2025 Marine Energy Collegiate Competition

Final Report: Business Plan, Technical Design, Build & Test

Coupling Wave Energy with Reverse Osmosis: An Efficient Desalination Approach

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Executive Summary

Burgeoning global water scarcity poses a humanitarian and economic environmental challenge, augmented by climate change and unsustainable resource management. Addressing the issue requires solutions that delve further than conservation efforts and instead emphasize sustainable methods of water renewal and purification. Technologies such as solar powered desalination, wind driven water extraction, and hydroelectric powered filtration systems have demonstrated great potential in reducing reliance on limited freshwater sources, while simultaneously minimizing environmental impact. Among these, wave energy converters (WECs) combined with desalination, which utilize wave motion to initiate reverse osmosis for water purification, stand out as an efficacious solution. Through employing the ocean's abundant source of kinetic energy, WECs drive desalination and filtration while eliminating immense carbon footprints and reducing operational costs associated with traditional energy intensive methods. In alignment with our mission to contribute to the effort to ensure long-term water security, we have constructed a wave energy converter to improve the reliability of Guam's water supply.

CSalt is working towards developing wave-powered desalination equipment that will enable communities to not only harness the power of wave energy but develop alternative means of producing freshwater, especially when existing resources are dwindling and water use is precarious. Various teams within CSalt, such as the Mechanical team, are developing this technology to be not only effective, but durable and accessible to various groups. More specifically, the Membrane team is developing filtration technology in order to enable the desalination process, as semipermeable membranes have been chosen as the mechanism for removing not only impurities in water but salt content. The Business Team supports the other subteams through market analysis and ensuring CSalt's development is not only scientifically feasible but also economically robust. The Business Team has focused on Guam specifically as a potential market for this technology given the island's rising population, military presence, water scarcity, and reliance of aquifers. Lastly, the Community Connections team has leveraged the Cornell community, hosting events and spreading awareness of this technology as well as other environmentalist initiatives. Through these subteams, CSalt is not only developing and engineering a WEC machine, but creating a well-rounded project aimed at solving a specific, pressing problem occurring in Guam while simultaneously raising awareness of key environmental issues.

Team and Team Goals

CSalt operates through four subteams–Membrane, Mechanical, Business, and Community Connections. While the Membrane and Mechanical subteams refine filtration technology and system design, the Business and Community Connections subteams spearhead funding acquisition, cultivate partnerships, and enhance public engagement to amplify the project's impact in sustainable solutions. In this report, the Business subteam examines a promising market and expounds upon wave energy converters as the selected device to fulfill market needs. This is followed by a comprehensive analysis on the device's competitive advantage and a detailed business plan. Subsequently, the Membrane and Mechanical subteams present an evaluation on the performance of our device, followed by a synopsis of interviews conducted with industry experts in which we provide insights on the viability of marine energy solutions.

Business Challenge

1.1 Market Opportunity

Guam's clear and unmitigated reliance on groundwater in addition to supplementary surface and spring water sources, has enabled the territory to meet its population's water demand. However, factors such as the population's consistent growth, economic development, and the threat of climate change will challenge Guam's water availability. Exploration of renewable alternative sources like desalination will ensure that Guam's water resources remain viable, although it is crucial to consider ongoing efforts to curtail water shortages.

A primary groundwater source for Guam is the Northern Guam Lens Aquifer (NGLA), which supplies 80% of the island's human drinking water. This limestone aquifer has an estimated sustainable yield of 80 million gallons per day. The NGLA is a groundwater resource intended for the Northern portion of the island where it is located. Additionally, the main source of Guam's drinking water is groundwater from underground aquifers. Surface sources are mainly the Ugum River, where there is an impoundment and water is purchased from the US Navy Water System. An alternative to these sources could be desalinating seawater utilizing wave energy. The Guam Waterworks Authority, the public utility responsible for providing water services in Guam, has developed numerous level of service (LOS) criteria that are fundamental services to Guam. One of these LOSs is the "reliability of water supply" which emphasizes the need for stronger water resources.

According to the GWA, "the population of Guam is expected to grow from approximately 159,000 in 2010 to 212,000 in 2050" (ES-8), demonstrating the heightened need for a reliable water supply. By 2026, the non-civilian (military) population will also experience a considerable growth, as an additional 5,000 Marines and 1,300 military dependents will be transferred from Okinawa, Japan to Guam. This represents a 50% increase in the military population from 2014. Similarly, civilian attractions such as the numerous commercial development programs planned for the island (such as hotels, residential subdivisions) will mean that water supply will increase, although the exact projections are dependent on the finalization of these developments. Looking at these statistics as well as comparing our findings to the current LCOE of approximately $0.231 kWh and unit cost of water of $16.26 per 1000 gallons will be pertinent issues to consider in our feasibility analysis.

1.2 Stakeholders

1.2.1 Stakeholder 1: US Government/Department of Renewable Energy

Potential stakeholders for advancing drinking water access as well as renewable marine energy in Guam are governmental bodies, specifically the US Government. Renewable energy has become extremely relevant with the advancement of self-replenishing technology, and interest in marine energy specifically has increased significantly over the past few years due to its ability to provide renewable power to hard to reach communities. Recently, the US Government announced an initiative to allocate up to $112.5 million to boost marine energy technologies. Additionally, the availability of clean drinking water in American states and territories has been a top priority for numerous years, and programs such as the Bipartisan Infrastructure Law have made historic investments in delivering clean drinking water to those in need. In relation to this, the US Government announced a nearly $23 million investment to improve Guam drinking water, wastewater, and stormwater infrastructure. These investments demonstrate the U.S. Government's interest in advancing both marine energy technologies and drinking water resources in Guam, implying potential support for our product.

1.2.2 Stakeholder 2: Foundations & Charities

Another potential source of stakeholders includes various foundations and charities dedicated to renewable energy or drinking water advancements. The US Energy Foundation has recently announced a significant funding initiative to support wave energy projects, and the Foundation for Renewable Energy and Environment has allocated about $10 million to innovative projects that will accelerate development and testing of marine energy technologies. There are additionally many charities organizations who dedicate resources to providing clean drinking water to those in need, and Guam is one area that is of specific interest to these organizations due to the challenges of water ability that the region faces. One example of a foundation dedicated to this cause is The Water Project which dedicates over $7 million to fund clean water projects around the world each year. Therefore, various foundations and charities could be interested in providing funding support to advance both marine energy development and drinking water access in Guam.

1.3 End Users

1.3.1 Military Presence

One of the most important considerations for our wave-powered desalinator is identifying its end users—who will benefit from the renewable production of fresh water? A key potential user is the military presence in Guam. As a U.S. territory, Guam serves as a strategic defense location in the western Pacific Ocean, resulting in a large military population. According to the 2020 census, nearly 15% of Guam's population consists of military families. Given their significant presence and substantial water usage, the military is likely to play a major role in the adoption of our product.

1.3.2 Local Communities and Households

Additionally, Guam's local communities and households represent another critical group of end users, as they face ongoing challenges in accessing sustainable and reliable fresh water sources. The island has struggled with water infrastructure issues for decades, including damage from natural disasters and stormwater management problems that contribute to pollution. As a result, many residents have limited access to clean water. A sustainable water source could reduce dependence on traditional supplies that are vulnerable to shortages or contamination, providing communities with a more secure and reliable option. In particular, residents of Southern Guam—who rely more heavily on surface water and are especially susceptible to droughts and climate change impacts—could benefit significantly from this technology. In his interview with our Community Connections team, Guam Researcher Dr. Fujimura mentioned that members of heavily impacted regions like Southern Guam are very supportive of renewable energy. He noted that they would be interested in testing such products and utilizing them once implemented, thus highlighting the region's importance to potential end users of our product.

1.3.3 Agricultural Sector

Furthermore, the agricultural sector in Guam stands to gain from our desalinator, as consistent access to irrigation water could enhance crop yields and support food security. Reduced rainfall and declining streamflow have long posed challenges for local agriculture, limiting water availability for farming. By providing a renewable and dependable water source, our product could help the agricultural sector thrive, easing concerns about freshwater access and supporting long-term sustainability.

1.4 Competition

1.4.1 Aquifers

Groundwater accounts for 80% of the drinking water supply in Guam. The sources of freshwater on the island vary geographically. In Northern Guam, the primary source of water is the Northern Guam Lens Aquifer (NGLA), a limestone aquifer accessed through pumped wells. In contrast, Southern Guam obtains water from surface water reservoirs and rivers. However, the NGLA faces significant challenges due to overuse. Excessive pumping poses the risks of saltwater intrusion, decline in water quality, and reduced water supply- all of which may be exacerbated by rising sea levels- thereby increasing the vulnerability of the aquifer to salinization. While retrieving water from an aquifer is not inherently difficult, the sustainability of extraction is dependent on the aquifer's geological characteristics. There is a "practical sustained yield" for each aquifer that should not be exceeded. Pumping beyond this limit depletes the aquifer faster than it can recharge.

1.4.2 Solar and Wind

Solar radiation from the sun is used by solar technologies and transformed into various forms of energy. Guam has an already established system for utilizing solar power- and currently receives 13% of the power on the island through solar photovoltaic arrays. Wind energy involves the use of wind turbines, which operate through harnessing the movement of wind to spin generators that create electricity. Wind turbines are not capable of generating electricity when wind is under the 'cut-in speed'- indicating the minimum speed necessary in order to continue generating energy. Though Guam has high potential for harnessing wind power, the island is located in the Pacific's "Typhoon Alley", requiring wind turbines to be engineered to withstand frequent natural disasters. Turbine construction is also affected by significant military presence on the island, as well as the presence of endangered species. The instability of wind power is the cause of minute wind generation on the island. The LCOE in Guam is $0.231 per kwH. Guam's daily per capita water consumption is approximately 250 gallons, significantly exceeding the U.S. average of 98 gallons. The elevated consumption is due to factors such as Guam's tropical climate and local infrastructure. At $16.26 per 1000 gallons, water is relatively expensive reflecting the challenges in providing freshwater to the island.

1.4.3 How are WECs Cost Competitive

Wave energy converters convert the kinetic and potential energy sourced from the movement of ocean waves into mechanical or electrical energy. Recent data highlights the financial superiority of WECs due to the rise in costs of fossil fuels. One of the benefits of WECs stems from their efficiency and reliability. Wave energy converter levelized cost of energy is roughly $0.50 kwH in Guam. Solar and wind power are prone to the effects of weather variability, while ocean waves provide a consistent energy source, thereby minimizing energy loss during conversion. Though wave energy has yet to be fully cost competitive due to the high capital costs associated with construction and maintenance, the advantage in certain regions may override cost barriers. Guam in particular has limited available land to utilize solar and wind energy. Wave energy is a suitable alternative in this region as the island's ocean resources are utilized. The geographic advantage of the region establishes the superiority of WECs as the solution for Guam's energy demands.

1.5 Risk Management

Implementing a Wave Energy Converter (WEC) involves addressing various risks across environmental, technical, social, and financial domains. By identifying and mitigating these challenges early, we can enhance the feasibility and sustainability of WEC projects while aligning with stakeholder expectations and environmental considerations. This section outlines key risks and proposes strategies to manage them effectively.

1.5.1 Environmental Concerns

One significant concern with WECs is their impact on marine ecosystems, particularly through electromagnetic fields generated by the device's components. Many marine species, such as sharks, stingrays, sea turtles, and salmon, use natural electric and magnetic fields to navigate, orient themselves during migrations, and detect prey or predators. Studies indicate that marine species like Chinook salmon and green sturgeon can detect anthropogenic EMFs from subsea cables or other sources but appear able to navigate through these areas without significant disruption. However, limited evidence exists to fully confirm the long-term effects of these interactions. Electroreceptive predators, such as sharks and rays, rely on electric fields for close-range prey detection. Similarly, prey species may use electric field sensitivity to detect predators and exhibit freeze responses to avoid detection. Some species, like the little skate, have shown increased exploratory and foraging behavior when exposed to EMFs from DC cables, while others, such as the small-spotted catshark, display behaviors typically associated with feeding near AC cables. These interactions highlight the complexity of marine responses to EMFs and the importance of minimizing potential disruptions. To address these risks, we should prioritize locating installations in areas with minimal overlap with sensitive species and conduct long-term monitoring to assess EMF impacts.

1.5.2 Technical Risks

Technical challenges inherent to WECs include device reliability and resilience in harsh marine conditions. Saltwater corrosion, biofouling, and wave impact stresses can compromise the device's performance and longevity. To address these issues, materials and coatings resistant to corrosion and biofouling must be employed. For instance, stainless steel grades such as SS 316 can withstand the high pressures and corrosive environment of seawater. Design optimization also plays a pivotal role in risk management. Incorporating modular components enables easier replacement and reduces downtime during repairs. Additionally, including fail-safes, such as water sensors and automatic shut-off systems, can prevent damage to electrical components in the event of water intrusion.

1.5.3 Financial Risks

WECs represent a significant financial investment, with high initial capital costs for production, installation, and maintenance. Securing funding from government initiatives or private sector investments is essential to mitigate financial risks. Demonstrating the long-term benefits of WECs, such as reduced reliance on fossil fuels and potential cost savings, can attract investors. Furthermore, engaging with stakeholders early in the project lifecycle ensures alignment of interests and promotes collaborative funding opportunities. Maintenance and operational costs pose another financial risk. To manage these costs, designing WECs with low-maintenance components and implementing predictive maintenance strategies can reduce expenses over the device's lifecycle. Employing a Run-to-Failure (RTF) maintenance model for non-critical components could also streamline operations and minimize unnecessary expenditures.

1.5.4 Social Risks

Social acceptance and stakeholder support are crucial for the success of WEC projects. Concerns from coastal communities about the visual impact, noise, and potential environmental effects of WEC installations may lead to opposition. Engaging with local stakeholders through public consultations and transparency in communication can address these concerns and build trust. Additionally, WEC projects present opportunities to create jobs and stimulate local economies. By integrating community involvement in operations and maintenance activities, WEC initiatives can foster a sense of ownership and support among local populations. Highlighting these benefits in public communications can further enhance social acceptance.

1.5.5 Market Risks

The adoption of novel technologies like WECs can face market resistance due to limited empirical data on performance and reliability. Investors may hesitate to support such projects, especially in competitive energy markets where proven technologies dominate. To mitigate market risks, pilot projects and small-scale deployments can provide valuable performance data, demonstrate feasibility, and build investor confidence . Moreover, partnerships with governments, non-profit organizations, and private enterprises can help secure long-term energy purchase agreements, ensuring a stable revenue stream. By aligning WEC projects with global renewable energy goals, project developers can leverage regulatory incentives and subsidies to enhance market viability.

1.6 Deployment, Maintenance, and Upkeep

To evaluate the economic viability of the desalination system in Guam, we conducted a comprehensive financial analysis grounded in real-world implementation costs, projected water output, and regional pricing benchmarks. This analysis aims to assess both the short-term and long-term feasibility of WEC systems in relation to conventional water provision methods.

The system is designed to supply desalinated freshwater using wave energy as a partial water substitute to pre-existing infrastructure, making it particularly well-suited to remote island communities like Guam. This analysis assumes the deployment of WEC units each capable of producing a maximum of 495,000 gallons per day, or approximately 182.5 million gallons annually. Capital and operational costs were derived from actual material and labor estimates, with a 15% contingency added to account for uncertainty and project variability.

All cost estimates are based on one full-scale system unit, with performance expectations held constant across a projected system lifespan of 10 years. The analysis also benchmarks against Guam's current water cost of $16.26 per 1,000 gallons, and considers Guam's population growth as a metric for our water production goals.

1.6.1 Capital and Operational Costs

The total capital cost per unit, inclusive of raw materials, fabrication, shipping, and installation, was calculated at approximately $2.53 million (see Figure 1). This figure reflects the comprehensive scope of early-stage development, particularly for a novel, large-scale wave-powered desalination system engineered for deployment in marine environments. The bulk of the cost stems from specialized materials and structural components necessary to ensure the system's durability, efficiency, and long-term operability under high-pressure, corrosive ocean conditions.

Core material inputs include high-grade seawater reverse osmosis membrane elements, durable fiberglass pressure vessels, and a marine-grade steel frame composed of hot-rolled 1018 and A-36 steel components. These structural materials were selected for their proven resistance to corrosion, mechanical stress, and biofouling, which are critical factors in offshore environments. Additionally, a custom-fabricated steel piston, integral to the motion of the wave flap and the energy transmission system, accounts for a significant portion of the budget. This component was modeled using volumetric analysis of the piston and shaft, multiplied by the average market price of structural steel and augmented by machining and finishing costs typical of bespoke marine hardware fabrication.

Shipping logistics also constitute a nontrivial share of capital expenses, given the size and weight of components and the remote nature of Guam. Freight charges, overseas transport, and specialized marine handling requirements were factored into the unit shipping cost for each major item.

ComponentID	1	2	3	4	5	6	7	8
Component Name	FilmTec™ SW30XHR -440i	Pentair Codeline 80E100-1 Pressure Vessel	6" x 6" Hot Rolled 1018 Steel Square	4" x 4" Hot Rolled A-36 Steel Square	12 inch Dia. 1018 RT Hot Roll Steel Round	6 inch THICK A36 Steel Plate	Urethane Foam	Custom Piston
Cost Per Unit ($)	818.41	1260.6	10914.75	3136.32	14968.8	4890.76	302	500000
Dimensions	7.9” Dia x 40	7.9” Dia x 80	6" x 6" x 20'	4" x 4" x 20'	12" Dia x 12'	2' x 4' x 6"	9 gallons	2.6 Dia x 100'
Shipping Cost Per Unit ($)	20	25	350	200	600	350	10	100000
Count Per Device	75	75	34	22	8	25	3400	1
Cost Per Device ($)	62880.75	96420	383001.5	73399.04	124550.4	131019	1060800	600000
Raw Material Cost ($)	2532070.69							
RMC (Million $)	2.53207069							

Figure 1.1: This chart shows the component breakdown for each device in our system, including the quantity of each component required per device and the total cost per device.

Deploying a full-scale unit requires approximately 350 hours of specialized labor, divided between critical operations such as underwater welding and mechanical assembly. Underwater welding, one of the most technically demanding and safety-sensitive tasks, accounts for 150 hours at a prevailing rate of $100/hour, totaling $15,000 per device. Mechanical assembly requires an additional 200 hours at $50/hour, adding $10,000 to labor costs. When accounting for overhead, project management, and a contingency reserve, the total labor cost per unit is approximately $28,750. While labor constitutes a relatively small portion of the overall system cost (~0.9%), it is a bottleneck in terms of scalability and production timelines. As the system transitions from prototype to scaled production, potential automation will be essential to reduce lead time and labor overhead, enabling faster deployment across island communities like Guam. So, despite the intensive assembly timeline, it is reasonable given the system’s long lifespan.

Annual maintenance costs per device represent a significant component of the system’s long-term operational expenditures and are a key determinant in calculating its levelized cost of water (LCOW). These costs reflect the need for regular servicing, real-time monitoring, and risk mitigation inherent to offshore desalination systems operating in dynamic and corrosive marine environments. The current estimate places average annual maintenance costs at $166,497.50 per unit, derived from the following recurring service needs:

- Membrane replacement: Reverse osmosis membranes are central to the desalination process but degrade over time due to pressure cycling, fouling, and salt crystallization. Replacements are scheduled every three years at a cost of $72,497.50, equating to an average of $24,165.83 annually when distributed across the replacement cycle.

- Routine inspection and cleaning: Monthly on-site servicing ensures the continued performance of mechanical components and removes marine growth or sediment buildup that could impede wave energy transfer or clog membrane inlets. These tasks incur a $20,000 annual cost and are essential for maximizing efficiency and avoiding costly system downtime.
- Data monitoring and diagnostics: Given the system's offshore location and reliance on continuous energy input from wave action, daily remote monitoring is required to track pressure levels, membrane performance, fluid flow, and structural integrity. This component includes both software tools and personnel oversight, costing $50,000 per year.
- Insurance: To protect against liabilities associated with system damage, marine hazards, and operational risks, each unit is covered under a comprehensive insurance policy valued at $24,000 annually. This coverage is particularly critical in regions like Guam, where typhoons, salt corrosion, and high wave exposure pose persistent threats to marine infrastructure.

Collectively, these items ensure the long-term reliability and safety of the WEC system. While maintenance costs are relatively high during the initial technology deployment phase, they are expected to decrease through a combination of design refinements, automated diagnostic tools, and modular component upgrades. Over time, such innovations will reduce manual labor requirements and extend component lifespans, ultimately improving cost efficiency and making wave-powered desalination more economically competitive with conventional infrastructure.

1.6.2 Water Production Cost Analysis

Using the system's maximum daily output of 500,000 gallons, we calculated the cost of water per 1,000 gallons under two deployment scenarios: Per Unit and Systemwide. The systemwide scenario assumes the installation of 28 CSalt units, which aligns with the projected 33% increase in Guam's population over the next 25 years and the corresponding rise in water demand. This model allows for targeted deployment across coastal zones and communities most vulnerable to groundwater depletion or climate-driven disruptions.

While the initial cost of water production is high, primarily due to capital intensity, custom fabrication, and early-stage inefficiencies, the long-term financial outlook is significantly more favorable. As capital investments are amortized over time and membrane replacement cycles are spread out, the cost per 1,000 gallons drops substantially. By Year 10, this cost reaches approximately $57.50, and by Year 25, it falls further to just $33.69 per 1,000 gallons as shown in (Figure 2). This trajectory reflects a strong trend toward cost parity with Guam's municipal rate of $16.26 per 1,000 gallons, particularly when the system is used in supplementary or emergency water supply roles for remote, drought-prone, or disaster-impacted areas.

Importantly, this analysis must be viewed in the context of Guam's existing capital planning. The Guam Waterworks Authority (GWA) has publicly outlined nearly $500 million in planned water system upgrades, much of which is directed toward well development, pipeline rehabilitation, and aquifer protection. While these investments are necessary, they are also bound by the limitations of groundwater dependency: finite recharge capacity, vulnerability to salinization, and escalating maintenance needs in the face of climate change.

Scale	Total Cost (Year 1)	Total Cost (Year 10)	Total Cost (Year 25)	Cost per 1,000 Gallons (Year 1)	Cost per 1,000 Gallons (Year 10)	Cost per 1,000 Gallons (Year 25)
Per Unit	$2,675,780	$3,710,423	$5,434,827	**$414.68**	**$57.50**	**$33.69**
Systemwide (28 units)	$74.9M	$103.9M	$152.2M	**$414.68**	**$57.50**	**$33.69**

Figure 1.2: This chart shows the total cost breakdown of the WEC system and cost per 1,000 gallons of water over the 25 year timeframe.

1.6.3 Cost Competitiveness

At present, water production remains approximately 2.1 times more expensive than Guam's average municipal water rate. However, as outlined in our accompanying technology forecast, multiple factors are expected to lower the levelized cost of water (LCOW), including:

- Declining material costs via bulk procurement and design iteration,
- Improved throughput efficiency from next-generation membranes and piston design,
- Reduction in O&M costs through predictive maintenance and automation,
- Federal or grant-based subsidies aimed at promoting renewable infrastructure.

The most prominent factor influencing the current cost of water production is the relatively low efficiency of the reverse osmosis membranes in the pilot system. The membranes operate at an estimated 2–5% efficiency, meaning that only a small fraction of the mechanical energy harvested from wave motion is effectively converted into purified water. This inefficiency stems from several factors, including pressure losses, membrane resistance, and suboptimal flow dynamics. However, this figure is expected to improve dramatically over time through advancements in membrane material science, nano-engineered pore structures, and improved energy coupling mechanisms. As efficiency increases, the volume of water produced per unit of input energy will rise significantly, which in turn will reduce the levelized cost of water (LCOW). Even a modest efficiency gain—from 5% to 10%—could effectively double water output without increasing capital or operational costs, halving the per-gallon cost. Over a 5–10 year horizon, as new membrane generations are adopted and integrated into the system, this metric will be a primary driver in pushing water production costs down toward competitive levels, further enhancing the system's economic and environmental viability.

Technical Design Challenge

2.1 Introduction

This reverse osmosis membrane system was designed to integrate with oscillating surge flap wave power, focusing on efficiency, durability, and cost-effectiveness. The primary objectives that shaped the design were to remove 99% of total dissolved solids (TDS) and other contaminants from the seawater, minimize energy consumption, and optimize consistent, long-term performance. A comprehensive filtration system, including both pre- and post-filtration components, was incorporated to further enhance the membrane's lifespan, reduce the frequency of maintenance, and maintain low operational costs, all while meeting the essential needs of the user.

The system utilizes a direct mechanical pressurization approach to improve energy efficiency. This design translates mechanical motion from the WEC directly to water flow and pressure, bypassing the conversion into electricity. This approach eliminates conversion losses, additional costs, and points of failure in the system, ensuring that a maximum of available wave energy is used effectively. Sustainability efforts were an important consideration throughout the design process. To minimize environmental impact, this reverse osmosis system incorporates proper brine disposal to prevent marine ecosystem disruption and careful selection of material that resists corrosion.

Furthermore, the system was developed on a user-centric approach, considering factors such as high salt rejection rates, ease of maintenance and implementation, and an economical freshwater output. By achieving a balance between these priorities, this water purification design provides a sustainable and reliable solution for producing drinkable water in Guam, while offering competitive operational costs and minimizing the long-term environmental footprint.

2.2 Objective

2.2.1 Mechanical System

The mechanical aspect of the design is focused on achieving three key objectives: efficiency, consistency of pressure, and durability.

Durability was the primary design consideration for the WEC because the location and nature of the design make maintenance difficult and expensive to perform. Additionally, the literature reviewed rarely addressed durability and survivability under extreme conditions, so those factors were made a focus in the design.

The design aims to maintain a relatively consistent pressure on the membrane while maintaining a limited mechanical complexity to minimize the risk of potential system failures. Keeping a consistent pressure on the membrane reduces the wear on the membrane, allowing the system to operate without intervention for longer periods of time.

The efficiency of the design is crucial to achieving a point of financial viability. Operating in an unproven market, especially in a region with limited funding for such projects, makes financial viability essential.

To reduce costs, electrical components were removed in order to limit the need for maintenance and optimize energy efficiency.

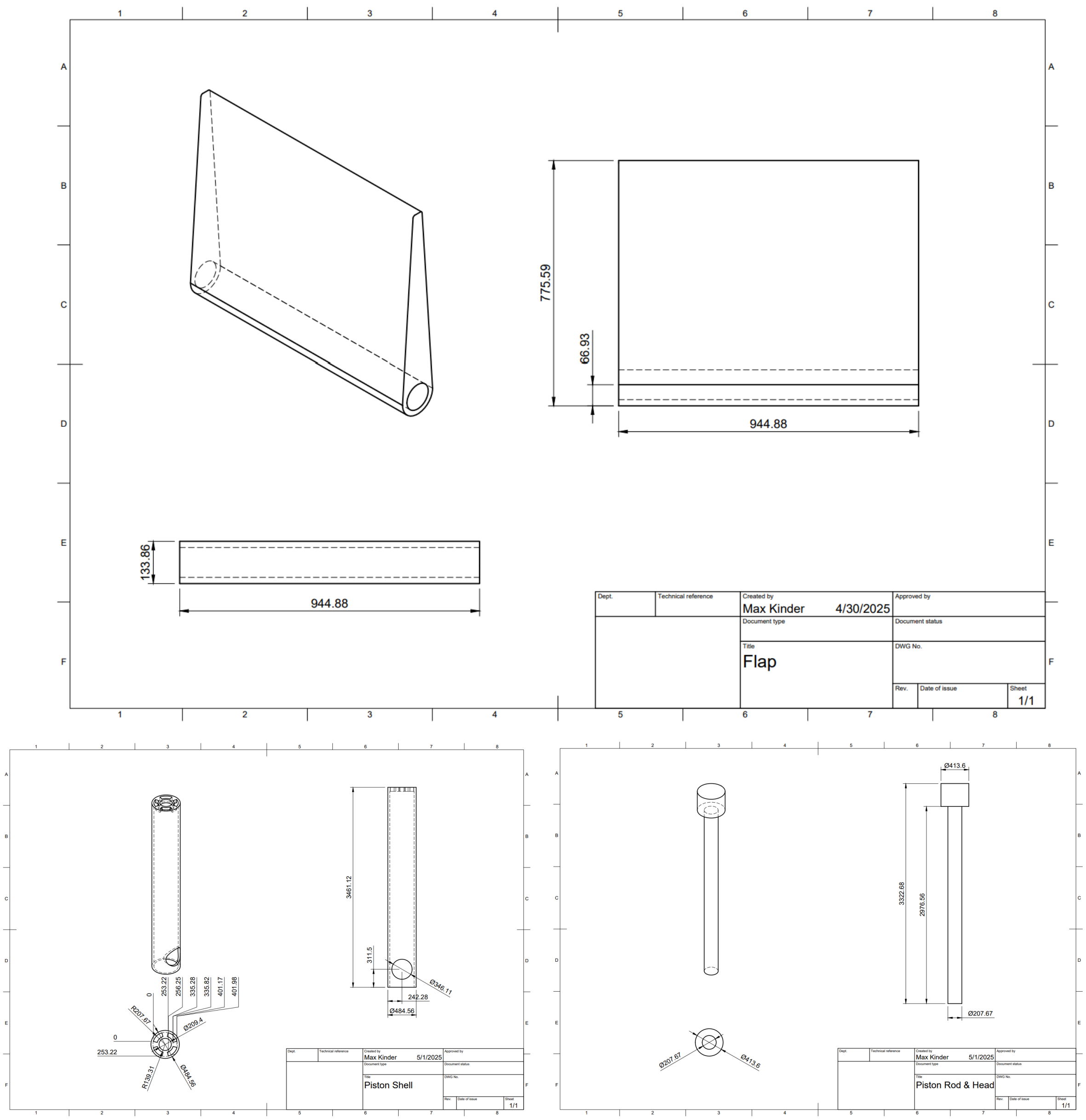

Figure 2.1: Engineering diagrams of the piston and flap of the wave energy converter (units: inches)

2.2.2 Desalination Membrane

The desalination design is focused on achieving four key objectives: contaminant removal, efficiency, durability and reliability, and cost-effectiveness. First, the system is designed to effectively remove contaminants, eliminating up to 99% of total dissolved solid, microbes, chlorines, and chloramines. Additionally, TDS and salt concentration testing will be conducted to ensure optimal performance.

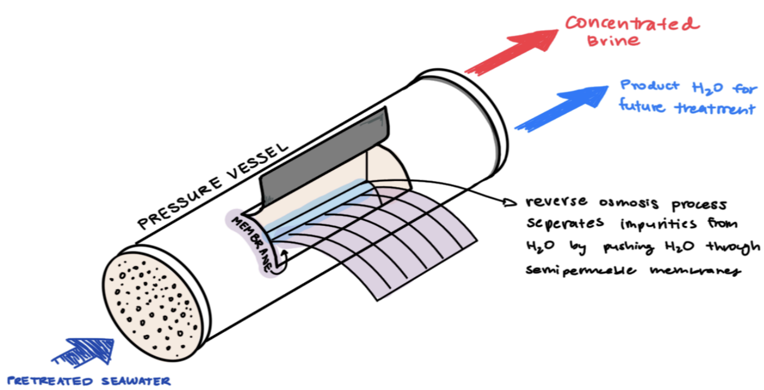

Figure 2.2: Diagram of pressure vessel and reverse-osmosis membrane

Efficiency is a priority, with an emphasis on reducing the amount of input water that is rejected and minimizing energy consumption. This is complemented by pre-treatment optimization to enhance overall system performance.

Durability and reliability are crucial aspects of the design. The system aims to ensure membrane longevity while making sure the pre-filtration system lasts as long as the membrane. Reliable pump systems are incorporated to minimize wear, and anti-scaling measures are implemented to protect the membrane from potential damage.

Cost-effectiveness is considered by taking into account operational costs and optimizing efficiency to reduce expenses. By improving performance and longevity, the design enhances return on investment (ROI), making the system both sustainable and economically viable.

2.3 Input Water Processing

2.3.1 Pressurization

In order to pretreat the saltwater to start the desalination process, the water must be pressurized beforehand. This is done using a hydraulic piston in the WEC system that is sized to create the most water at the desired pressure using the force applied by the flap. The following piston is attached to the flap and the frame on hinges, allowing it to rotate along with the flap. Between waves, the flap rotates away from shore and the piston expands, creating a vacuum that intakes water from the ocean through a check valve in the side of the piston. As the wave comes, it pushes the flap towards the shore, closing the check valve and causing the water to be pushed out of the piston through another check valve to the membrane system. This guarantees the seawater is at the correct pressure to be pretreated. Once the water stops flowing through or is not at sufficient pressure, the valve closes, and the process restarts.

2.3.2 Pretreatment

Before desalination, the input seawater passes through a pretreatment system to remove suspended solids, organic material, and other contaminants. In the first stage, the water flows through organic filter tanks with material layers such as gravel, carbon, and other porous materials that capture larger particles in the water.

After the first pretreatment, the water goes through a second pretreatment stage: microfiltration. At this stage, finer and microscopic impurities and contaminants are removed. After both stages of pretreatment, most substances except for dissolved salts and minerals are removed, and the water can proceed to reverse osmosis.

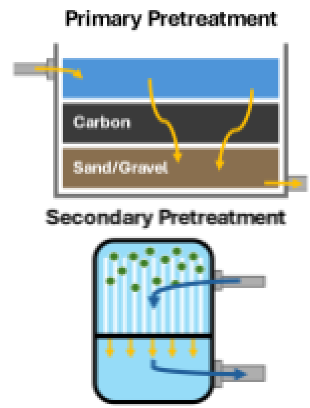

Figure 2.3: Diagram of pre-treatment processes

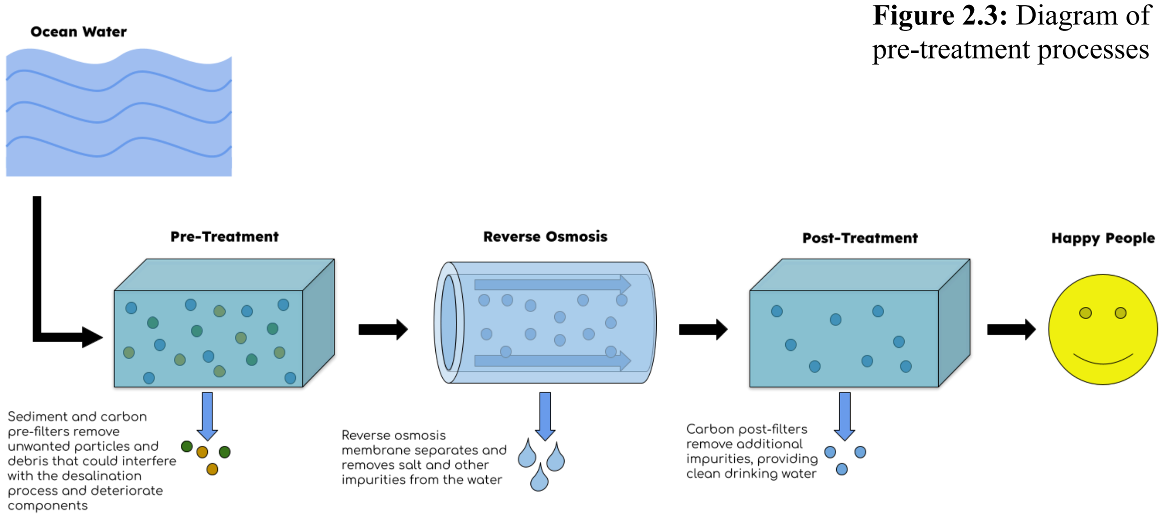

Figure 2.4: Diagram displaying full treatment process of the desalination system

2.4 Scaling Considerations

To estimate the appropriate full-scale size of the system, calculations were performed based on the motion and force characteristics of the WEC as well as the water input specifications of the membranes. Firstly, to scale up the test design and determine the pressurized water output of the full system, the length of the piston motion first had to be established. To determine this length the distance the middle of the flap moves was found to be 5.685 m. Using this value the volume of the piston displacement could be calculated using the area of the piston head. To find the piston head area the force the flap could realistically output was found using the energy value found in the power performance section. This value was found to be 2379.05 kN. Using this force and the pressure required by the membrane the area of the piston head could be calculated to be 0.493 m^2. Using this area and the pressure in the piston, a piston thickness of 0.0273 m using a safety factor of 5. Multiplying the piston head area by the length of the piston motion gives the volume of 2.803 m^3 which is the volume of the water pushed out of the piston with each stroke of the piston. To compare to values of the membrane the m^3 value was converted to 740.34 gallons. The gallons value can be divided by the average wave period to get an approximate gallon flow rate of 77.8 gallons per second. Finally this flow rate was scaled up to be 6,720,000 gallons per day.

After water is pressurized from the WEC system, it travels via underground pipes to the water treatment center on land. At this stage, the pretreatment, desalination, and post treatment will be carried out on the output water. Specifically, after passing through the pretreatment system outlined above, the water will enter the reverse osmosis stage. For the scaled up version, the membrane specifications are based on those used in the Carlsbad Desalination Plant in California, which uses the FilmTec™ SW30XHR-440i spiral-wound membrane. The membrane has the ability to produce 6,600 gallons of permeate per day and has an approximate intake flow rate of 62 gallons per minute or 89,280 gallons per day. With that, 75 membranes would be required per scaled WEC, producing 495,000 gallons of clean drinking water each day if placed in parallel. Aligning the membranes in parallel allows the most water to be purified simultaneously, optimizing the system.

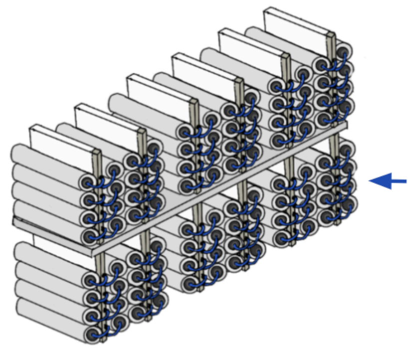

Figure 2.5: Scaled-up version of reverse osmosis system

Figure 2.6: FilmTec™ SW30XHR-440i Spiral-Wound Membrane

2.5 Power Performance

The power performance analysis of the oscillating surge flap wave energy converter (WEC) has two main sections. The first section involves analyzing the amount of raw energy that the WEC can capture ideally over a period of time. The second section involves analyzing the efficiency of the power transfer from the WEC to the piston.

2.5.1 Power Capture

Oscillating surge flaps generate power by harnessing it from the oscillating motion of ocean swells. An equation can be derived to solve for the power that an ideal surge flap can harness from this motion. To start, the wave energy per unit area is expressed by equation (1).

$$E = \frac{1}{8}\rho g H^2 \quad (1)$$

This equation was derived by Dean and Dalrymple (1991) in *Water Wave Mechanics for Engineers and Scientists*. It takes into account both the kinetic and potential energy of a wave. To solve for the power a wave has, the group velocity of the wave packet has to be determined. Dean and Dalrymple also derive equation (2) for the group velocity.

$$c_g = \frac{gT}{4\pi} \quad (2)$$

This equation however is very general and is not as accurate as would be ideal for a shallow water operating flap. Therefore a new group velocity had to be derived. The general dispersion relation for surface gravity waves is defined by equation (3).

$$\omega^2 = gk\tanh(kd) \quad (3)$$

Where ω is the angular frequency and k is the wave number. For shallow scenarios (small d), an approximation can be made (4).

$$\tanh(kd) \approx kd \quad (4)$$

This simplifies the relation to:

$$\omega^2 = gk^2d \quad (5)$$

$$\omega = k\sqrt{gd} \quad (6)$$

The group velocity is generally defined as:

$$c_g = \frac{d\omega}{dk} \quad (7)$$

Therefore, the group velocity for shallow water can be simplified to:

$$c_g = \sqrt{gd} \quad (8)$$

Symbol	Significance	Value
E	Wave energy per unit area	2810 J/m^2
ρ	Density of seawater	1020 kg/m^3
H	Significant wave height	1.5 m
c_g	Group velocity	7.43 m/s
T	Wave period	9.52 s
d	Depth of water	15m

Figure 2.7: Table displaying variables and their meanings

Taking this equation back to equation (1), an equation for power of a wave in shallow scenarios can be solved for. The power equation is defined as the energy of the wave per unit area multiplied by its group velocity and width that it covers. For an oscillating surge flap it hopes to harness the wave power over its own width. Therefore the equation can be defined as:

$$P = \frac{1}{8}\rho g H_{m0}^2 w\sqrt{gd} \quad (9)$$

Where H_{m0} is defined as the significant wave height or the height between peak and trough of a wave. Using data from Li, Ning et al., this wave height was found to be 1.5 meters. The design for this flap has a width of 22 meters and the designated location has a depth of approximately 15 meters. Using these values and the numerical constants, the ideal power that could be generated by a flap of this size can be calculated to be 749.8kW.

This number assumes the flap will harness all power of the wave. This is a faulty assumption because if all power was harnessed then the wave would no longer oscillate after passing across the flap and the flap would not operate as intended. According to Folley and Whittaker in "The efficiency of a near-shore oscillating wave surge converter."(1), in a realistic wave state, most surge flaps have a power yield of about 30-50%. Taking this into account as well as the fact that the calculated power output is optimal, a safe assumption for maximum power yield is 33%. Thus, the new proposed power that the WEC would harness in its desired environment would be 249.9kW.

2.5.2 Power Transfer

The raw power captured by the flap is transferred into the piston to produce the necessary pressure for water to be pushed through the membrane. In order for water to flow through the membrane, there must be a minimum pressure of 700 psi in the piston and against the membrane wall. In order to calculate the minimum power required to maintain this pressure, the structure of the piston was analyzed. The piston moves with the flap, compressing and expanding at the same rate as the flap oscillates. Thus, this force is directly applied by the piston and by extension the flap. The power required by the piston is represented by equation (10).

$$Hydraulic\ Power\ Required\ =\ V(P\ +\ \frac{1}{2}\rho v^{2}\ +\ \rho gh) \quad (10)$$

This equation is the generic equation used for hydraulic power produced by a piston depending on the pressure against the piston, the piston's speed, and any height changes across the piston. It takes into account the pressure, kinetic, and potential energy for a piston (the potential energy of this piston is assumed to be 0 since there is no major height change and the system is underwater).To solve for the necessary power the piston needs to operate at the membrane's ideal pressure, the volumetric flow rate, V, and the speed of the piston, ν, need to be determined from the flap's oscillation rate. For the desired location, Guam, the average oscillation rate varies with time of year, weather conditions, and moon phase. However, for the purpose of this calculation the average rate is assumed to be 6 oscillations per minute, or 1 oscillations per 10 seconds, as stated by the Secretariat of the Pacific Community (3). This oscillation rate can be converted to volumetric flow rate by equation (11).

$$V\ =\ (Volume\ of\ Piston)\ *\ \frac{1\ oscillation}{10\ seconds} \quad (11)$$

And can be converted to speed by equation (12).

$$v\ =\ (Length\ of\ Piston)\ *\ \frac{1\ oscillation}{10\ seconds} \quad (12)$$

The piston for the design has a length of 5.685 meters and radius of 0.493 square meters. Solving equations (11) and (12), the volumetric flow rate is assessed to be 0.0141m^3/s and the speed is found to be 0.05m/s. The desired pressure from the membrane is 700 psi(4.826e+6 Pa). Using these values and numerical constants, equation (10) can be solved to find the power needed to operate the piston at peak operating pressure. This desired power was determined to be 249.9kW. This number resembles the assumed output of the flap because the piston was designed to operate at the proposed efficiency.

2.5.3 Power Performance Analysis for Desalination

Multiple tests will be done to get an accurate analysis of the power of the membrane. Each will have a varying amount of pressure being pumped through the system. This will help determine the amount of power that will be needed to be put into the system to keep up with demand. By interfacing with the WEC, the output power of the membrane will be in a set range that varies depending on the varying pressure of 500-800 psi. The system's power will ultimately come from the wave energy converter (WEC), but for testing, a motor is used to simulate the conditions the system will experience during real-world operation.

2.6 Load Analysis

An in-depth understanding and examination of the different mechanical loads upon the system is crucial in determining current structural successes and failures, predicted performances, long-term safety, and potential unexpected scenarios. Given the wind-bound and volcanic environment in which the system will be surrounded, hydrodynamic, hydrostatic pressure, buoyancy, and corrosion loads will take a large toll on operational capabilities.

2.6.1 Hydrodynamic Loads

Hydrodynamic loads arise from the variations of fluid pressure and velocity caused by waves and tides relative to the surface dimensions of the system. Waves and tides impact the system in different ways. Waves depend on the strength and power of the wind, its approach angle, and any underground activity. Contrarily, tides are formed due to the gravitational pull that the earth and the moon exert on each other. Waves tend to be less predictable than tides as waves are often dictated by perpetually changing weather conditions. The chosen location of the design resides on the east side of Guam, which experiences heavy winds daily, increasing the wind currents that the system must tolerate.

To quantify the effects of the aforementioned mechanical loads on the system, Ansys was utilized to run a hydrodynamic diffraction simulation. The following table describes the conditions and assumptions for analysis. The free surface level was determined based on the location of the system. Wave period values were taken from the 2015 WACOP wave climate report and PacIOOS Wave observation data.

ANSYS Conditions and Assumptions					
Free surface level (m)	Minimum wave period (s)	Maximum wave period (s)	Mean wave period (s)	Mean number of wave components	Flap point mass definition
17.5	5	10.4	9.52	4.13	X: 0m Y: 0m Z: -10m

Figure 2.8: A table displaying the numerical conditions and assumptions

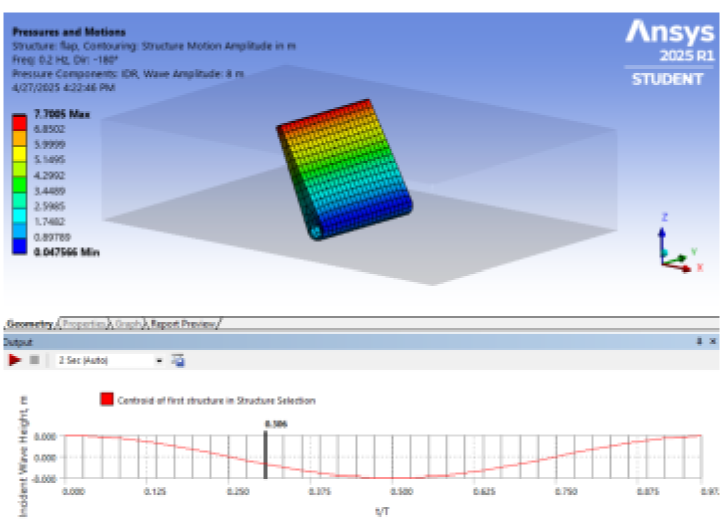

Figure 2.9: Force analysis on flap

The Ansys "Hydrodynamic Diffraction" simulation was carried out for the flap alone due to Ansys Student meshing constraints. In this simulation, only first order linear loads were considered. Because this oscillating surge flap is fixed in place at the hinge and not located in extremely harsh wave conditions, first order non linear wave loads can sufficiently define the loads this system experiences. In addition to the pressures and motions the flap experiences, the three main linear loads that were analyzed are:

(1) Froude-Krylov force: pressure on the system due to undisturbed wavefields (2) Diffraction: the force created when the body disturbs the surrounding waves (3) Radiation (radiation damping and added mass): the forces created by the wave that is generated from the motion of the body.

The Pressures and Motions Simulation (Figure 2) provides insight into the displacement of the flap when it encounters waves of varying heights. The maximum incident wave height was set to be 8 meters, as found in the 2015 WACOP wave climate report. The top of the flap reached a maximum displacement of 7.7005 meters, while the lowest point of the flap at which the flap hinges reached a minimum displacement of .047566 meters. Ideally, the flap should rotate 45 degrees in order to compress the hydraulic pistons sufficiently. At an angle of 45 degrees, the displacement at the top of the flap is theoretically 19 meters. According to the simulation, the flap will not reach this level of displacement, reaching a maximum tilt angle of 24 degrees.

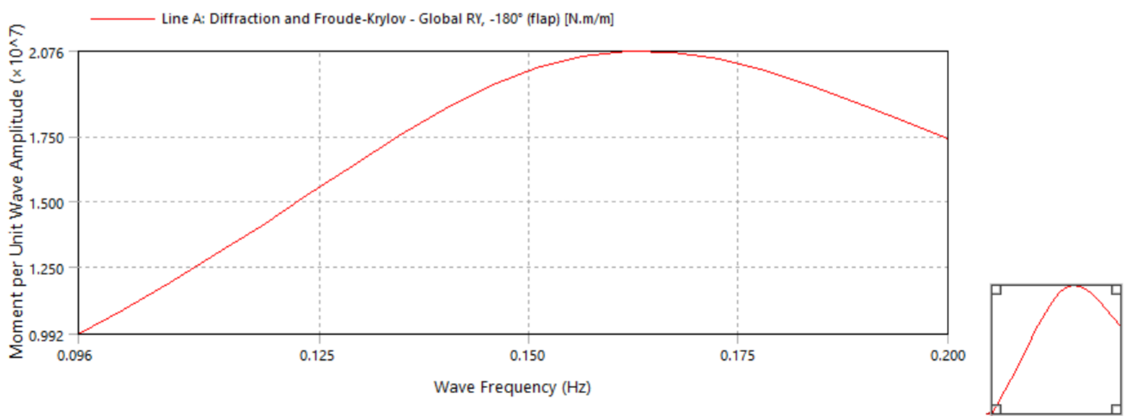

Figure 2.10: Diffraction and Froude-Krylov forces

The combination of the linear loads of diffraction and Froude-Krylov forces represents the total non-viscous forces acting on the flap. The Diffraction and Froude-Krylov test shown in Figure 3 represents the total non-viscous forces exerted on the flap occurring during various wave frequencies. Total non-viscous forces exert a maximum impact of 2.076 moment per unit wave amplitude at roughly 0.1625 hz, or a period of 6.15 seconds. At the specified Guam location, the mean wave period is 9.5 seconds, or a frequency of .1053 hz. At this wave frequency, the simulation suggests that the flap experiences a moment per unit wave amplitude of roughly 1.5, which is about 25% less than the moment experienced at the most intense frequency. Thus, it is plausible that the flap will be able to withstand Guam’s wave climate as peak non viscous forces are not present at Guam’s most common wave frequencies.

Shortly after reaching its peak, the moment per unit wave amplitude exhibits an abrupt decline as the wave frequency increases. A steep decline, rather than a horizontal asymptote, could indicate that the flap possesses strong damping characteristics, meaning that higher-frequency waves might be absorbed or dissipated effectively. This is beneficial in reducing the overall hydrodynamic loads on the flap. Stronger damping characteristics exhibited during high frequencies, or short wavelengths, could be due in part to the large size of the flap, as shorter waves often pass by large structures without significantly affecting its motion. However, these benefits may not be fully utilized because the location's specific mean frequency is not in the range of frequencies where damping is most effective.

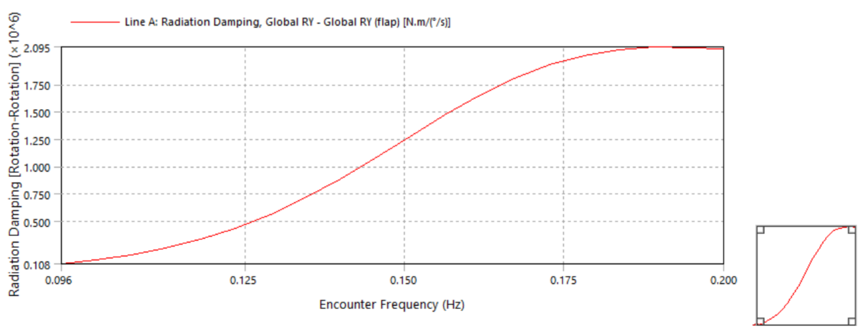

Figure 2.11: Radiation damping

The flap would experience the most damping at an encounter frequency of 0.2 Hz. Because encounter frequency is typically slightly higher than wave frequency, the encounter frequency of 0.2 Hz coincides with the 0.1625 Hz wave frequency at which the maximum diffraction and Froude-Krylov forces occurred. This alignment of the frequencies of maximum damping and maximum moment per unit wave amplitude could indicate that the flap exhibits optimal energy transfer at a 0.1625 wave frequency. While in terms of energy efficiency, it would be ideal for this frequency to be close to Guam's mean wave frequency of 0.11 Hz to produce the most energy output, in terms of structural stability, it would not be as beneficial to the system due to the high wave excitation forces that the structure would experience.

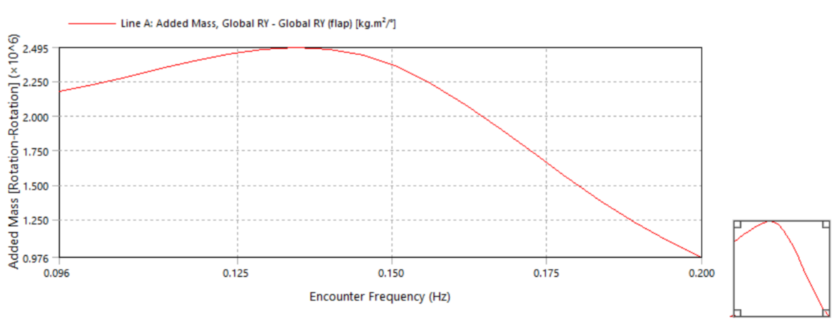

Figure 2.12: Added mass

The flap experiences a decreasing added mass with higher frequencies which means the effects of the water's inertia on the flap becomes less significant, allowing the flap to move more freely in the water. Added mass peaks where diffraction-Froude-Krylov forces are low, which could suggest that the flap has optimal levels of wave force absorption and thus low levels of shock forces, reducing structural stress on the system. The added mass peak also occurs roughly around an encounter frequency that coincides with Guam's mean wave frequency of 0.11 Hz. Higher added mass means that the flap moves slower in response to the waves, which is corroborated by the Pressures and Motions simulations detailed earlier, that shows that the flap does not move significantly when excited by waves. A high added mass is beneficial for reducing stress on the system because the slow, stable movement of the flap reduces wear and tear. However, a high added mass will not allow for as much energy capture as a lower added mass would. Thus, it is important to strike a fine balance between structural stability and energy output requirements when designing the WEC system.

2.6.2 Materials Selection

The aforementioned forces and the effect of corrosion on the system were considered holistically when determining which materials to use to construct the system. For marine structures, commonly used materials include 316 Stainless Steel and titanium. 316 Stainless Steel was determined to be the most optimal material as it is considerably more cost effective while still exhibiting effective mechanical properties. 316 Stainless steel is strongly encouraged for marine applications due to its corrosion resistant properties. As stated by Steel Pro Group, this material consists of 16-18% chromium, 10-14% nickel, and 2-3% molybdenum; the introduction of molybdenum makes 316 Stainless Steel more resistant to corrosion compared to other steel varieties. It is also known to have a higher tensile strength than other steel variants, with an ultimate tensile strength ranging up to 580 MPa. The location of the system, the east side of Guam, demands consideration of the island's volcanic history when choosing durable materials. Compared to standard ocean water, higher corrosion rates are plausible due to the presence of excess metals lingering in the ground soil and surrounding environments from previous volcanic activity. To ensure the safety and longevity of the design, the thickness of the frame members was prioritized in order to minimize the risk of the frame's decreased structural integrity over time as the ocean water corrodes the system.

2.7 Mechanical Integrity

2.7.1 Structure Endurance

To calculate the safety factor for the WEC, a static stress simulation in Fusion 360 was completed.

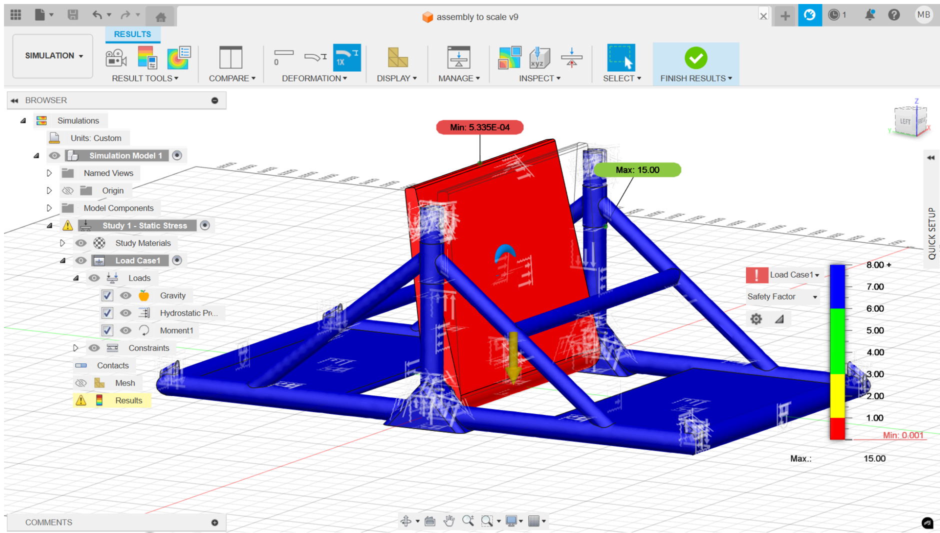

Figure 2.13: Fusion 360 Static stress simulation

For structures in which reliable materials are used under difficult and environmental conditions, an ideal safety factor is in the 3-4 range. The frame exceeds this necessary safety factor. However, it is important to keep in mind that the parameters for analysis only took into account hydrostatic pressures and a singular moment of wave pressure. On the other hand, the flap's safety factor is essentially zero which is not in compliance with safety requirements for large structures such as this. It is suspected that this safety factor is not completely accurate as the simulation may not have been constrained properly to yield accurate results. Further investigation into safety factors and stress analysis parameters would have to be done in order to accurately represent the safety of this WEC. Regardless, if the flap's safety factor of zero is accurate, some ways that the safety of the design could be improved is to adjust the general design of the flap to more closely resemble a streamlined shape. A smoother top end rather than an abrupt corner would provide less resistance and allow water to pass more easily without an extensive amount of force causing deformation. Additionally, the safety bars already implemented in this design could be reinforced to maximize prevention of the flaps excessive displacement.

2.7.2 Desalination Durability Analysis

The system is designed to directly convert mechanical movement from the oscillating surge flap into pressurized water flow without the use of intermediate electrical or energy conversion. This optimization approach concentrates mechanical forces in key points of the desalination process, particularly at the force transfer piping and pressure vessel assembly. To ensure durability and safety with continuous usage, stress analysis was conducted for each component to verify each its ability to withstand cyclical loading and forces with appropriate safety margins.

All components for the desalination system design were selected to withstand the standard operating mechanical forces and moments associated with a maximum operating pressure of 1000 psi. This provides a sufficient safety factor for the desalination process as the expected pressure will not exceed 800 psi. Important elements, such as the pressure vessel, piping, seals, fittings, and structural supports were chosen for this design based on their ability to maintain integrity in high pressure conditions generated by the energy converter. The pressure vessel is constructed from strong-coated FRP/fiberglass and contains stainless steel end plates and locking components, allowing it to maintain structural integrity at 1000 psi. Additionally, all NPT fittings are also made of stainless steel for increased strength and corrosion resistance. This intentional design and materials selection process ensures that the reverse osmosis and filtration unit can operate safely and consistently in the marine environment, without risk of mechanical failure, load deformation, or leakage.

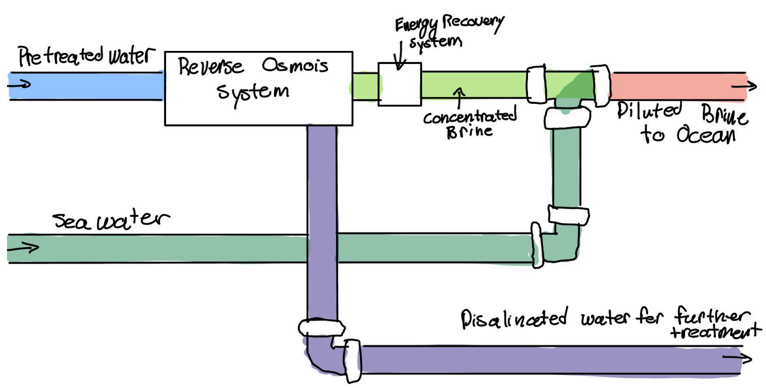

Figure 2.14: Dilution of concentrated brine before re-entering the ocean

2.8 Optimization

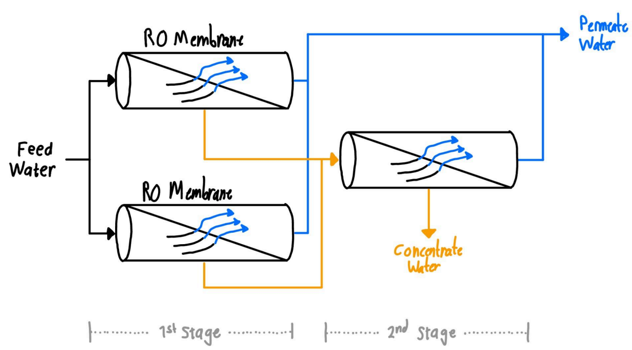

Figure 2.15: Diagram of double desalination process

A core optimization in the wave-powered desalination system is the direct use of mechanical energy to pressurize the membranes, eliminating the need for intermediate electrical conversion, which typically results in approximately 6% energy loss due to heat, according to the US Energy Information Administration (EIA). This energy utilization avoids the inefficiencies associated with energy storage and conversion infrastructure. To achieve this optimization the oscillating motion of the wave was utilized by using the pressure of the wave to create a similar oscillatory motion in the flap of the WEC. This oscillatory motion is used to move the piston. The pistons motion comprises ocean water to the pressure needed by the membrane and then the pressurized water gets pushed to it. In the back stroke the piston creates a low pressure region that draws water in from the ocean through a loose filter to keep large debris out of the piston preventing jams. By operating directly off variable wave input, the system can continuously drive desalination without energy buffering. Furthermore, a strategy that can be implemented to further optimize the system is a double desalination process, outlined in Figure 12. In this method, feed water is passed through a Reverse Osmosis membrane and the discarded concentrate water from multiple membranes is passed through an additional RO membrane. Though this additional step increases the number of membranes needed, this process significantly increases the amount of water produced in the system.

2.9 Sustainability Factors

The sustainability of a wave-powered desalination system depends on environmental, social, and economic factors. Environmentally, it reduces carbon emissions by using renewable wave energy. Marine ecosystem disruption will also be minimized and responsible brine disposal will be ensured. A large area in desalination research surrounds how to dilute brine to meet regulation when re-entering the ocean. Additionally, the energy from the WEC system does not need to translate into electrical energy which means this system is optimized in energy use. Socially, it enhances water accessibility, benefits coastal communities through job creation, and involves stakeholders in its implementation. Economically, it lowers long-term operational costs, offers scalability for different locations, and can be supported by government incentives. By balancing these factors, wave-powered desalination provides a sustainable solution for freshwater production while reducing reliance on fossil fuels.

The WEC system is also placed strategically in a geographic location that would allow for the system to be accessible in the case of required repair. This location will limit the economic cost of repairs and allow them to have a minimal impact on the surroundings of the WEC. The placement of the system on the sea bed rather than mooring it makes its area of impact slightly larger, but this loss in sustainability is offset by the carbon emissions required to desalinate water using traditional energy sources. One area of sustainability the WEC system falls short is the materials the WEC is made out of. Most of the materials are not sustainably sourced and many have very dirty production methods. This is an area that requires additional research to provide the necessary evidence that a significantly more sustainable material would not compromise the functionality of the WEC. Furthermore, the membrane specific environmental impacts were taken into account as well. To follow brine output guides for reintegration back into the ocean, the desalination system will dilute the brine with seawater to a daily maximum concentration of 2.0 ppt above natural background salinity.

2.10 User Needs

The design system was developed with key user needs in mind, including the production of clean, safe drinking water with minimal salt content while maintaining affordability and ease of maintenance. To maintain sodium levels below 30-60 mg/L, which according to the Environmental Protection Agency is the taste threshold for sensitive members of the population, the selection of the reverse osmosis membrane was strongly influenced by salt rejection rate. Sediment and carbon pre-filters and post-filters are incorporated into the final design to enhance water purity and prolong the lifespan of valuable components by protecting them from large debris, thus reducing user costs for repairs. Piping materials were carefully selected to minimize corrosion and contamination risks in specified areas. Duplex stainless steel was used in the high pressure reverse osmosis system due to its high pressure rating and resistance to sea water corrosion. HDPE pipes were used for both seawater intake, brine discharge, and posttreatment due to its corrosion resistance and general durability. Additionally, commercially available parts and a modular design were intentionally chosen to simplify system maintenance and make the process of obtaining replacement parts cheaper and simpler. With these incorporations, the scaled version is believed to provide a sufficient 15 liters of water per minute while also keeping water production costs competitive with Guam's current water rates, therefore providing an economical and sustainable solution for local communities.

2.11 Technical Design Student Contribution

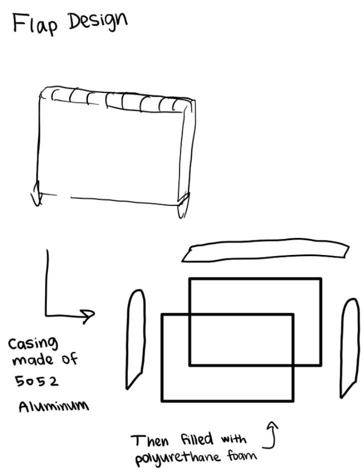

Figure 2.16: Preliminary sketches of flap design

The technical design process, which was led predominantly by undergraduate students, showed student growth and equal contribution from all members. At the beginning, after declaring the issue and goals, key design constraints and challenges were collaboratively identified. A few examples of this are flap survivability in storm conditions, ease of repair, limiting wear on the membrane, and flap efficiency. Working off this, the general direction of the design through physical and digital modeling was determined.

These were then refined into more digital diagrams, and eventually a Fusion360 assembly file. This represented the hydraulic system components and overall structure. The team additionally worked to compare benefits of embedded plate anchors, and rope mooring systems, and when making these decisions criteria such as material cost, efficiency, durability, and ocean floor conditions were taken into account.
Each member contributed research into the system's components. Energy conversion methods were explored. This included point absorbers, oscillating water columns, hybrid devices, and oscillating surge flaps. Each of these had different power takeoff mechanisms. Particular attention was given to the systems that aligned with the desalination approach to minimize unnecessary mechanical complexity.

Regarding deciding on the membrane, in early stages the team explored numerous aspects of the desalination process to determine which one would be most effective for experimentation. Each member researched and compared pre–filtration options, reverse osmosis membrane models, post–filtration method, and water transfer materials. As a collective, it was decided that using the reverse osmosis (RO) membrane would be most beneficial to focus on. This was driven by the membrane's role and ability to determine freshwater recovery and salt rejection, which is extremely important in desalination setups. Other components such as carbon post filters for final polishing, and piping materials (CPVC or HDPE) were also considered in team research. Though these were not part of the initial testing plan, learning about their chemical properties and structural performance broadened the team's understanding and will aid in creating future stages of development.

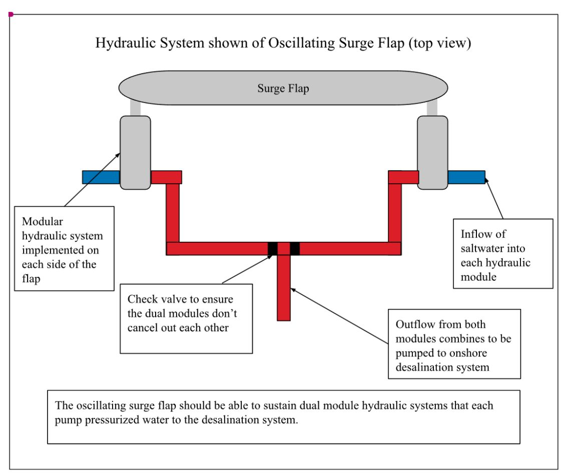

Figure 2.17: Diagram of piston system

Cornell University

Build and Test

3.1 Introduction

In the early stages of the design process, the wave energy converter (WEC) system was heavily inspired by the RM5 design from NREL. This design is a great option because it allows mechanical energy to be fully utilized without the loss of efficiency and increased complexity of converting to electrical energy. The preliminary idea which was built upon is directly connecting a piston to the flap and the frame. As the flap oscillates, the mechanical motion pressurizes water with a piston. Once a desired pressure is reached, a check valve allows the pressurized water to flow through the membrane.

The initial plan was to create a moored floating oscillating surge flap system. However, after consulting with an advisor, it was concluded that the efficiency for the system would be higher if placed on the ocean floor. Mounting to the sea floor provides higher energy outputs from the motion of the waves since the frame is fixed. Thus, the velocity of the water motion is larger relative to a fixed frame compared to one that can move with the wave. Therefore, after analysis of the ocean floor at the proposed site, the eastern side of Guam, it was found to be a suitable place for the system.

The model-scale membrane system was designed to evaluate performance under realistic conditions and facilitate scaling to full-size applications. The 2.5 x 14-inch prototype balances experimental feasibility with accurate representation of key parameters such as pressure management, structural integrity, and permeability.

To assess membrane integration within a wave energy converter (WEC) desalination system, reverse osmosis (RO) performance was tested under variable pressure conditions, simulating wave-driven fluctuations. The setup included a synthetic saltwater mixture, a pump with a variable frequency drive, an actuated needle valve for pressure control, and sensors for monitoring pressure, flow rate, and salinity. Multiple trials were conducted at varying pressures to analyze water output, salt rejection efficiency, and system stability, providing data for optimization.

3.2 Engineering and Design Process

3.2.1 Mechanical System Design and Testing

The testing design was mainly done after the full scale design was completed in order to allow the test to serve as a true proof of concept for the full scale model and to allow an iterative loop to take place. The full scale is adjusted due to data from the small scale test, informing the decisions for the next round of testing. As a consequence, the testing timeline was quite tight from the start of the project, and the delays in funding further tightened the timeline. This caused smaller delays along the way that added up into an infeasible testing timeline where the team has to complete testing after the competition.

The facilities that the team had access to were the primary consideration when designing and planning the testing of the wave energy converter. Permission to test in the wave tank at Cornell University was given, but exact dates were not established until a fully functional system was built for testing. While access to

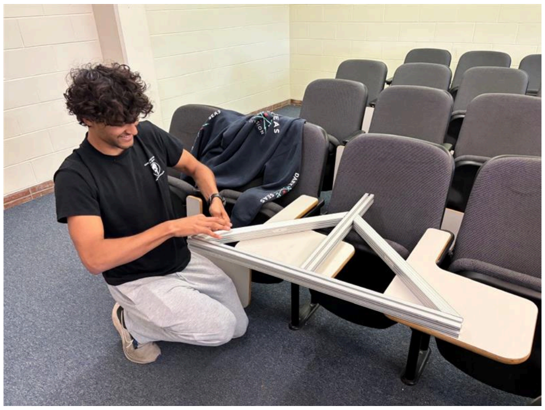

Figure 3.1: Deven Chakrabarti ‘27 constructing the WEC frame

using lab space and storage space were given, very little access to machining spaces was given which severely limited the design freedom, particularly in the piston design. For the testing of the frame and flap, no machining was required and minimal power tools were needed, so both pieces were completed. However, the lack of access to machining restricted the design of the piston and stretched its timeline to lag behind the rest of the assembly. Ultimately, this was the aspect of the design that put the testing timeline past the end of the competition. Despite the timeline being outside of the competition, a testing plan was still made to be executed once the assembly of the testing system is complete.

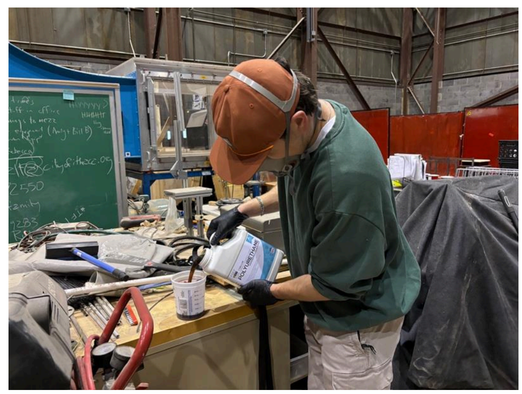

Figure 3.2: Matt Pianka ‘27 pouring marine foam to cast the WEC flap

The prototype was initially fabricated in two parts, the flap and the frame. When fabricating the flap, the primary concern was finding the optimal center point to keep the center of mass of the flap low while ensuring the flap is strong enough to withstand the waves. This issue is much more significant for the scaled up design because of how scaling a design affects both strength and weight disproportionately. For the scaled down prototype, a decision was made to have the flap be heavier than necessary. This was done in order to err on the side of caution for resilience and more accurately simulate the true weight of the scaled up flap. Additionally, the increased complexity to cast a tapering flap would not be worth the value it provided for the tests. The taper made a casting failure much more likely, and the marine foam was one of the most expensive parts of the tests. Taking this into account, the flap was cast as a rectangular prism. In order to cast the flap, a mold was made to create a flap of the right size and shape to pour the liquid marine foam into. A variety of materials were considered to do this casting, mainly focusing on options that were easily and cheaply available. The primary two materials that were considered were plywood and acrylic because they are both easy to cut and cheap. Ultimately, the porousness of the wood and the risk of the wood flexing made it a bad material to cast in. To shape the acrylic, a score and snap method was used.

Figure 3.3: Matt Heering ‘27 scoring and cutting an acrylic sheet for the cast of the WEC flap

While there are other effective options for cutting acrylic, most of them require access to expensive or power intensive tools. Once the acrylic was cut, it had to be assembled into a mold of the flap. This assembly was done by caulking the seams of the acrylic to seal the edges and to hold the box together. This assembly method was not completely effective so a cardboard box was assembled around the acrylic to provide additional support to the box against the expanding foam. Marine foam was picked as the material for the flap because it would not deteriorate significantly under ocean conditions and it could be dense enough to withstand the forces continuous wave impacts would cause. Two different types of marine foam were considered for the flap. These were cast marine foam or marine foam sheets. The marine foam sheets were simpler to use but provided less options for density while restricting the design space to specific predetermined dimensions. Due to these factors, it was decided cast marine foam was a better option for the flap. To cast the flap, solution A and solution B of the marine foam were mixed and stirred thoroughly before being poured into the acrylic box. The casting of the foam did not end up covering the whole base of the box so it expanded unevenly. For future casting, the box would either be rotated to make the base smaller or the solution would be spread prior to its solidification using even pressure across the base so that it rises and solidifies evenly.

The frame was built using 80/20 aluminum due to its corrosion resistance and ease of assembly. Using 80/20 as the frame material caused it to be much less dense than the full scale design, resulting in an inability to test the mooring system. However, due to the inability to replicate the seafloor in the testing wave tank, weights would be added to replicate mooring in this round of testing. Assembling the frame with 80/20 was a simple process involving mostly using an allen key to screw joints, although some delays occurred. This was because some of the parts ordered did include joints as ordered, which delayed the assembly of the frame.

3.2.2 Desalination Membrane Design and Testing

In choosing what membrane to use, the team considered a variety of factors, chief among them being the size of the membrane itself. This aspect of the membrane was important as it directly affects both performance and system scalability. The membrane size was especially evaluated to ensure compatibility with the chosen pressure vessel and to optimize surface area. Through preliminary research, it was found that larger membranes offered increased throughput but required higher pressure ratings, meaning a more robust pressure vessel. This would have greatly increased costs and potentially could lead to harder serviceability. On the other hand, smaller membranes were found to be easier to maintain and run, but could require multiple membranes to meet operational demand. One other important factor that was considered during prototyping was the pressure rating of the membrane. The goal was to find a membrane that could reliably handle up to 800 psi to match the pressure that would be produced by the WEC. It is important to note that this value is an upper limit for pressure, as the energy produced by the WEC is not constant, therefore introducing variable pressure conditions to the membrane. Ultimately, the selected membrane met both the pressure and size requirements: Filmtec SW30-2514 RO, a 21’’ long, 2.4’’diameter membrane that can handle up to 800 psi.

Figure 3.4: Pressure vessel in the lab

When selecting the optimal pressure vessel for the system, several factors were considered such as the compatibility with the chosen membrane and long-term reliability. The primary consideration in ensuring the compatibility of the pressure vessel with the membrane was the pressure rating of the vessel. This pressure value would determine what the maximum operating pressure would be for the entire system. Another factor considered was the size of the pressure vessel itself, making sure it was large enough to accommodate the membrane. Price was also a critical point when choosing a vessel, as budget constraints limited available options. Other miscellaneous factors that were considered during vessel selection were material (to prevent corrosion from seawater) and ease of loading and unloading membranes for easy maintenance.

To achieve precise control over fluid flow through the system—a crucial component for stable pressure and reliable membrane performance—the membrane subteam decided to incorporate a needle valve into their build. The team can carefully control flow rates and maximize filtration efficiency thanks to the needle valve's fine-tunable adjustments, which are not possible with standard valves. This degree of control is particularly crucial in testing situations where even minor changes can have a big impact on the outcomes.

3.2.3 Mechanical Scaling Factors

When designing and fabricating the scaled down model of the WEC system, the primary limitation was the size of the wave tank accessible to the team. As a result, the dimensions of the tank were used to create a scaled down model that is as similar to the full scale model as possible while maintaining feasibility and the critical aspects of the design for testing. These critical aspects were ensuring the top of the flap is at the surface of the water and the piston attaches by hinges on both ends. Both of these design choices have a potential to be very impactful on the power output of the WEC. When scaling different numbers in the design, Froude Scaling was used where possible.

One place the design was intentionally changed despite it being possible to be more accurate to the original design is the size of the piston, and therefore, the pressure of the water output. In order to reach the target pressure, the size of the flap would have forced the output to be a small jet of water. Due to this issue as well as the inherent danger of water pressurized to extremely high pressures, the decision was made in the interest of the safety of the team and equipment to scale up the piston. This resulted in a safe operating output pressure while making the output volume, the primary testing metric, larger, causing small distinctions to be more noticeable and spillage less impactful.

Figure 3.5: Preliminarily assembled WEC

3.2.4 Desalination Scaling Factors

In designing and fabricating the model-scale membrane device, key scaling factors were systematically applied, guided by dimensionless analysis, particularly using Reynolds, Sherwood, and Schmidt numbers. These dimensionless numbers provided critical insights into flow regimes, mass transport characteristics, and momentum-mass transfer interactions, significantly enhancing understanding of membrane operation at various scales. The chosen prototype membrane size was strategically selected to effectively evaluate important parameters such as pressure management, structural integrity, and membrane permeability, ensuring realistic representation of larger-scale models.

To maintain consistent and optimal operation, the membrane surface area was scaled proportionally to the flux rate, helped sustain uniform pressure gradients across the surface and prevent localized fouling. Operating pressures were adjusted accordingly to reflect increased flow rates. Additionally, the prototype featured dedicated pretreatment processes and waste streams to proactively manage contamination risks, providing valuable data for scaling these components effectively.

Recognizing structural integrity as a priority, robust support structures were integrated to withstand increased mechanical stress from higher pressures and velocities. Temperature control was carefully managed through material compatibility considerations and targeted insulation strategies, maintaining stable and efficient operational conditions. Collectively, these detailed considerations in the prototype design offer a comprehensive and practical foundation for successful future scale-up.

Figure 3.6: Filmtec SW30-2514 RO Membrane

3.3 Mechanical Experimental Test Plan

The goal of the experimental testing of the mechanical system is to provide evidence that the wave energy converter can consistently produce the volume of pressurized water expected based on the calculations. It will incorporate a 10% leeway into the calculations to account for some inevitable leakages and to allow the system to not be perfectly assembled as it is experimental and can not be held to industrial standards.

3.3.1 Experiment Setup

The setup for the experiment will be similar to a scaled down version of the full design. The primary means of data collection is volumetric data over time. The key components of the design are:

- **Wave Machine:** A large tank that has a mechanical system to create waves in the tank in a consistent sinusoidal pattern.
- **Flap**: Marine foam flap that will translate the waves in the water into an oscillatory mechanical motion.
- **Piston:** Translates the oscillatory motion of the flap in a linear compressive motion that pressurizes water to the desired pressure.
- **Check Valves:** Ensures that the water the piston is producing is at the acceptable pressure before allowing it to be measured and creates a safety mechanism that releases the water back into the tank if the water reaches a dangerous pressure.
- **Flow Meter:** Measures the rate the pressurized water flows out of the check valve to allow the comparison of the rate to the calculations.

3.3.2 Data Collection

In the experiment to test the wave energy converter effectiveness, the main data collected is flow rate. Through the check valves, water is maintained at a sufficient pressure but also not too pressurized so the membrane is not damaged in a full system. Using this data the effectiveness of the wave energy converter to the calculated effectiveness of the wave energy converter will be compared.

3.4 Desalination Experimental Test Plan

The use of desalination with wave energy converter systems poses many obstacles for membrane integration. The biggest challenge identified was reverse osmosis membrane performance under variable pressures. Therefore, the goal of this experiment is to evaluate how an RO membrane performs under variable pressure conditions, simulating the oscillating wave-driven input from a WEC system. This experiment would prove if the RO membrane can maintain efficient desalination performance with consistent water output and salt rejection, without a pressure stabilizer.

3.4.1 Experiment Setup

In the experimental setup for RO testing, pressure control is necessary for evaluating membrane performance under variable conditions. As such, the membrane testing apparatus has several key components:

- **Input water source:** As ocean water is not readily available near the testing facility, a synthetic saltwater mixture is prepared using trace mineral drops.

- **Pump and Motor:** A pump, which is driven by a motor regulates the flow rate and pressure of the feed water before it enters the membrane. The motor used is a Squirrel Cage Three Phase Induction Motor and the pump used is CAT Pumps 430.3000.
- **Pressure Vessel:** This component houses the membrane and maintains the high pressure conditions during testing. A 2.5" x 14" Fiberglass/FRP Seawater Pressure Vessel from Applied Membrane Inc will be used in this experiment.
- **Membrane:** The subject of the experiment, the membrane desalinates the input water under controlled pressure to evaluate its performance. The membrane is a Filmtec SW30-2514 RO.

The system is designed to operate within a pressure range 500 and 800 psi, with an average target pressure of approximately 650 psi. This range fluctuates up to the optimal pressure for the selected membrane while also testing its performance under broader operating conditions to evaluate compatibility with the WEC system.

Figure 3.7: Pump, motor, drive, found counterclockwise from top left

The system used is adapted from the SEA Lab at cornell. Their testing apparatus is designed to only test high pressure pretreatment; however, this setup contains many of the necessary elements for variable pressure testing. Specifically, the motor, pump, and sensors described above are pre-integrated into the testing set up. With this apparatus as a base, many adjustments still have to be made for this testing. The pressure vessel mount has to be adjusted to fit the wider and shorter structure of the Filmtec membrane, while keeping the water flow at the same height. Furthermore, the output angles for the brine must be adjusted for the experimental setup.

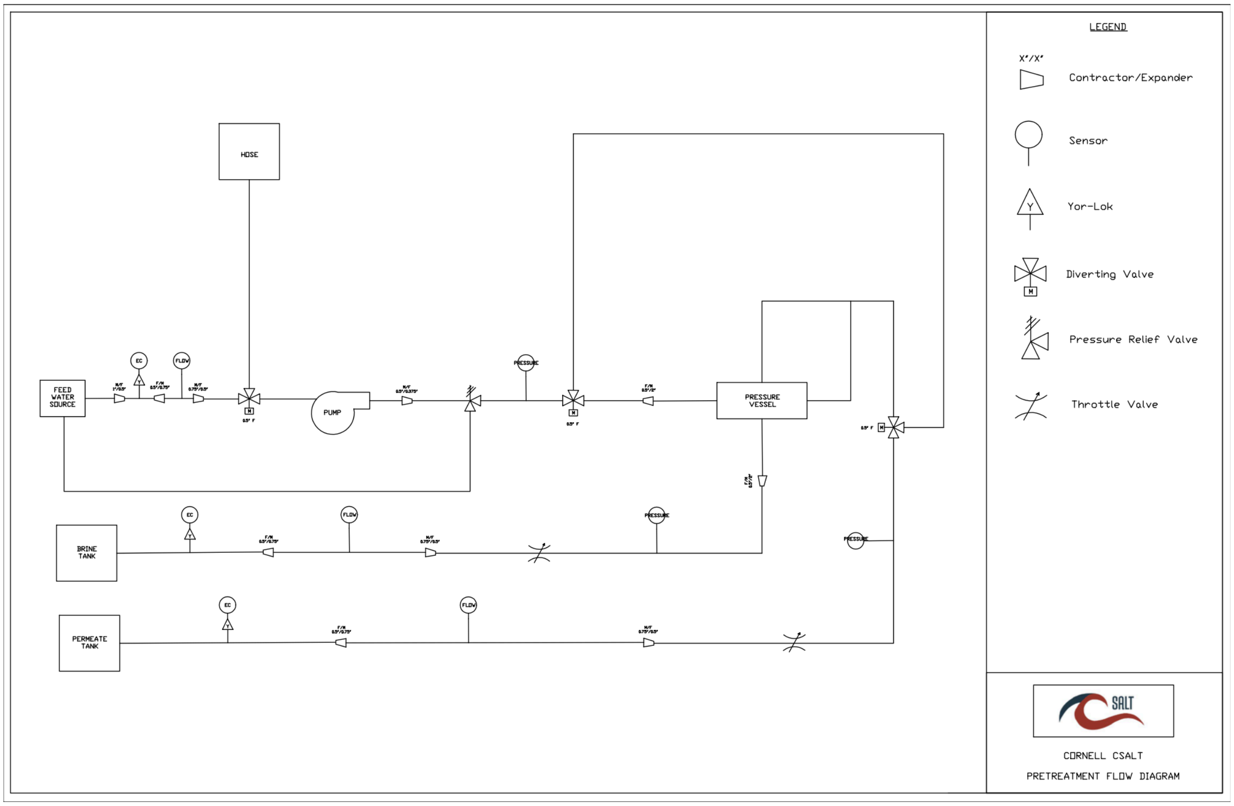

Figure 3.8: Process flow diagram displaying the desalination system

3.4.2 Data Collection

In the experimental setup for RO testing, data collection and a thorough testing process is necessary to evaluate the membrane performance under varying conditions. Thus, the following variables are carefully measured throughout experimentation.

- **Water output:** Measured by flow rate sensors, the recorded water output helps in the determination of how fluctuations affect desalination volume.
- **Pressure:** Pressure sensors measure the system's current pressure, both before and after entering the membrane. Acting as the independent variable to assess the membrane's ability to handle instability. The Rosemount 2051T Pressure Transmitter was used to record pressure, connecting the outputted 4-20 mA analog signal to Arduino to collect data in real time.
- **Salt rejection:** Conductivity meters compare the salinity levels of input and output water, enabling an evaluation of the membrane's desalination efficiency. The 5V (charged node) of the sensor was wired to the AREF pin on the Arduino to collect data points.

This testing process involved conducting multiple trails at varying pressure fluctuations and frequencies. Real-time data is logged into charts and graphs for comprehensive analysis. This approach allows for proper assessment of the membrane performance in order to achieve the experimentation goal.

This experiment evaluates RO membrane system performance under fluctuating pressure in a wave-driven desalination system. By measuring water output and salt rejection efficiency, the test will determine the impact of pressure variations on effectiveness. The results will also identify any performance limitations and provide insight into potential design adjustments, such as optimizing pressure input methods or selecting a more suitable membrane, to improve overall system efficiency.

To test whether the membrane is successfully desalinating the saltwater while working in tandem with the wave energy converter system, an environment with controlled variable pressure was maintained. The water pushed through the membrane needs to be held at a certain pressure to ensure the prototype is functioning, and so conductivity meters need to be implemented to test for desalination. The chosen membrane works to desalinate water through a reverse osmosis system. To simulate the wave driven input for the WEC system, and thus the variable pressure exerted on the membrane as well, a wave simulation was created by using an Arduino board controlling a Squirrel Cage Three phase induction motor . A KBDA-24D driver in the following layout (Figure 3.9A) was implemented. A relay was required to control and protect the motor efficiently, and configured as shown in Figure 3.9B.

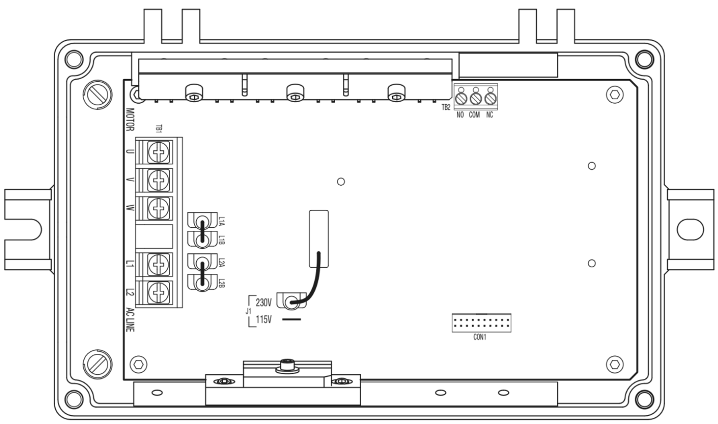

Figure 3.9A: Driver configuration

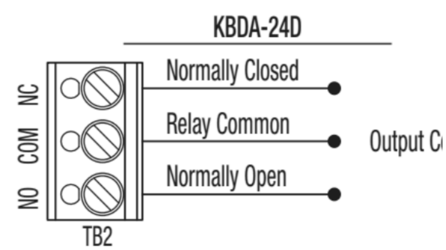

Figure 3.9B: Relay of motor driver configuration

The AC line input of the motor was connected to the terminal block TB1. The motor configuration "Model KBDA-24D" was chosen since this makes the motor designed for single-phase AC line input only. The configuration was rated for 208/230 Volt AC line input with Jumper J1 set to the "230V" position (factory setting) and rated for 115 Volt AC line input with Jumper J1 set to the "115V" position. The motor was also grounded. The motor is shown above in Figure 3.9.

To control the flow of the fluid, two prototype options were explored and planned to be tested. An actuated needle valve and a solenoid valve are both viable options for controlling fluid flow. The highlighted key difference between these two options lies in their actuation method: solenoid valves use an electromagnet (controlled by electricity) to move a plunger, while actuated needle valves use compressed air pressure to move a piston or diaphragm. However, due to time constraints on purchasing a needle valve compared to the easier access of the solenoid, a solenoid was further prototyped.

A solenoid valve functions with an electromagnet as the inductive load. The solenoid in this case is of the configuration “normally closed”. This means that once the electromagnet is powered with the expected current, the valve will open. A 12V / 0.4 A NC solenoid was used for the prototype. Adapters were used to solenoid valves to the source of water and to the output. A MOSFET is also used, which is a type of transistor acting as a switch to control the flow of current between the source and drain terminals by applying a voltage to the gate terminal. A N-channel MOSFET (specific model: FQP50N06L) is used here, connecting the solenoid to ground. Since an Arduino is being used to control the solenoid, a 85% efficient DC-DC buck converter is also required. This is because excess voltage can overheat the Arduino very easily, since there is limited heat sink capability built into the board. The schematics for wiring were followed according to the MOSFET datasheet to connect to the Arduino.

3.5 Future Plans

The future plans are to conduct all of the experiments above. Additionally, there are plans to continue refining the design of the full scale wave energy converter with the information from experimental results. Specifically, the testing of different materials for the flap would provide insight on buoyancy, efficiency, and performance, allowing for further optimization. For desalination, future experiments involve testing different pre- and post-filtration techniques in order to increase output efficiency. In further experimentation of variable pressure, sea state wave patterns will be used. This will give a more accurate reflection of wave frequency specific to Guam. Once the WEC and desalination design are more finalized, the scaling will be adjusted so the two prototypes can be used together to simulate the full system. Finally, an ocean test would be completed to fully confirm the success of the design.

Cornell University

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