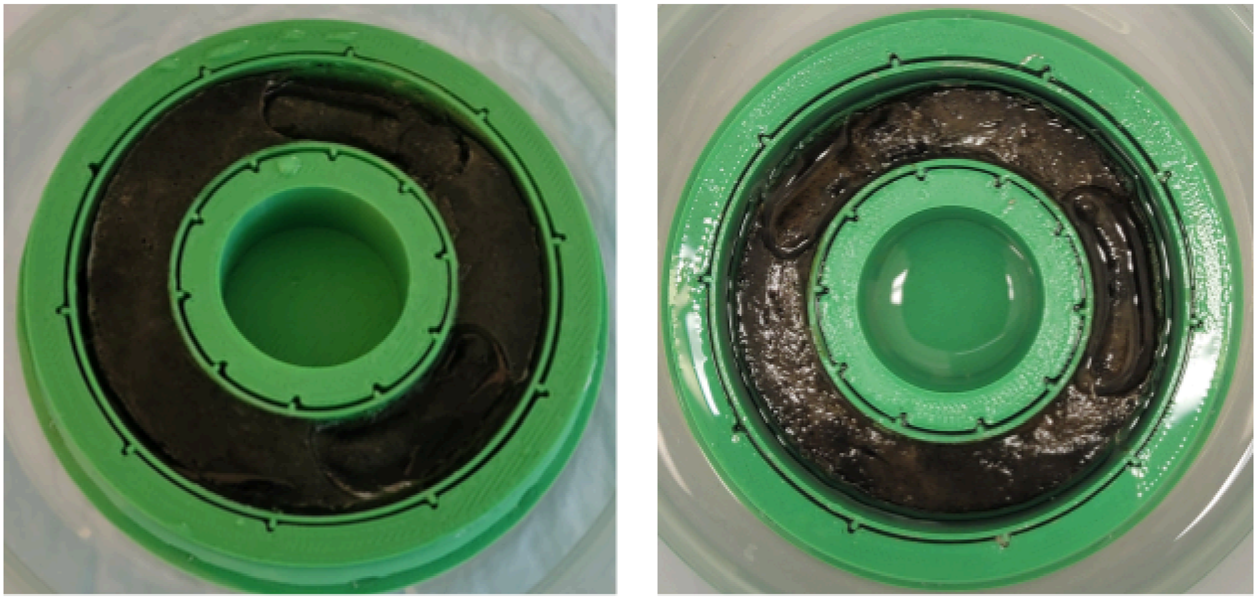

Figure 6: Initial (left) and day 90 (right) of hydration in 3.5% salinity

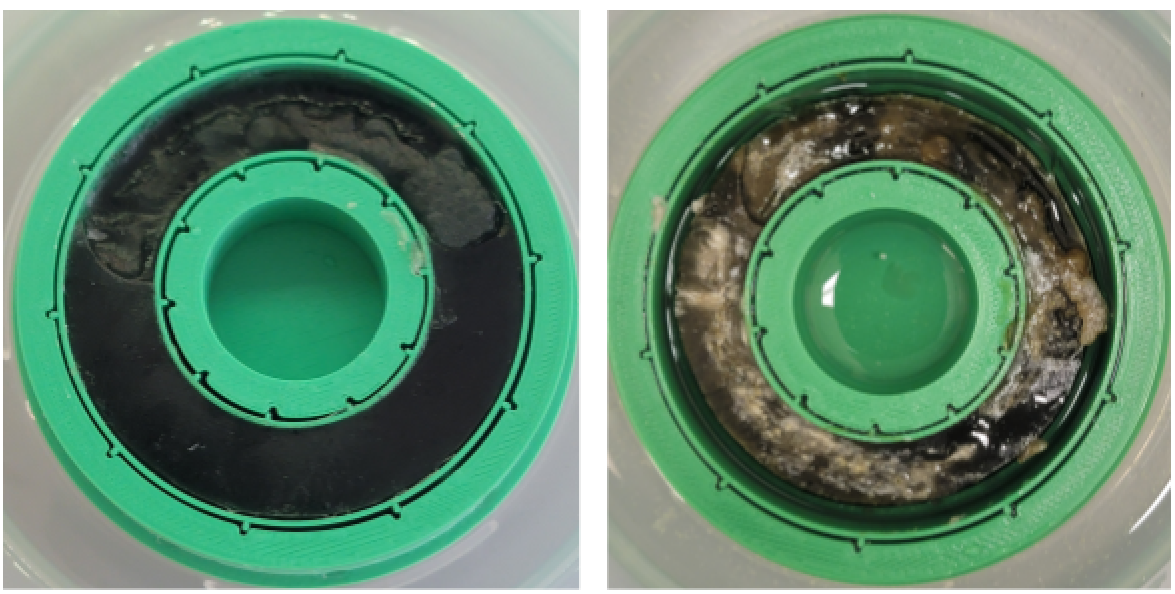

Figure 7: Initial (left) and day 90 (right) of hydration in 7.0% salinity

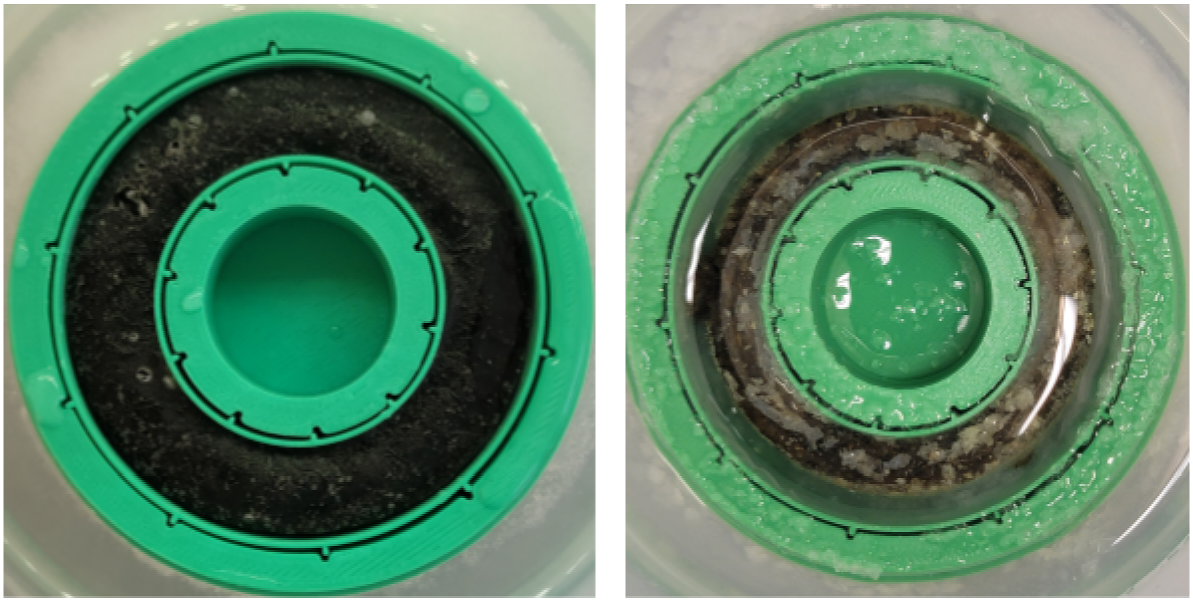

Figure 8: Initial (left) and day 90 (right) of hydration in 43.0% salinity

Discussion:

After 90 days, we can take away that our filter can last comfortably in the average salinity of seawater. This is because the hydrogel stayed mostly the same as the original hydrogel. The 7% gel has performed the worst, but we believe this is due to the poor fabrication of this hydrogel. Finally, the 43% hydrogel has changed the most regarding size and firmness, probably due to the high salt concentration in the water. These changes that we saw in our hydrogels may be mitigated by changing the composition of our hydrogel, using a colder temperature for physical crosslinking, or scaling up the hydrogel size. We would like to continue running this experiment by leaving the hydrogel in place to see if it can last six months and then 12 months. This would alleviate our most significant limitation in terms of time. We plan to run new tests by creating new gels with stricter mixing to use more quantitative analysis methods. These methods are massing the hydrogels, using SEM, and rheology or compression testing. Another improvement would be to combine this test with evaporation testing to see the effects of the long-term usage of hydrogel and its purification and evaporation rate.

<u>Test #2: Swell Ratio</u>

Methods

a. Materials/Equipment
    i. Ohaus SPX422 balance
    ii. -25°C Freezer
    iii. -80°C Freezer
    iv. Hexagonal weigh boats

v. DI water
vi. 3.5% salt water
vii. Swelling ratio mold that is 1 mL^3

b. Procedure
   i. Mixed hydrogel at given ratios and cast into the swell ratio molds
   ii. Molds were used to cast the gel for each test type at the three temperatures and times.
   iii. After casting, gels were placed in a -25°C freezer on the bench top and a -80°C freezer on the bench top. The molds on the bench top were covered.
   iv. A single cycle comprises 20 hours of freezing and 4 hours of thawing.
   v. After the gels underwent their respective cycles, the molds were carefully removed.
   vi. Weigh boats were massed, then zeroed. Each gel was placed separately on the boat to be massed before soaking.
   vii. The gels were soaked in 3 mL of distilled water and 3 mL of 3.5% salt water (separately).
   viii. In other tests, measurements were taken at 30 minutes, 1 hour, and 24 hours, and at intervals of 1 hour, 2 hours, and 24 hours.
   ix. The swell ratio was calculated by dividing the final mass by the initial mass.

Results

Table 1: Swell Test with DI water

	Freeze type					
	-25			-80		
	Cycle 1	Cycle 2	Cycle 3	Cycle 1	Cycle 2	Cycle 3
Time (min)	Mass (g)					
0	0.7	0.69	0.58	0.67	0.91	0.65
30	0.85	0.76	0.68	0.65	0.89	0.67
60	0.83	0.79	0.69	0.66	0.88	0.68
1440	0.89	0.79	0.71	0.73	0.85	0.78
Swell Ratio	1.271	1.145	1.224	1.090	0.934	1.200

Table 2: Swell test for one cycle -25°C using 3.5% salt water

1 Cycle -25°C using 3.5% Salt Water							
	Mass (g)						
Time (hour)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7
0	0.58	0.69	0.38	0.64	0.67	0.83	0.36
1	0.57	0.7	0.39	0.67	0.64	0.81	0.37
2	0.55	0.64	0.36	0.63	0.59	0.72	0.34
24	0.57	0.64	0.36	0.61	0.57	0.73	0.35
Swell Ratio	0.983	0.928	0.947	0.953	0.851	0.880	0.972

Table 3: Swell test for two-cycle -25°C using 3.5% salt water

2 Cycle -25 °C using 3.5% Salt Water							
	Mass (g)						
Time (hour)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7
0	0.55	0.44	0.5	0.74	0.57	0.55	0.6
1	0.6	0.47	0.49	0.8	0.58	0.54	0.64
2	0.57	0.48	0.54	0.77	0.57	0.6	0.63
24	0.382	0.35	0.422	0.602	0.392	0.442	0.452
Swell Ratio	0.695	0.795	0.844	0.814	0.688	0.804	0.753

Table 4: Swell test for three cycles -25°C using 3.5% salt water

3 cycle -25°C using 3.5% Salt Water							
	Mass (g)						
Time (hour)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7
0	0.41	0.75	0.66	0.49	0.68	0.66	0.77
1	0.41	0.78	0.68	0.54	0.69	0.69	0.8
2	0.42	0.8	0.7	0.53	0.69	0.72	0.81
24	0.42	0.73	0.6	0.492	0.64	0.67	0.69
Swell Ratio	1.024	0.973	0.909	1.004	0.941	1.015	0.896

Discussion

The temperatures were chosen based on doing a literature review on the physical crosslinking of chitosan and PVA (Koosha et al.). We found that most used -20°C, but we only have access to a -25°C freezer, which was used instead. The -80°C tests were done because we found a paper that showed that gels formed smaller and more organized pore networks (Figueroa-Pizano et al.). We thought this could potentially influence our hydrogel's firmness, durability, and evaporation rate. The cycles are being tested because many papers used three cycles, but we want to see if we can cut down on our gel formation time to test more often. We wanted to see if the swell ratio differs significantly from cycle to cycle and temperature to temperature. The results from our initial tests show that there is not much of a difference between the cycles or temperatures. The full-scale hydrogel will take much longer to swell to maximum capacity, so if one of the gel cycles or temperatures takes too long to swell or can not swell as much, we can't use that method for the full-scale. We also performed a trial for the one-cycle freeze/thaw at -25°C using 3.5% salt water to see if the swell ratio and time are different when used with salt water, making a total of seven separate cubes for this test. Each separate hydrogel sample used in this test is referred to by the trials columns (Trial 1 - Trial 7) in Table 3. To calculate the swell ratio for the DI water and salt water tests, the final mass was measured after 24 hours. We can see that there is not much change in the mass, and for each trial, the mass went down. We believe this could be due to experimental errors in wiping excess water. Testing was also done with 3.5% salt water on two and three-cycle freeze/thawed hydrogels, as shown in Tables 4 and 5. As seen in Table 5, the swell ratio of the three-cycle gels was recorded to be larger than the swell values of both the one and two-cycle gels. With each ratio relatively close to a value of 1, there was not much total growth or swelling in these samples. Testing with 3.5% salinity water was only conducted with hydrogels made at -25°C, as there was no significant difference between the gels when made at -80°C. Based on preliminary results, -80°C samples were deemed unnecessary for swell ratio testing as they would only complicate the testing process.

Test #3: Rheology

Methods

a. Materials/ Equipment
    i. 1 mL 3D printed flat and circular tray molds.
    ii. 80 mL stock solution of hydrogel.
    iii. Rheometer.
b. Procedure
    i. The hydrogel was cast into the 1 mL 3D printed trays from the stock hydrogel.
    ii. The trays were split into two groups. One group was placed at -25°C, and the other at -80°C.
    iii. Between the two freezers, the gels were split into groups based on 1, 2, or 3 freeze-thaw cycles. Each cycle consisted of 20 hours of freezing and 4 hours of thawing.
    iv. Three samples (-25°C 1 and 2 cycles, -80°C 2 cycles) were then placed in the Rheometer, and their loss and storage moduli were calculated.

Results

As seen in Figure 9 below and Tables 6, 7, and 8, which can be found in the appendix, the gels kept at -25°C had very similar values for their storage modulus, while the gel kept at -80°C was about 20,000 Pa lower in storage modulus. Although not as close as the former, the gels kept at -25°C also had similar values for their Loss modulus, while the gel kept at -80°C was again significantly lower. According to the consistent measurements of larger storage moduli compared to the loss moduli, our hydrogel samples acted more as solids than as liquids at both low and high frequencies. We can also determine that the difference between cycles at -25°C did not significantly affect the hydrogel's overall performance. A constant between the two temperatures tested was using a two-cycle crosslinked gel in this testing. This constant allows us to directly compare the two temperatures with this method of physical cross-linking. By comparing the storage modulus of the two-cycle gels at each respective temperature, it was determined that the gel was stiffer (acted more solid-like) when physically crosslinked at -25°C than when physically crosslinked at -80°C. It is unknown if this trend would be the same when using one cycle and three cycles of physical crosslinking, but it would likely remain constant, or the two temperatures would be relative to each other at the very least.

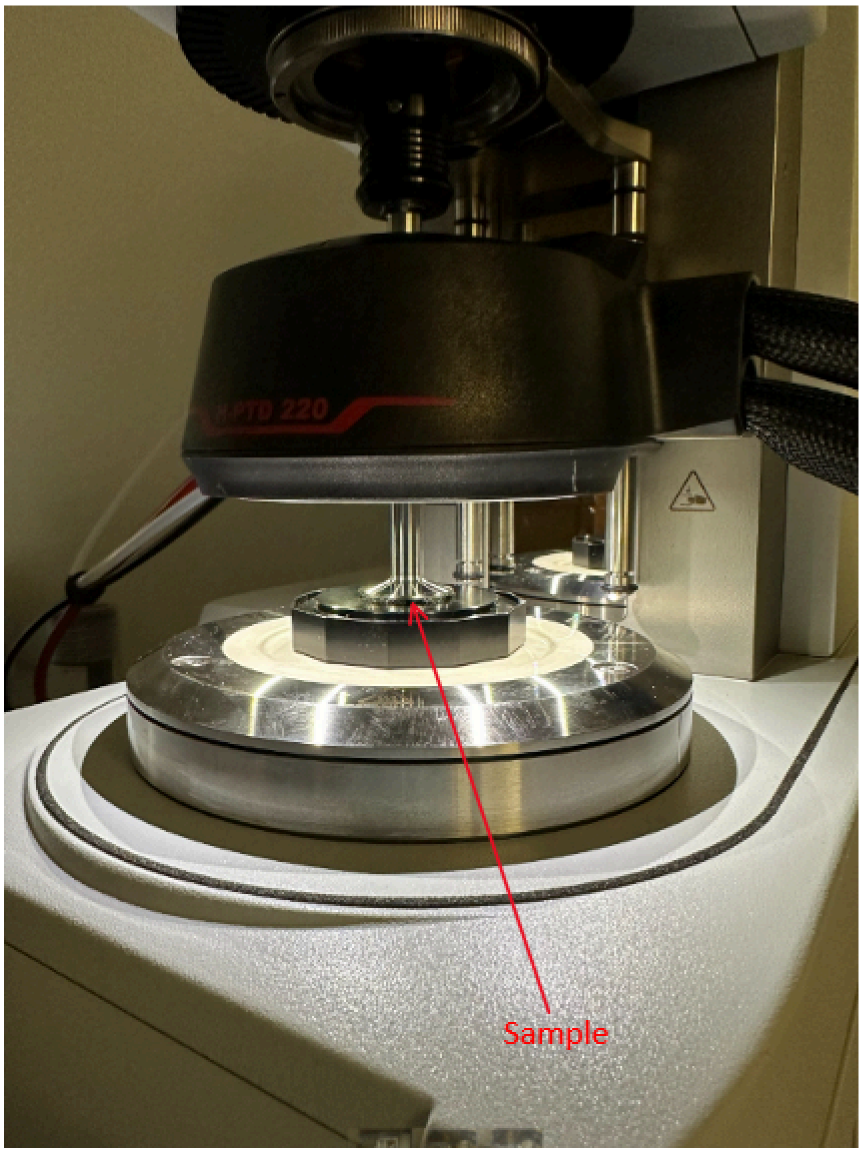

Figure 9: Rheometer Setup

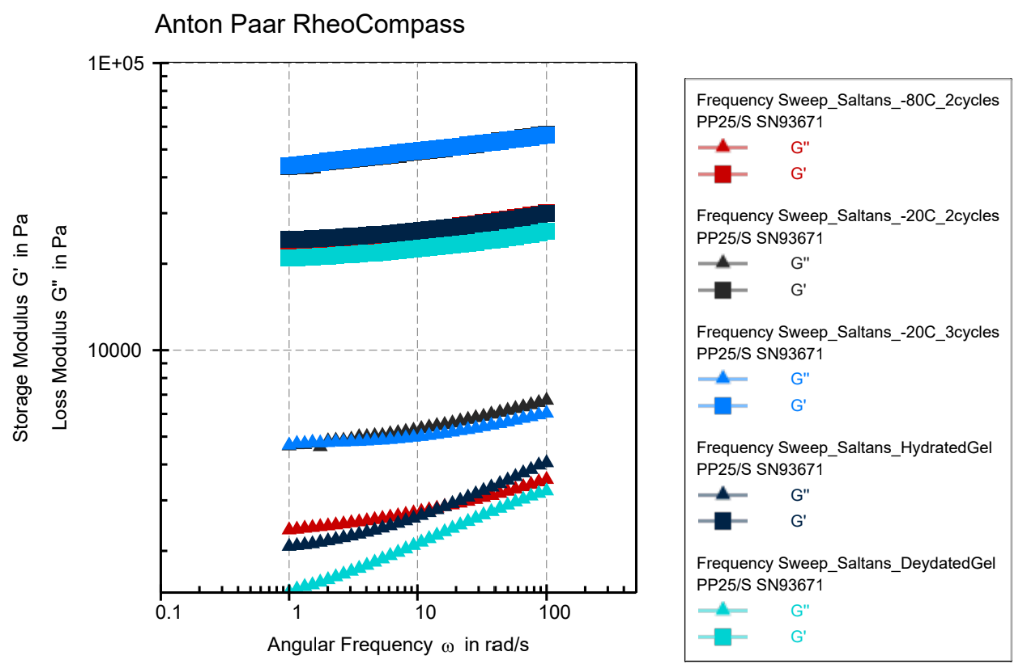

Figure 10:Storage and Loss moduli according to Rheology Testing

Discussion

The results showed that the hydrogels kept at -25°C were stiffer overall. However, we cannot yet determine if stiffer hydrogel is necessarily better. The hydrogel could have simply been a better slice or better cared for. We have only done one test, and this is where the next steps come in. We will need to conduct more to collect more data to determine if the hydrogels kept at -25°C are indeed stiffer than hydrogels kept at -80°C and if a stiffer hydrogel is what we want for our product, as it is possible that a softer hydrogel could perform better in other aspects. For each gel type, three trials need to be run for us to make an informed conclusion. Before conducting these trials, we would like to conduct SEM testing to ensure they are fully formed. When conducting rheology testing, it was essential for us to do this testing as soon as possible after the gels were fully formed. Taking too long to conduct the testing may have resulted in a loss of physical properties (such as stiffness) in our gels. No further rheology testing has been done as of now. Although we would have liked to conduct rheology on all cycles for both temperatures, we could not do so due to the time-consuming nature of the rheology process. We chose to use other methods to determine the most optimal gel.

<u>Test #4: SEM</u>

Methods

a. Materials/Equipment
    i. 1 mL 3D printed cube molds

ii. 80 mL stock solution of Hydrogel
iii. Liquid Nitrogen
iv. Lyophilizer
v. Sputter coater
vi. Scanning Electron Microscope

b. Procedure
   i. Three gels were made, each with the same amount of Chitosan and PVA.
   ii. Once the gels were made, a different freezing process was conducted for each. The first gel used was frozen in the -80°C fridge for a total of three cycles. Each cycle consisted of the gel staying in the refrigerator for 20 hours and then being taken out to thaw for 4 hours. The exact process was done for the gel put in the -25°C fridge; the other gel stayed at room temperature.
   iii. Once each gel had been processed, they were flash-frozen in liquid nitrogen for 5 minutes and then lyophilized for 12 hours.
   iv. The gels were then placed into a sputter coater and coated with a thin layer of gold.
   v. The samples are finally placed into the scanning electron microscope, where the pore size analysis is conducted.

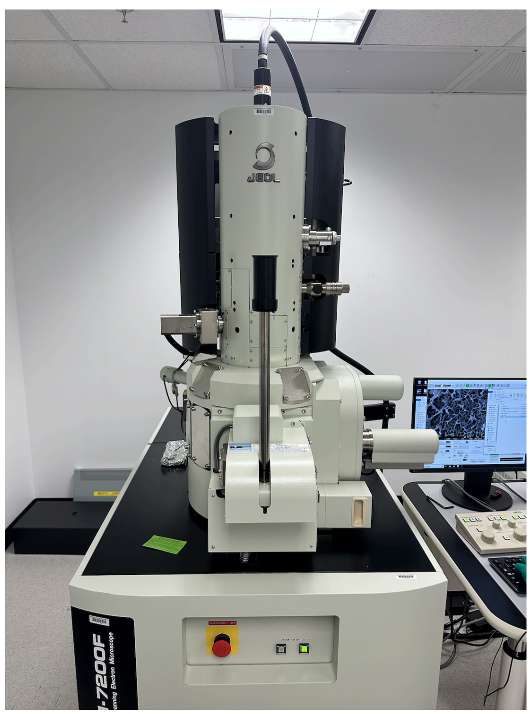

Figure 11: Scanning Electron Microscope

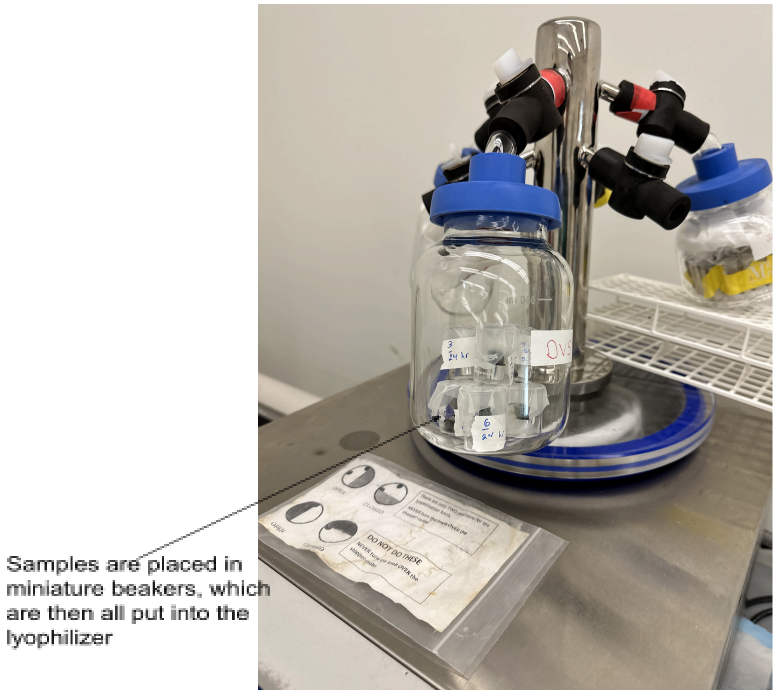

Figure 12: Lyophilizer

Results:

We found the average for the -80°C three-cycle gel was 0.752 µm for the X length and 1.239 µm for the Y length. For the -25°C three cycles, the X length average was 1.099 µm, and the Y length average was 1.525 µm. The room temperature had an X length average of 0.305 µm and a Y length of 0.496 µm. The standard deviations for the pores for the -80°C three-cycle gel are 0.314 for X and 0.493 for Y. The standard deviation for the -20°C three-cycle gel was 0.335 for X lengths and 0.459 for Y lengths. Finally, we found the standard devi for the room-temperature gel actions to be 0.123 and 0.166 for Y, respectively.

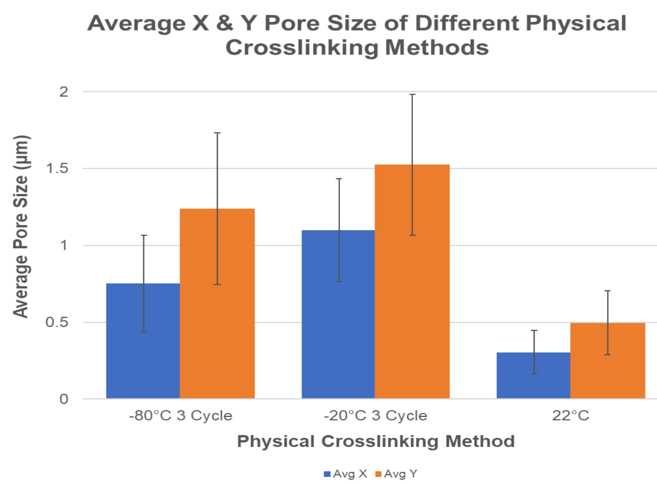

Figure 13: Average X and Y Pore Size of Different Physical Crosslinking Methods. The error bars represent the standard error present in the average pore size of each gel.

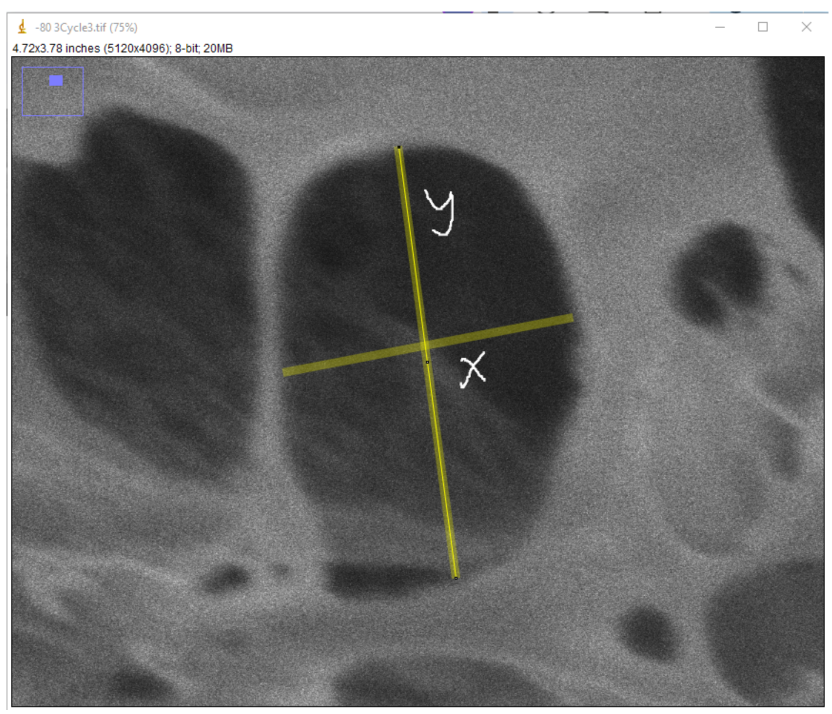

Figure 14: Representation of pores were measured

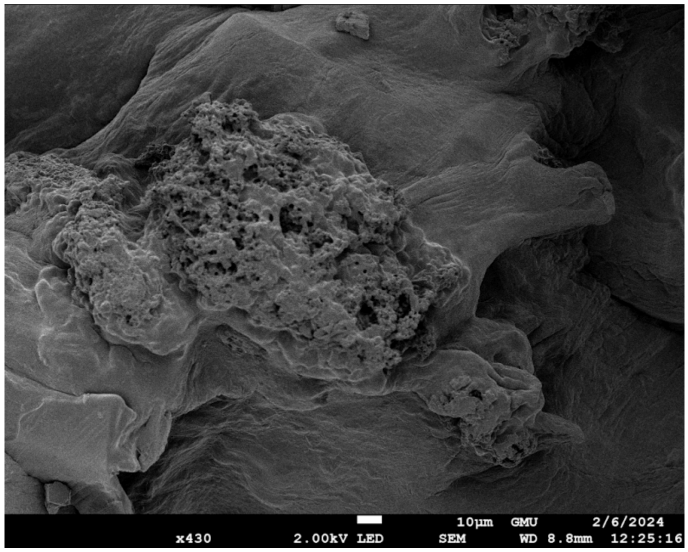

Figure 15: SEM Image showing the chitosan clumps

Discussion:

When analyzing the gels in the SEM, we found a large amount of chitosan, as it may not have been mixed properly. We could determine this by looking at known SEM images of chitosan, and there were strong similarities between our image and the known image. The gel itself needed to be remade, and the resulting data was unexpected.

Test #5: Evaporation Testing

Methods

c. Materials/Equipment
   i. 40 mL 3D printed hydrogel holder for evaporation testing
   ii. Stock solution of hydrogel
   iii. Regular tap water
   iv. Sharp angle lens
   v. Shallow angle lens
   vi. Hexagonal Weighing Boats, W-H102-WA-50
   vii. Graduated cylinder
d. Procedure
   i. Gels were placed into evaporation holders and covered with the lens. These holders have tick marks on the inside in increments of 5 mL.
   ii. They were then placed into weighing boats.
   iii. The weigh boat was filled with tap water until the water level was at about 25 mL
   iv. The testers were then placed into direct sunlight, and the water level was periodically checked.

Figure 16: Holder with tick marks

Results:

Table 5: Water collected after 3 hours of sitting out in the sun

Water Accumulated		
Lens	Trial No.	Water (mL)
Shallow	1	25
	2	24
	3	20
	4	16
Sharp	1	12
	2	13
	3	14
	4	7

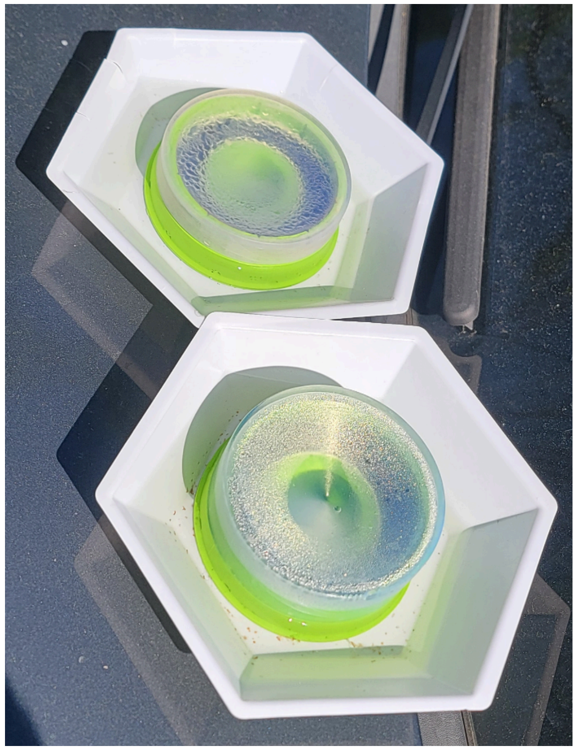

Figure 17: Setup of the test

This week, we have gotten these results from letting the holders sit in the sunlight. After 5 hours of the holder being left out, the water amount was checked, and it consistently filtered about 5-10 mL of water.

Discussion:

So far, these are rough preliminary results since the time intervals were only sometimes on the dot for 3 hours. They show that our device can desalinate water consistently at this small scale. Some of these trials were performed on cloudy and rainy days, but our device could filter and collect water even then. Another observation we had was that the lids would collect with water droplets that would slowly trickle down into the reservoir. These droplets were not included in these preliminary trials, but we will consider them as they are being filtered out. We have also noticed that our sharper lens is less effective at collection, so we chose to make the full-scale lens shallow. We could desalinate 120 mL of water over five hours with our final prototype. As this is just a proof of concept, the final device would be scaled up and normalized to a square meter to increase the surface area of the gel. With the scaled-up device, we could calculate that this device could desalinate 3-4 liters per hour/square meter. The equation used to figure out this proportion is: $\frac{120\,mL}{Surface\ Area\ of\ Big\ Device} = \frac{x}{SA\ of\ 1\,m^2}$

Conclusion

As mentioned, water scarcity is a growing global issue, and solutions are needed to provide desalinated and uncontaminated water. Current solutions have flaws, warranting a user-friendly, eco-friendly, reliable, energy-efficient, affordable alternative that generates drinkable water.

The proposed device is a solar-powered desalination filter that utilizes hydrogels to desalinate incoming water. As for how the device functions, water enters through holes within the device, resulting in the hydrogels' absorption of the incoming water. As this process occurs, the sun hits the lens of the filter, causing the device to heat up and allowing for the evaporation of the absorbed water, leaving salt and contaminants within the hydrogel layer. The vapor builds up and then condenses on the lens, eventually allowing droplets of water to fall within the reservoir. Once this process is concluded, fresh water can be taken from the valve. Additionally, a floatation device is attached to the filter to prevent the device from sinking in the water, while an anchor is utilized to keep it in place.

The hydrogels are developed primarily using PVA, Chitosan, and PPy. The housing unit was mainly developed using 3D printing, specifically ABS and Acrylic. All chosen materials are food-safe, water-resistant, eco-friendly, and affordable, all necessary to create the filter for the intended purpose.

A series of tests were conducted to assess the filter's function. The tests conducted for this process are long-term hydration in salt water, swell ratio, rheology, and scanning electron microscopy (SEM). Each test evaluated a specific aspect of the hydrogel and its performance, all of which also pertain to a certain requirement that the hydrogel must meet.

As mentioned previously, the device that was built is a prototype. The final design will have a few improvements to it. First, the design will be scaled up to 2 feet tall and slightly over 3 feet wide. This will allow for more hydrogel surface area, enabling a faster desalination rate. At this size, about 3-4 liters of desalinated water will be produced every hour. Additional improvements include using stainless steel instead of ABS and making the lens of acrylic rather than resin. A functional GPS unit and lights will also be added to the design to quickly locate and keep track of the device in the water.

The tests showed that the hydrogels functioned adequately, with no strange or unexpected results. The prototype has many advantages and ultimately meets the requirements of the project. The device is energy efficient, as it is dependent on solar power. The device has a user-friendly design, as it is durable, modular, and scalable. The parts of the device are easy to take apart and easily replaceable if needed. The device is also environmentally friendly, as the hydrogels themselves are biocompatible. The device also entirely removed salt, heavy metals, and other contaminants, as the water quality testing proved. All in all, a functioning prototype was successfully developed for desalinated water utilizing solar energy and hydrogels.

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Appendices

Budget Performance:

Materials costs and staying within a specific budget are critical for a smooth production process for our proposed design. Many components must be taken into account when developing the budget plan. The group's budget is $4000, and the total spent must fall within this threshold.

Table 6. Purchased Hydrogel Materials

Hydrogel Materials	
Material	Cost
1% Acetic Acid (4x)	$123.48
Chitosan Powder (50 g) (2x)	$166.20
PVA Powder (25 g) (3x)	$163.80
Glutaraldehyde (10x10ML)	$60.00
Ppy (5 g) (2x)	$346.00
Distilled Water	$1.34
Calcium Chloride (500 g)	$8.25
Lube	$14.95
Glutaraldehyde (10 ML)	$14.80
PVA 500g	$153.00
Water Testing Kit	$24.99

The first materials we have to consider are those that will be used to build the hydrogel. Table 6 displays a table of the materials purchased to develop the hydrogels, along with the amount purchased and the cost. The hydrogels will be composed of a Chitosan/PVA mixture, and the following are the necessary materials to build them.

Table 7. Purchased Housing Unit materials

Housing Unit Materials	
Material	Cost
Acrylic Tube	$93.71
ABS (2x)	$138.00
SR 30 (2x)	$338.00
Black Resin	$99.00
Clear Resin	$99.00
Silicone Sealant	$7.42
PLA Filament	$20.99
GPS Feather Wing	$26.87
Development Board	$68.99
Anchor	$16.11

The materials used to develop the housing unit must also be considered. Table 7 displays a table of the materials purchased to develop the housing unit, along with the amount purchased and the cost. The housing unit is primarily composed of 3D-printed parts and Acrylic.

A few materials not listed previously also go into the desalination production process. These weren't listed in the budget plan, however, since they are already present within the lab workspace for use. This includes any lab equipment used in the prototyping phase. Chitosan and PVA are also present, but more needs to be purchased for this project to develop a hydrogel filter.

Table 8: Image of the maximum values for contaminants

Contaminant	Secondary Standard
Aluminum	0.05 to 0.2 mg/L
Chloride	250 mg/L
Color	15 (color units)
Copper	1.0 mg/L
Corrositivity	noncorrosive
Flouride	2.0 mg/L
Foaming Agents	0.5 mg/L
Iron	0.3 mg/L
Manganese	0.05 mg/L
Odor	3 threshold odor number
pH	6.5-8.5
Silver	0.10 mg/L
Sulfate	250 mg/L
Total Dissolved Solids	500 mg/L
Zinc	5 mg/L

Table 9: Frequency Sweep, -80°C, 2 cycles sample

Point No. Nº	Angular Freq ω [rad/s]	Storage Mod G' [Pa]	Loss Modulus G'' [Pa]	Loss Factor tan(δ) [1]	Shear Strain γ [%]	Shear Stress τ [Pa]	Torque M [mN·m]	Status Stat
1	100	30078	3528.2	0.117	1.01	304.48	1.3979	TruStrain™
2	87	29764	3460.3	0.116	1.01	301.27	1.3831	TruStrain™
3	75.6	29466	3392.5	0.115	1.01	298.2	1.369	TruStrain™
4	65.8	29186	3327.6	0.114	1.01	295.31	1.3557	TruStrain™
5	57.2	28906	3268.5	0.113	1.01	292.43	1.3425	TruStrain™
6	49.8	28635	3209	0.112	1.01	289.64	1.3297	TruStrain™
7	43.3	28366	3155.5	0.111	1.01	286.89	1.3171	TruStrain™
8	37.6	28103	3100.7	0.110	1.01	284.19	1.3047	TruStrain™
9	32.7	27848	3054.4	0.110	1.01	281.58	1.2927	TruStrain™
10	28.5	27592	3004.7	0.109	1.01	278.97	1.2807	TruStrain™
11	24.8	27343	2960.2	0.108	1.01	276.43	1.2691	TruStrain™
12	21.5	27093	2918.3	0.108	1.01	273.89	1.2574	TruStrain™
13	18.7	26847	2876.1	0.107	1.01	271.39	1.2459	TruStrain™
14	16.3	26602	2839.7	0.107	1.01	268.88	1.2344	TruStrain™
15	14.2	26366	2798.9	0.106	1.01	266.5	1.2235	TruStrain™
16	12.3	26131	2764.7	0.106	1.01	264.1	1.2125	TruStrain™
17	10.7	25901	2729.9	0.105	1.01	261.77	1.2017	TruStrain™
18	9.33	25673	2696.1	0.105	1.01	259.46	1.1912	TruStrain™
19	8.11	25451	2665	0.105	1.01	257.2	1.1808	TruStrain™
20	7.05	25231	2635.8	0.104	1.01	254.97	1.1706	TruStrain™
21	6.14	25010	2607.8	0.104	1.01	252.74	1.1603	TruStrain™
22	5.34	24784	2580.6	0.104	1.01	250.45	1.1498	TruStrain™
23	4.64	24569	2557	0.104	1.01	248.28	1.1398	TruStrain™
24	4.04	24362	2532.1	0.104	1.01	246.17	1.1302	TruStrain™
25	3.51	24155	2510.3	0.104	1.01	244.09	1.1206	TruStrain™
26	3.05	23950	2492.2	0.104	1.01	242.02	1.1111	TruStrain™
27	2.66	23750	2469.2	0.104	1.01	239.99	1.1018	TruStrain™
28	2.31	23551	2449.9	0.104	1.01	237.99	1.0926	TruStrain™
29	2.01	23357	2431.5	0.104	1.01	236.02	1.0836	TruStrain™
30	1.75	23159	2416.8	0.104	1.01	234.04	1.0744	TruStrain™
31	1.52	22971	2400	0.104	1.01	232.14	1.0657	TruStrain™
32	1.32	22776	2385.6	0.105	1.01	230.17	1.0567	TruStrain™
33	1.15	22597	2365.9	0.105	1.01	228.37	1.0484	TruStrain™
34	1	22420	2353.5	0.105	1.01	226.58	1.0402	TruStrain™

Table 10: Frequency Sweep, -20°C, 2 cycles sample

Point No. Nº	Angular Frequ ω [rad/s]	Storage Mod G' [Pa]	Loss Modulus G'' [Pa]	Loss Factor tan(δ) [1]	Shear Strain γ [%]	Shear Stress τ [Pa]	Torque M [mN·m]	Status Stat
1	100	56622	6656.4	0.118	1.01	573.2	2.6315	WMa,TruStrain™
2	87	56051	6532.1	0.117	1.01	567.42	2.605	TruStrain™
3	75.6	55507	6422.1	0.116	1.01	561.78	2.5791	TruStrain™
4	65.8	54970	6311.7	0.115	1.01	556.2	2.5535	TruStrain™
5	57.2	54464	6230.3	0.114	1.01	551.1	2.53	TruStrain™
6	49.8	53955	6136	0.114	1.01	545.87	2.506	TruStrain™
7	43.3	53470	6044.2	0.113	1.01	540.9	2.4832	TruStrain™
8	37.6	52998	5956.5	0.112	1.01	536.08	2.4611	TruStrain™
9	32.7	52505	5849	0.111	1.01	531.04	2.438	TruStrain™
10	28.5	52068	5789.2	0.111	1.01	526.59	2.4175	TruStrain™
11	24.8	51637	5708.4	0.111	1.01	522.18	2.3973	TruStrain™
12	21.5	51218	5636.7	0.110	1.01	517.94	2.3778	TruStrain™
13	18.7	50816	5549.1	0.109	1.01	513.85	2.359	TruStrain™
14	16.3	50420	5479.1	0.109	1.01	509.83	2.3406	TruStrain™
15	14.2	50014	5434.3	0.109	1.01	505.73	2.3217	TruStrain™
16	12.3	49611	5369	0.108	1.01	501.6	2.3028	TruStrain™
17	10.7	49228	5303.4	0.108	1.01	497.69	2.2848	TruStrain™
18	9.33	48874	5231.6	0.107	1.01	494.07	2.2683	TruStrain™
19	8.11	48523	5182.2	0.107	1.01	490.54	2.252	TruStrain™
20	7.05	48172	5133.1	0.107	1.01	486.96	2.2356	TruStrain™
21	6.14	47780	5087.5	0.106	1.01	483	2.2174	TruStrain™
22	5.34	47462	5020.3	0.106	1.01	479.73	2.2024	TruStrain™
23	4.64	47137	5011.2	0.106	1.01	476.46	2.1874	TruStrain™
24	4.04	46820	4975.7	0.106	1.01	473.25	2.1727	TruStrain™
25	3.51	46502	4969.2	0.107	1.01	470.08	2.1581	TruStrain™
26	3.05	46221	4871.4	0.105	1.01	467.18	2.1448	TruStrain™
27	2.66	45945	4828.7	0.105	1.01	464.41	2.132	TruStrain™
28	2.31	45661	4829	0.106	1.01	461.55	2.119	TruStrain™
29	2.01	45379	4807.8	0.106	1.01	458.73	2.106	TruStrain™
30	1.75	45135	4588.4	0.102	1.01	456.05	2.0937	TruStrain™
31	1.52	44199	4724.4	0.107	1.01	446.83	2.0514	TruStrain™
32	1.32	44013	4665	0.106	1.01	444.94	2.0427	TruStrain™
33	1.15	43790	4660.3	0.106	1.01	442.68	2.0323	TruStrain™
34	1	43617	4615.9	0.106	1.01	440.91	2.0242	TruStrain™

Table 11: Frequency Sweep, -20°C, 3 cycles sample

Point No. Nº	Angular Freq ω [rad/s]	Storage Mod G' [Pa]	Loss Modulus G'' [Pa]	Loss Factor tan(δ) [1]	Shear Strain γ [%]	Shear Stress τ [Pa]	Torque M [mN·m]	Status Stat
1	100	56119	6002.5	0.107	1.01	567.48	2.6052	WMa,TruStrain™
2	87	55627	5922.9	0.106	1.01	562.42	2.582	TruStrain™
3	75.6	55158	5832.5	0.106	1.01	557.59	2.5599	TruStrain™
4	65.8	54702	5757.3	0.105	1.01	552.95	2.5385	TruStrain™
5	57.2	54262	5673.1	0.105	1.01	548.41	2.5177	TruStrain™
6	49.8	53829	5594.7	0.104	1.01	543.99	2.4974	TruStrain™
7	43.3	53403	5521.4	0.103	1.01	539.62	2.4773	TruStrain™
8	37.6	52985	5451.8	0.103	1.01	535.37	2.4578	TruStrain™
9	32.7	52580	5385.4	0.102	1.01	531.25	2.4389	TruStrain™
10	28.5	52177	5320.4	0.102	1.01	527.14	2.42	TruStrain™
11	24.8	51780	5261.6	0.102	1.01	523.11	2.4016	TruStrain™
12	21.5	51394	5217.2	0.102	1.01	519.2	2.3836	TruStrain™
13	18.7	51009	5158.2	0.101	1.01	515.29	2.3656	TruStrain™
14	16.3	50637	5109.3	0.101	1.01	511.54	2.3484	TruStrain™
15	14.2	50272	5063.6	0.101	1.01	507.81	2.3313	TruStrain™
16	12.3	49913	5019.9	0.101	1.01	504.2	2.3148	TruStrain™
17	10.7	49556	4980.3	0.100	1.01	500.59	2.2981	TruStrain™
18	9.33	49210	4948.2	0.101	1.01	497.09	2.2821	TruStrain™
19	8.11	48860	4916.6	0.101	1.01	493.56	2.2659	TruStrain™
20	7.05	48518	4885.9	0.101	1.01	490.11	2.2501	TruStrain™
21	6.14	48181	4858.5	0.101	1.01	486.71	2.2345	TruStrain™
22	5.34	47841	4833.9	0.101	1.01	483.29	2.2188	TruStrain™
23	4.64	47494	4824.5	0.102	1.01	479.82	2.2028	TruStrain™
24	4.04	47154	4799.9	0.102	1.01	476.39	2.187	TruStrain™
25	3.51	46821	4784.1	0.102	1.01	473.04	2.1717	TruStrain™
26	3.05	46490	4778.6	0.103	1.01	469.72	2.1565	TruStrain™
27	2.66	46157	4761.6	0.103	1.01	466.38	2.1411	TruStrain™
28	2.31	45820	4767.5	0.104	1.01	463.02	2.1257	TruStrain™
29	2.01	45487	4741.9	0.104	1.01	459.67	2.1103	TruStrain™
30	1.75	45157	4730.1	0.105	1.01	456.37	2.0951	TruStrain™
31	1.52	44839	4753.4	0.106	1.01	453.21	2.0806	TruStrain™
32	1.32	44498	4708.6	0.106	1.01	449.75	2.0648	TruStrain™
33	1.15	44135	4707.8	0.107	1.01	446.12	2.0481	TruStrain™
34	1	43814	4644.3	0.106	1.01	442.85	2.0331	TruStrain™

Many factors must be taken into account when conducting rheology. Tables 6, 7, and 8 show the storage modulus, loss modulus, shear stress, strain stress, and many other factors essential to rheology measurements.