TECHNICAL NARRATIVE

DESIGN STAGE

The ROOWaC Desalinator

By Wells Engineering, LLC

(Reverse Osmosis powered by an Oscillating Water Column)

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0. Introduction

In June 2019, the U.S. Department of Energy (DOE) Water Power Technologies Office (WPTO) launched a prize competition to develop wave energy-powered desalination systems. The Waves to Water Prize is a four-stage contest to accelerate the development of small, modular, wave-powered desalination systems capable of providing potable drinking water in disaster relief scenarios and remote coastal locations.

This is the second stage of the prize; the DESIGN Stage. This Technical Narrative describes the innovation potential, technical feasibility, system scalability and other benefits, and the overall build plan of the ROOWaC system designed by Wells Engineering, LLC, shown in Figures 1 and 2. Details of the design approach and modeling results are provided separately in the Modeling Documentation.

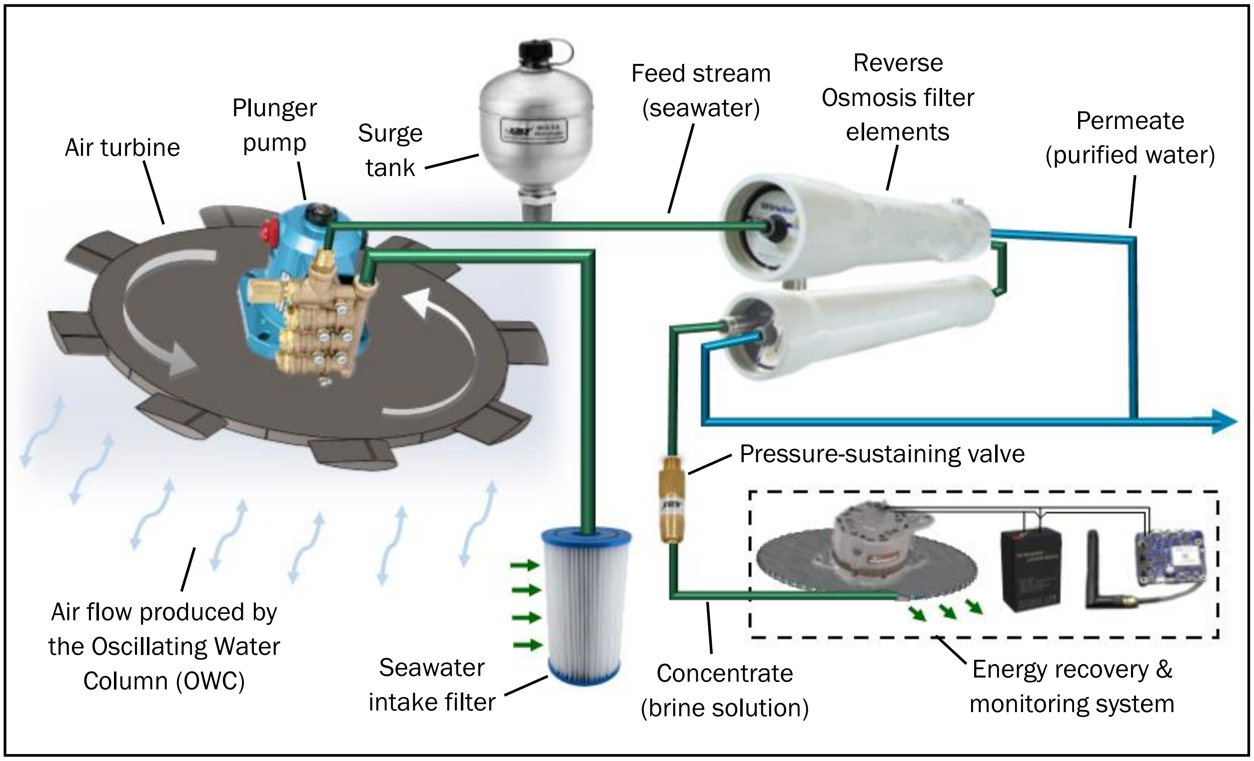

Figure 1. ROOWaC system – simplified schematic.

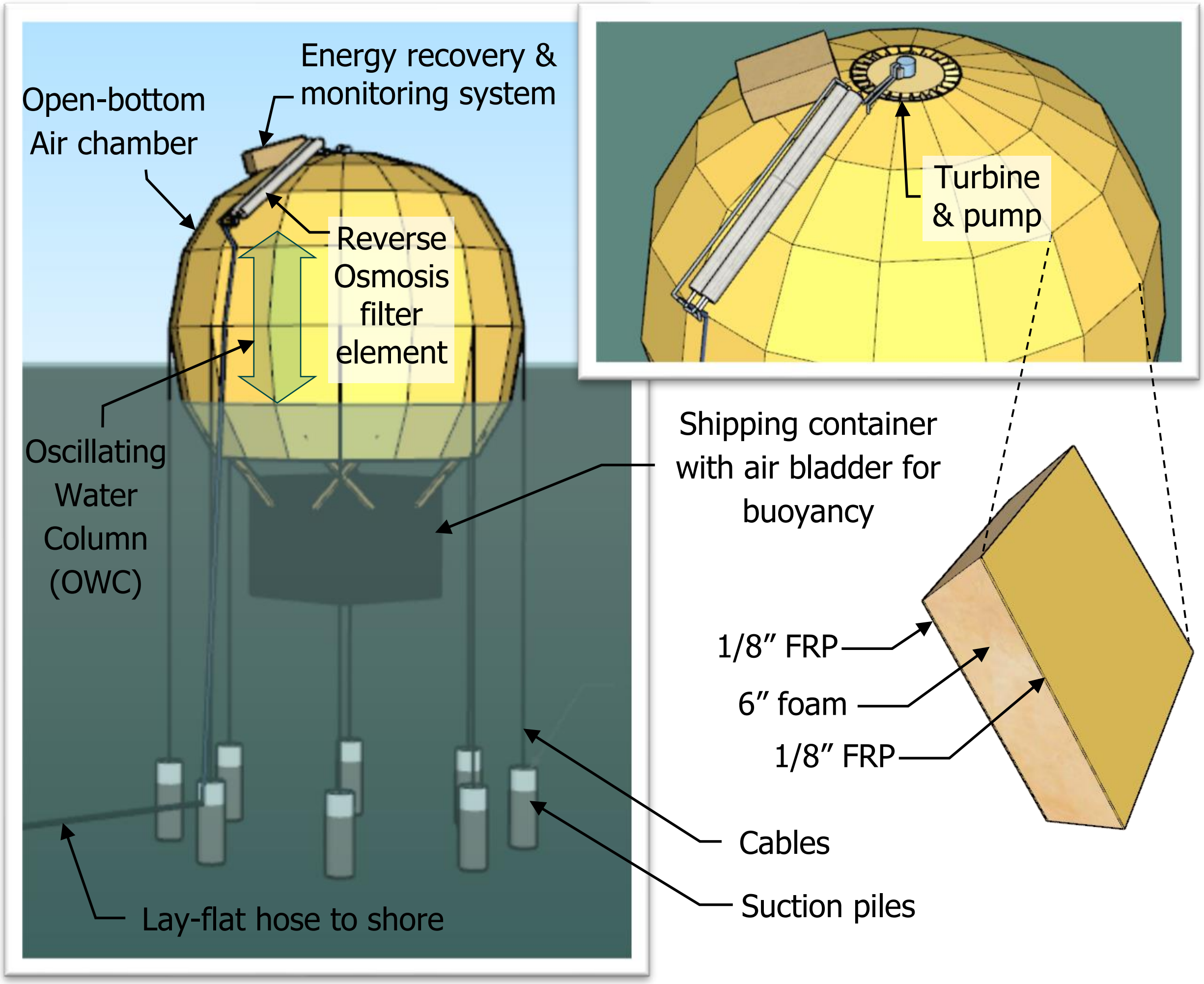

Figure 2. ROOWaC system overview.

The ROOWaC system uses wave energy from the up and down motion of the water inside the chamber – the "oscillating water column" (OWC) – to desalinate seawater with reverse osmosis (RO) membranes. The system meets the following Waves to Water Prize criteria:

- **Criteria 1: Innovation**—the system represents a novel solution that can deliver water during disaster relief and recovery, and in remote coastal communities.
- **Criteria 2: Technical Feasibility**—the solution is technically feasible.
- **Criteria 3: Scalability and Other Benefits**—the system has attributes that would be valuable for other applications beyond the prize.
- **Criteria 4: Plan**—a clear pathway is given to achieving the team's goals.

Some background on OWC and RO technologies is given below. The rest of this Technical Narrative is organized into sections based on the four criteria above.

0.2 Background on Desalination

The desalination method used by the ROOWaC is Reverse Osmosis (RO). A brief description of the method follows.

The various filtration technologies which currently exist can be categorized on the basis of the size of particles removed from a feed stream. Conventional macro-filtration of suspended solids is accomplished by passing a feed solution through the filter media in a perpendicular direction. The entire solution passes through the media, creating only one exit stream. Examples of such filtration devices include cartridge filters, bag filters, sand filters, and multimedia filters. Macro-filtration separation capabilities are generally limited to undissolved particles greater than 1 micron. This type of filtration will be used for pre-treatment of the intake seawater before the feed water passes through the pump.

For the removal of small particles and dissolved salts, crossflow membrane filtration is used. Crossflow membrane filtration uses a pressurized feed stream which flows parallel to the membrane surface. A portion of this stream passes through the membrane (permeate), leaving behind the rejected particles in the concentrated remainder of the stream (concentrate). Since there is a continuous flow across the membrane surface, the rejected particles do not accumulate but instead are swept away by the concentrate stream. The general categories of crossflow membrane filtration are microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, with reverse osmosis being the finest.[1]

The phenomenon of (forward) osmosis occurs when pure water flows from a dilute saline solution through a membrane into a more concentrated saline solution until the solution strength is equalized. If pure water and a saline solution are separated by a membrane that is permeable to water but not to salt, water will permeate through the membrane into the saline solution to dilute it. The resulting natural pressure difference is called osmotic pressure. If pressure in excess of the osmotic pressure is applied to saline solution, the direction of water flow through the membrane can be reversed. This process, called reverse osmosis (RO), can be used to produce a pure water from a saline solution and is the process that will be used in the ROOWaC Waves to Water system.

The RO membrane generally acts as a barrier to all dissolved salts and inorganic molecules, as well as organic molecules with a molecular weight greater than approximately 100. Water molecules, on the other hand, pass freely through the membrane creating a purified product stream. The system requires pressurization of the feed water in order to overcome osmotic pressures.

[1] FILMTEC™ RO Membranes Tech Manual www.scribd.com/doc/94868763/FILMTEC-Technical-Manual

A system schematic is shown in Figure 1. Specific details on the RO membrane used in the ROOWaC system are provided in Section 1.1.

0.3 Background on Wave Energy

> *"As a concept, the OWC is probably the most studied and the best developed of all [wave energy] systems. In shore-based operation, it has demonstrated the reliability necessary for a viable plant, and there is no reason to believe that this reliability cannot be transferred [offshore]."*[2]

The wave energy method used by the ROOWaC is an offshore configuration of an oscillating water column (OWC). An OWC consists of two main parts: a chamber that transfers power from the waves to the air within the chamber, and a power take off (PTO) system that converts the pneumatic power into mechanical rotational energy. Air within the chamber is pushed and pulled across the PTO system as the water column rises and falls, causing an air turbine to spin. The air turbine in the ROOWaC system is a Wells turbine, which has a symmetrical blade cross section so that the turbine is driven in the same rotational direction no matter the direction of the air flow across the turbine.

In a typical OWC, the turbine is coupled with a variable-speed electric generator, and costly power electronics are required to regulate the frequency of the electricity that is fed into the grid. For the ROOWaC system, the turbine will be directly coupled to a high-pressure water pump that can accommodate the varying rotational speeds.

The largest-scale wave energy device ever to be grid-connected in the United States uses an offshore OWC. It just arrived to its test site December 2019. Featuring a 500-kilowatt turbine designed by SGT, Ocean Energy's OWC buoy will undergo 12 months of open ocean, grid-connected testing at the Navy's Wave Energy Test Site (WETS).[3] The hull of this device is massive, weighing in at 826 tons, or about 3,300 pounds per kilowatt (kW). That's because it was designed as a free-floating duct buoy,[4] so it needs the weight to develop draft and provide stability. The innovations described in Section 1.2 will allow the ROOWaC system to weigh in at less than 550 pounds per kW.

The next section will describe the innovative features of the ROOWaC's reverse osmosis filtration system and oscillating water column wave energy system.

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[2] Heath, T. V. A review of oscillating water columns. *Phil. Trans. R. Soc. A* (2012) 370, 235–245.

[3] https://www.energy.gov/eere/water/articles/ocean-energy-buoy-ribbon-cutting-ceremony

[4] Kelly, J., et al. *Challenges and Lessons Learned in the Deployment of an Offshore Oscillating Water Column*. Hydraulics and Maritime Research Centre, University College Cork, Ireland. 2014.

1. Innovation

The main technologies proposed in this solution – oscillating water column (OWC) for wave energy and reverse osmosis (RO) for desalination – are mature technologies that have both been proven in commercial installations.[5,6] The two technologies have straightforward operating principles and well-documented design methodologies and are relatively simple to implement. By combining these two mature technologies, our team endeavors to build a system with a very low risk of functionality, due to the knowledge base available to use in the design and construction.

Our innovative solution for combining these two established technologies (OWC and RO) will be able to deliver water in disaster relief and recovery circumstances when electricity is not available and in remote coastal communities where electricity is either not available or is very expensive. One reason this solution is well-suited as a disaster relief system is that nearly all of the mechanical and electrical equipment and structural components are available off-the-shelf, so the system can be procured and shipped with a very short lead time. Another reason is that the system's innovative configuration is able to harness a relatively large amount of wave energy in a small and light package that will be easy to transport.

1.1 Reverse Osmosis (RO)

Seawater will be pressurized with a plunger pump, described in Section 1.3, to pressures of approximately 550 to 1,250 pounds per square inch (psi) in order to overcome osmotic pressures. The seawater will be pass through two stages of FILMTEC™ SW30-2540 RO membrane elements manufactured by DuPont.

1.1.1 RO MEMBRANE CHARACTERISTICS

The RO membrane is a thin-film composite consisting of three layers: a polyester support web, a microporous polysulfone interlayer, and an ultra-thin polyamide barrier layer on the top surface. The combination of the polyester web and the polysulfone layer has been optimized for high water permeability at high pressure. The barrier layer makes FILMTEC membranes highly resistant to mechanical stresses and chemical degradation. The membrane is packed in a spiral-wound configuration. A cross section of the membrane and the configuration is shown in Figure 3.

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[5] Heath, T. V. A review of oscillating water columns. *Phil. Trans. R. Soc. A* (2012) 370, 235–245.
[6] www.dupont.com/content/dam/dupont/amer/us/en/water-solutions/public/documents/en/45-D02217-en.pdf

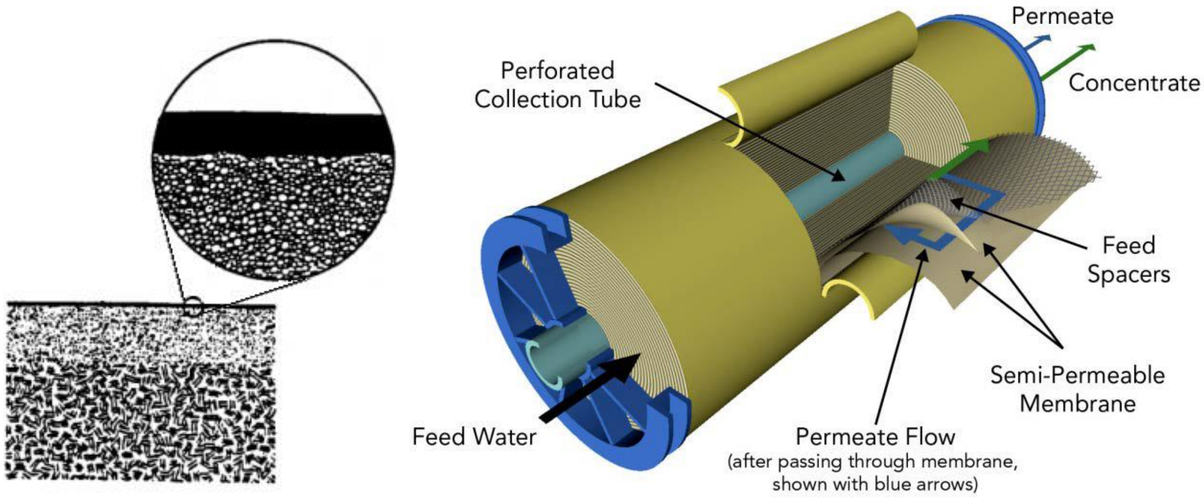

Figure 3. [left] R.O. membrane cross section[7]; [right] R.O. element configuration[8].

FilmTec™ Seawater RO membranes are produced with an automated fabrication process that ensures precision, consistency, and reliability. FilmTec™ SW30 membrane elements are ideal for use in small-sized seawater desalination systems. They have one of the highest flux rates available while maintaining excellent salt rejection and may also be operated at lower pressure to reduce pump size, cost, and operating expenses.[9]

Some RO systems are designed with internal concentrate recirculation to increase the recovery of the RO system, defined as the amount of permeate flow rate as a percentage of the feed water flow rate. Recirculation will not be included with this system, since the feed water available for this system is virtually unlimited and maximizing the recovery ratio is not necessary. The low recovery ratios also result in a design that is less susceptible to fouling, as described in the next section.

Details on the modeling of the RO system are included in the Modeling Documentation.

1.1.2 RO MEMBRANE RELIABILITY

The factor with the greatest influence on membrane system design is the fouling tendency of the feed water. Membrane fouling is caused by particles and colloidal material which are present in the feed water and are concentrated at the membrane surface. The concentration of the fouling materials at the membrane surface increases with increasing permeate flux (the permeate flow rate per unit membrane area) and increasing FILMTEC™ element

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[7] Image from FILMTEC™ RO Membranes Tech Manual www.scribd.com/doc/94868763/FILMTEC-Technical-Manual
[8] Image from Reverse Osmosis Optimization www.energy.gov/sites/prod/files/2013/10/f3/ro_optimization.pdf
[9] Product Data Sheet: FILMTEC™ Seawater RO Elements for Marine Systems www.dupont.com/content/dam/dupont/amer/us/en/water-solutions/public/documents/en/45-D01519-en.pdf

recovery. A system with high permeate flux rates is therefore likely to experience higher fouling rates and require more frequent chemical cleaning.[10]

A membrane system should be designed such that each element of the system operates within a frame of recommended operating conditions to minimize the fouling rate and to exclude mechanical damage. These element operating conditions are limited by the maximum recovery, the maximum permeate flow rate, the minimum concentrate flow rate and the maximum feed flow rate per element.

A continuous RO process designed according to the system design guidelines and with a well-designed and operated pretreatment system will show stable performance with no more than about four cleanings per year in standard applications and an expected membrane lifetime of more than three years.[11] Exceeding the recommended limits may result in more frequent cleanings, reduced capacity, increased feed pressure and reduced membrane life. A moderate violation of the limits for a short time – such as during the 5-day DRINK stage test – may be acceptable as long as the maximum pressures are not exceeded. However, considering the importance of reliable operation of the system in critical disaster relief scenarios, a conservative approach was taken in the design. The manufacturer's recommended guidelines,[12] based on their many years of experience with FILMTEC membranes, have been followed in order to ensure reliable, low-maintenance operation and a long membrane life.

Scaling is planned to be controlled by preventive membrane cleaning. This will allow the system to run continuously without chemical cleanings. The method of cleaning will consist of a forward flush at low pressure by opening the concentrate valve for approximately 30 seconds every 30 minutes. This valve will be controlled by the energy recovery battery described later.

DuPont has a long history of innovation in development and design of reverse osmosis membranes and has long focused its research and expertise on offering membranes with high permeability, high salt rejection and antifouling. Most recently, DuPont has developed the industry's first dry-test seawater reverse osmosis membrane element.[13] Dry elements offer significant advantages versus wet elements. Wet elements contain a preservation solution that needs to be checked after one year of storage, and may require eventual replacement. That would be a disadvantage for a system that is intended for use in disaster

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[10] FILMTEC™ RO Membranes Tech Manual www.scribd.com/doc/94868763/FILMTEC-Technical-Manual
[11] Ibid.
[12] Product Data Sheet: FILMTEC™ Seawater RO Elements for Marine Systems www.dupont.com/content/dam/dupont/amer/us/en/water-solutions/public/documents/en/45-D01519-en.pdf
[13] DuPont Dry Seawater Reverse Osmosis Elements www.dupont.com/content/dam/dupont/amer/us/en/water-solutions/public/documents/en/45-D01947-en.pdf

relief situations, where the system may be stored for long unknown periods of time before put into use.

1.2 Oscillating Water Column

The ROOWaC system uses the proven strategy of harnessing energy from an oscillating water column (OWC), with some significant innovations incorporated into the design.

The attraction of the OWC concept with an air turbine stems from its simplicity. The major advantages include:[14]

- there are very few moving parts and no submerged moving parts,
- the use of an air turbine eliminates the need for gearboxes,
- it is reliable and easy to maintain,
- it uses sea space efficiently.
- the concept is adaptable to an offshore system,

The following sections will describe the individual components that make up the ROOWaC's OWC wave energy system.

1.2.1 WELLS TURBINE

The Wells Turbine was named after Alan Arthur Wells, a professor of Queen's University Belfast who developed the turbine in the 1970s.[15] The airfoil shape chosen for the ROOWaC system is a NACA 0016.[16] The shape was chosen because it is in between the airfoil shapes that were used for the Wells turbines in two systems that the design was calibrated to.[17,18] The turbine was designed in SolidWorks so that it could be virtually tested for strength, and also so that the 3D drawing file could be provided to fabricators for quick turnaround using CNC (computer numerically controlled) fabrication. More details on the turbine are provided in the Modeling Documentation.

1.2.2 DOME STRUCTURE

A major innovation of the system is its anchoring method and structural aspects, borrowed from other engineering fields, that make it possible to keep the system within the size and weight requirements of the competition while maintaining a relatively large footprint for maximizing its power rating.

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[14] Heath, T. V. A review of oscillating water columns. *Phil. Trans. R. Soc. A* (2012) 370, 235–245.
[15] https://en.wikipedia.org/wiki/Alan_Arthur_Wells
[16] http://airfoiltools.com/airfoil/naca4digit
[17] *Islay LIMPET Wave Power Plant, 1 November 1998 to 30 April 2002*. Queen's University of Belfast.
[18] Takao, M. and Setoguchi, T. *Air Turbines for Wave Energy Conversion*. Intl J of Rotating Machinery, 2012.

The air chamber structure will be constructed from "sandwich" panels made up of fiberglass-reinforced polymer (FRP) and foam, which will be built on site using stock FRP panels and readily available, quick curing polyurethane spray foam. Sandwich panels are a relatively modern construction technology which increases a material's strength-to-weight ratio by moving material farther away from the cross-sectional neutral axis.

1.2.3 ANCHORING

The first offshore OWC devices have been under development by Ocean Energy, which use a free-floating system with mooring buoys.[19] This requires a large heavy structure relative to the power generation capacity in order to provide stability. The ROOWaC uses an innovative anchoring technique that was originally developed for offshore oil rigs. The system will be taut-moored using suction piles.

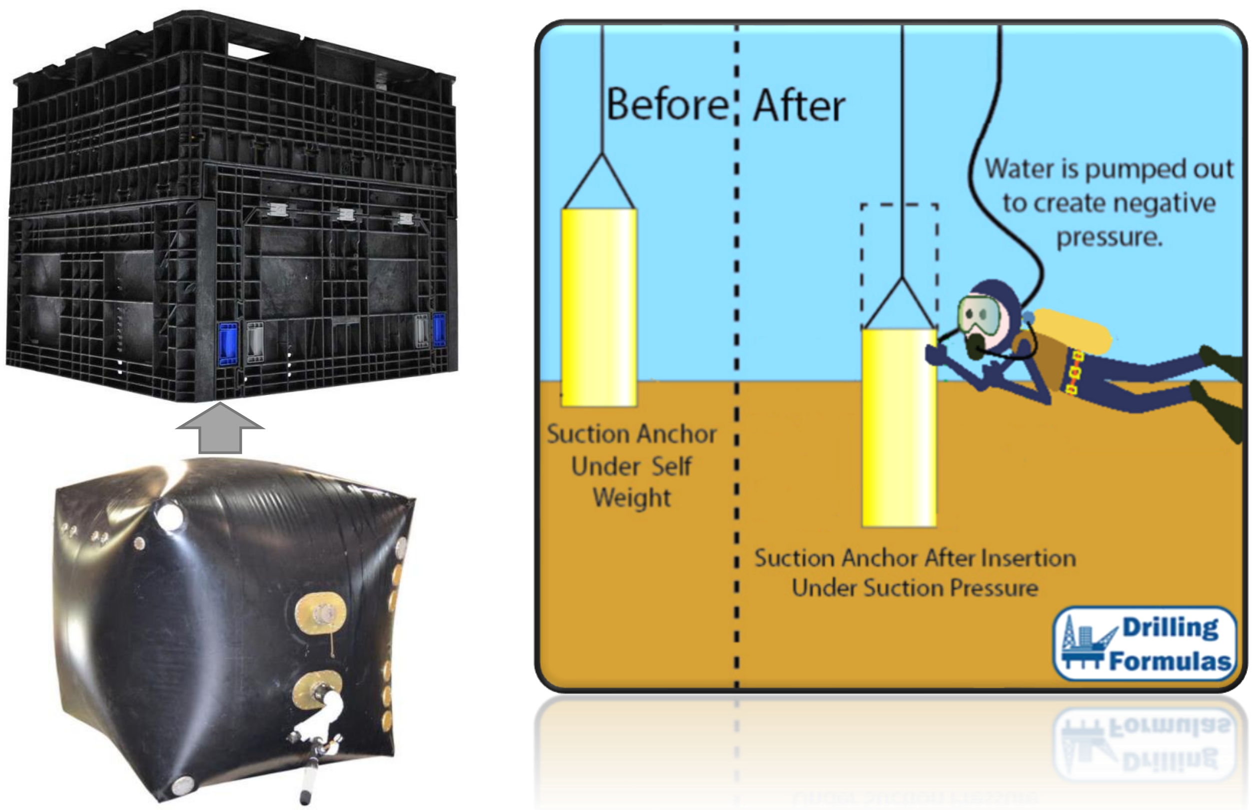

Figure 4. Taut-mooring system, consisting of [left] shipping container with air bladder used for buoyancy and [right] suction pile anchoring method.[20]

Taut mooring provides tension forces in excess of the buoyant forces so that the anchor lines are kept in tension. This sets the structure lower in the water than if it was free-floating,

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[19] Kelly, J., et al. *Challenges and Lessons Learned in the Deployment of an Offshore Oscillating Water Column*. Hydraulics and Maritime Research Centre, University College Cork, Ireland. 2014.

[20] Image adapted from http://www.drillingformulas.com/suction-anchor-calculation/

and provides necessary stability at a low shipping weight. It also prevents large dynamic loads that result when a slack anchor line gets pulled into tension.

Suction pile anchors (also called suction caissons) are a technology that was developed for offshore oil rig foundation installations. They utilize negative pressure to drive the suction anchors down into the ocean floor. Calculations following the example given at URL www.drillingformulas.com/suction-anchor-calculation/ show that eight 8-inch-diameter piles would only need to be embedded into the ocean floor less than 9 inches to anchor the structure with a safety factor of 2. Half of the piles will be 8-inch I.D. and half 8-inch O.D., so that the four smaller piles can fit inside the larger ones for shipping.

1.3 Mechanical/Electrical Equipment

After energy from the waves is harnessed with the OWC and the Wells turbine, the mechanical equipment will effectively transfer that the energy to the desalination system.

1.3.1 PLUNGER PUMP

This system uses a direct drive plunger pump manufactured by CAT Pumps, operating at the same rotational speed as the Wells turbine, to pressurize the seawater and convey it to the RO membranes. Plunger pumps are off-the-shelf items designed for high pressures. They are most widely used in pressure washers. The pump to be used in the ROOWaC has a built-in pressure regulation and relief valve, as shown in Figure 5, that will prevent pressure spikes that could be harmful to the RO system.

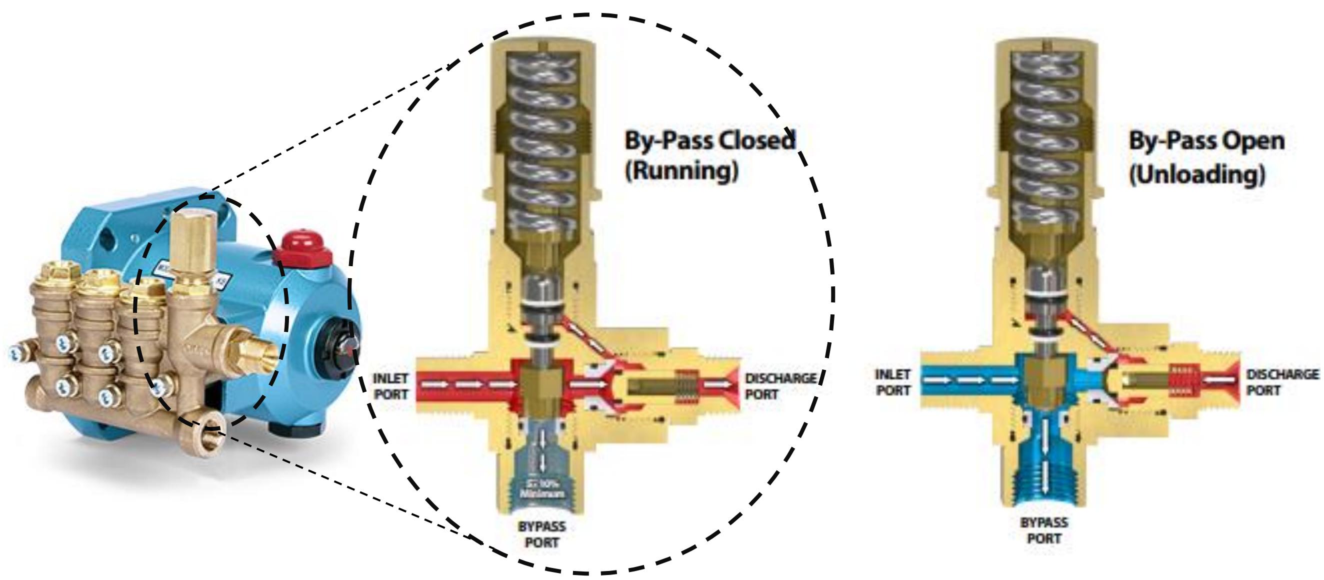


Figure 5. CAT Pumps plunger pump with built-in “unloader” pressure regulation & relief valve.[21]

[21] *High-Pressure System Design Guide*. CAT Pumps. 2019.

1.3.2 ENERGY RECOVERY

The system also includes an innovative energy recovery system that will recover energy from the high pressure concentrate discharge stream and use it to power a monitoring system. The monitoring system will be very helpful for optimizing the system parameters during the CREATE stage and also for troubleshooting during the DRINK stage. The system consists of what is likely to be one of the world's smallest Pelton wheel turbines, a standard car alternator, a 12V 240-Watt-hr lithium-ion battery, sensors, and a sensor hub. The energy recovery and monitoring system is shown in Figure 6 and is further described in Section 2.5.

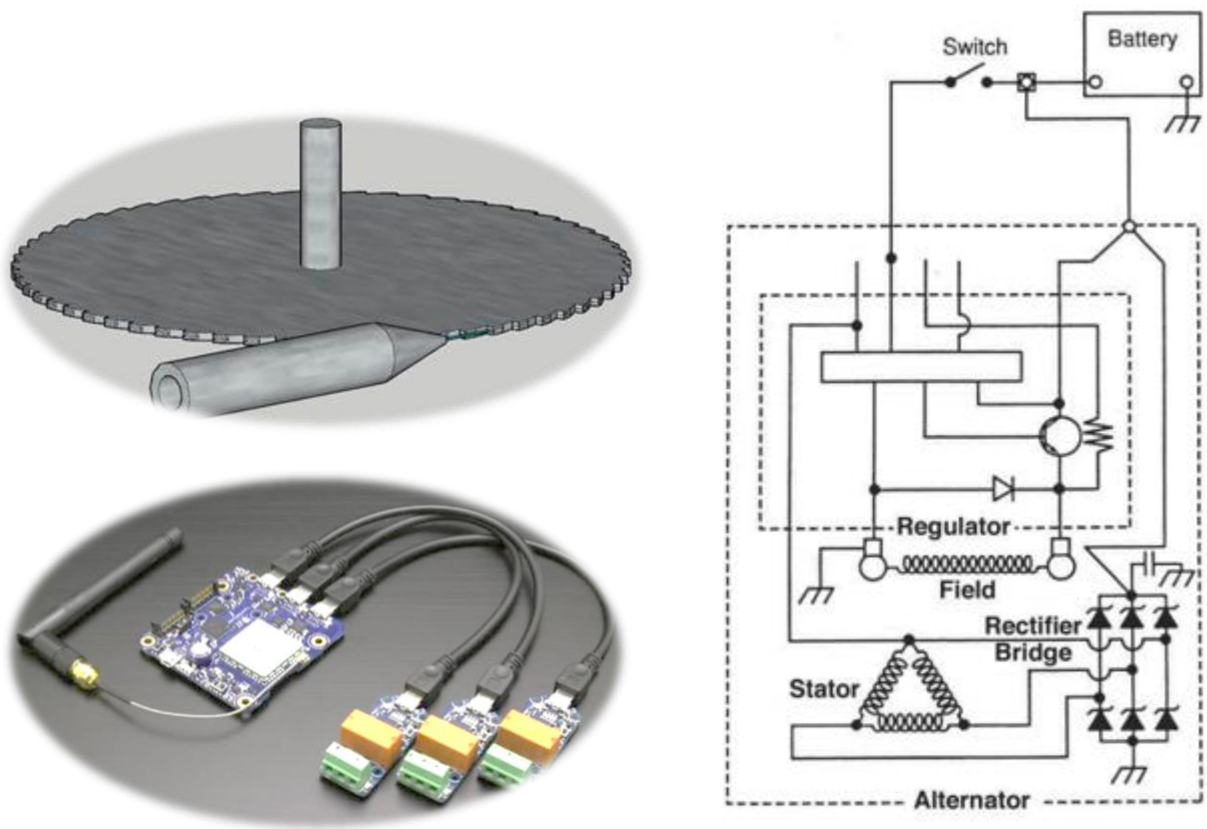


Figure 6. Energy recovery and monitoring system components; [top left] Pelton wheel with 153-mm (12-inch) wheel diameter, 60 buckets, and 1-mm (0.04-inch) jet diameter[22], [bottom left] 3G sensor hub[23], and [right] wiring schematic of a standard alternator circuit[24]

[22] Designed using the equations on page 718 of Fundamentals of Fluid Mechanics, 5th Edition, 2006.

[23] https://shop.valarm.net/collections/valarm-compatible-connector-hardware

[24] Bradfield, M. High Efficiency Alternators White Paper, Delco Remy, 2008. Accessed online at http://www.delcoremy.com/documents/high-efficiency-white-paper.aspx

2. Technical Feasibility

The ROOWaC system has been designed with both technical and economical feasibilities in mind. The materials and method of construction are such that the system can be built within the timeline and anticipated award amounts of the Competition. The technical characteristics established for the system during the DESIGN stage are summarized below and explained in the following sections.

- Estimated average water quality of 543 mg/L total dissolved solids (TDS)
- Approximately 2,900 liters of produced water volume over the 5-day test period
- Approximate shipping weight of 641 kg
- Less than 16 hours of active setup time (plus overnight curing of structural foam)
- 0.24 kWh of battery storage included for monitoring system, charged by the energy recovery system Pelton wheel and alternator
- All energy for desalinating water comes from wave energy.

The modeling methodologies and findings that support the first two characteristics are laid out in the Modeling Documentation.

2.1 Water Quality

The Modeling Documentation shows that our total dissolved solids (TDS) is expected to be well below the 1,000 mg/L maximum criteria for the competition, at an overall salinity of approximately 543 mg/L. This is within the 300 to 600 mg/L target level TDS listed in Appendix 2 of the Waves to Water Prize Official Rules and is very close to the 500 mg/L TDS level recommended by the U.S. Environmental Protection Agency (EPA) in their non-enforceable secondary drinking water standards.[25]

Regarding brine discharge, the system will produce an average concentrate TDS level of approximately 53,400 mg/L; about 53% higher concentration than the source seawater. This is deemed to be acceptable, considering the immediate dilution that will take place, and considering that the EPA does not even provide a recommended level of chloride in saltwater in their National Recommended Aquatic Life Criteria table.[26]

2.2 Produced Volume

As presented in the Modeling Documentation, the produced volume of purified water expected from the ROOWaC system during the 5-day test period for the given wave

[25] https://www.epa.gov/sites/production/files/2016-06/documents/npwdr_complete_table.pdf
[26] https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table

conditions is approximately 2,900 liters – over seven times the minimum criteria for the competition. The main reason we are able to accomplish this high of a produced water volume is that the rotational speeds of the turbine match very well with the rated rotational speeds of highly efficient off-the-shelf plunger pumps used in pressure washers and small desalination systems that are operated by gas or electric motors.

2.3 Shipping Weight

The shipping weight is the limiting factor for the power capacity of this system. The system was sized to achieve the maximum footprint (and thus power capacity) possible while meeting the shipping weight restriction. The estimated weight is 641 kg including the weight of the shipping container. The breakdown of the weights, and also lead times and material costs for the various components, are listed below.

Item	Weight (kg)	Supplier	Lead Time	Cost of materials
DuraGreen DGR454842 container	80	BulkContainer Express	in stock	$ 319
Suction piles (8"Φ FRP pipe)	40	FRP Supply	4-6 weeks	$ 729
Anchor cables	18	Home Depot	in stock	$ 100
300-gal air bladder	25	Ready Containment	4-6 weeks	$ 700
FRP structure	327	Strongwell	2 weeks	$ 2,351
Polyurethane spray foam	40	Home Depot	in stock	$ 770
Stainless steel turbine runner	14	Xometry	2 weeks	$ 2,117
CAT 4DX10ER plunger pump	5	Mist Works	2 weeks	$ 845
CAT surge tank	18	Mist Works	2 weeks	$ 200
Plumbing tubing and fittings	23	Home Depot	in stock	$ 100
RO element and housing	8	American RO	in stock	$ 1,290
Layflat hose, 3/4"x1000 feet	36	PlastiX	in stock	$ 381
Energy recovery/monitoring system	9	Custom built	4-6 weeks	$ 500
Total estimated weight	**641**	**kg**	Est. Total:	$ 10,402

Figure 7. Table of ROOWaC system component weights, lead times, and materials cost.

Figure 8 shows how the system will be packaged. As can be seen, there is ample space available for some miscellaneous tools, tarps, etc. that could help with the setup of the system, as long as the system weight limit can still be met with any additions.

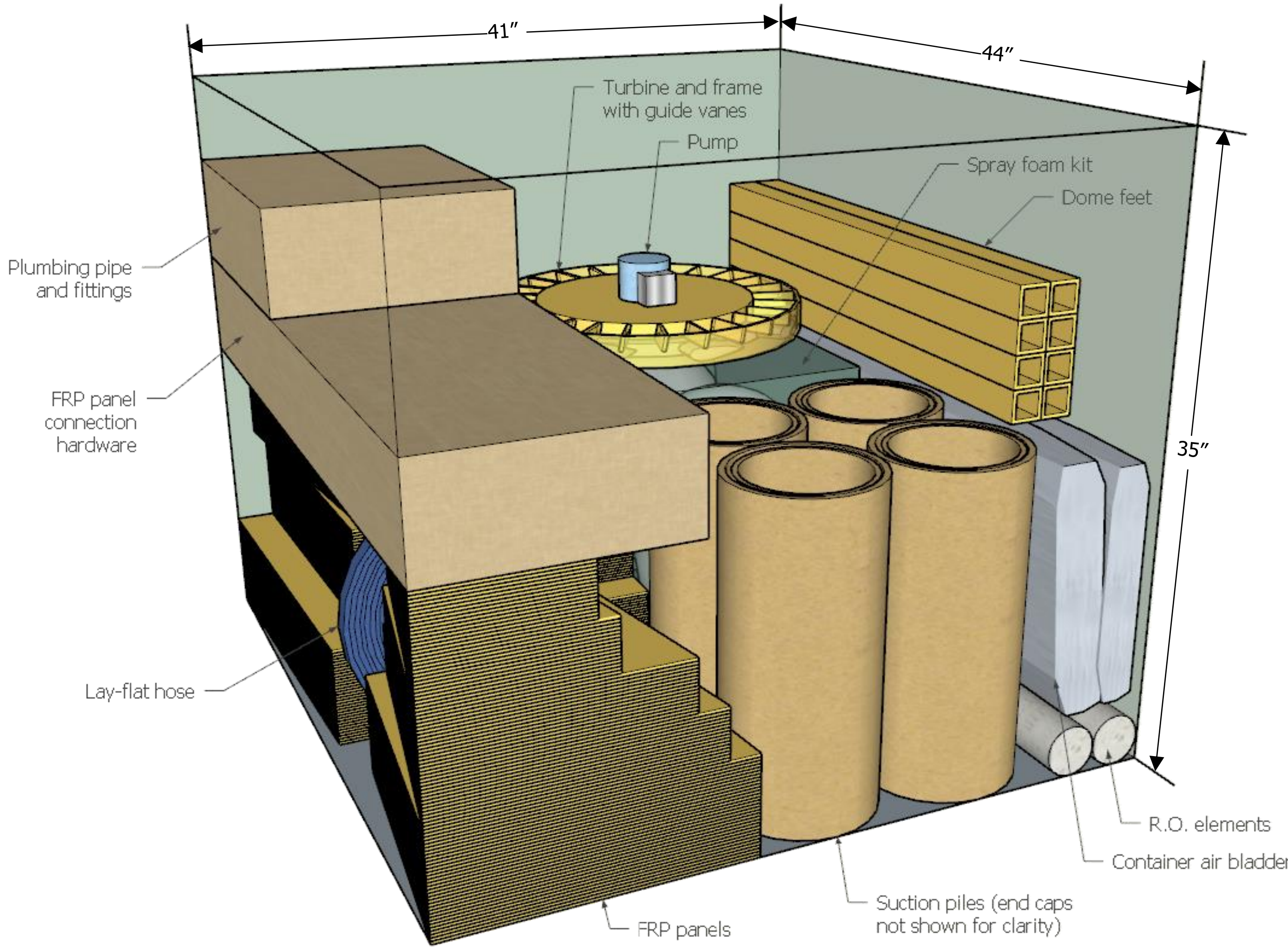


Figure 8. Packaging of the system into the standard shipping container.

2.4 Forty-eight-hour Setup

As shown in Figure 9, we anticipate being able to setup and deploy the system in two 8-hour days, with one overnight period for the structural foam to cure, resulting in a total setup and deployment time of 32 to 48 hours depending on the time of day that the setup is initiated. The dome will be put together the first day and the structural foam allowed to cure overnight. The pump/turbine, R.O. system, and energy recovery & monitoring system will be mounted to the structure the next day onshore. Thanks to the low-density structural foam, the overall system will be less dense than water, and can be towed with kayaks, small boats, or even swimmers out to the intended operating location. The container will be weighted down with sand bags to right the structure and keep it upright while the suction piles are installed and connected. The container bladder will then be slowly filled with air using a hand pump, and the cables will be lengthened incrementally with the help of ratchet straps until the structure sits at the desired elevation. Labor-hours are provided in Figure 9.

Task	Labor hours	Amount	Unit	Total labor hrs	Reference
DAY 1					
Construct outer dome	0.02	64	SF Flr.	1.3	RSMeans 13 34 23.15
Self-drilling screws	0.03	320	ea	9.6	Wells Eng. Estimate
1/4" bolts	0.08	80	ea	6.4	BNi Costbook 06050.10
Polyurethane foam	0.05	215	SF	10.8	Bni Costbook 07210.70
Construct inner dome	0.02	51	SF Flr.	1.0	RSMeans 13 34 23.15
Self-drilling screws	0.03	320	ea	9.6	Wells Eng. Estimate
				38.7	labor-hours
				5	-person crew
				7.7	**hours**
DAY 2					
Tow dome & float offshore	5	0.3	km	1.5	Wells Eng. Estimate
Install turbine, RO, & R/M box	3	1	LS	3.0	Wells Eng. Estimate
Plumbing	0.12	12	LF	1.4	RSMeans 22 11 13.44
Suction piles & cables	2.5	8	ea	20.0	Wells Eng. Estimate
Lay-flat hose	0.03	300	m	9.0	Wells Eng. Estimate
				34.9	labor-hours
				5	-person crew
				7.0	**hours**

Figure 9. Table of estimated time to set up and deploy the ROOWaC system once on site.

2.5 Storage Capabilities

The system uses mechanical energy, captured from an oscillating water column by a Wells turbine, to directly operate a high-pressure plunger pump. Battery storage is provided only for operation of the monitoring system. The battery charge will be maintained by the energy recovery system depicted in Figure 6. The system includes a miniature Pelton wheel and a standard car alternator. A standard car alternator is well-suited for this application, because it can be operated as varying speeds and has a built-in voltage regulator and rectifier to maintain proper battery charging voltage and to convert the alternator's AC electricity to DC.

The battery will provide energy to a 3G sensor hub that will collect data from several sensors and send it over standard cellular networks to the cloud. The sensor hub will be purchased through valarm.net and includes a one-year subscription to their cloud services[27], so we will be able to monitor the system in real time from any device with an internet connection during the CREATE stage and DRINK stage testing. Sensors anticipated to be used include

[27] https://shop.valarm.net/collections/valarm-compatible-connector-hardware/products/gsm-3g-sensor-hub-for-industrial-iot

wave surface level, pump discharge pressure, pump temperature, surge tank pressure, concentrate discharge pressure, and permeate discharge pressure.

2.6 Other Energy Sources

All energy for desalinating water comes from wave energy, including the monitoring system, which will use energy recovered from the R.O. system concentrate discharge stream.

3. Scalability and Other Benefits

The innovative lightweight taut-mooring design will ensure that the system can survive harsh wave conditions, since the anchors will always be in tension and are not subject to large sudden dynamic loadings. The system can operate under different wave conditions and different sites without major tuning to ensure operation at a wide variety of locations. The turbine and pump have been sized to be able to handle the maximum rpms that can be reasonably produced by the volume of air inside the structure. Once all of the air is expelled from the system, the turbine will become submerged and there is therefore no risk of overspeed. The energy recovery and monitoring system will be contained in a waterproof enclosure and all of the other components will be of materials that can be submerged.

3.1 Fishing piers

Fishing piers like the one in Tybee Island, Georgia often provide fish-cleaning stations with purified water. The ROOWaC could be incorporated into such existing structures without the need for its own anchoring and buoyant support, to provide an economic source of purified water right where it is needed.

3.2 Exotic vacation destinations

Some travelers prefer beachfront vacation destinations that are remote, secluded, and rustic, where electricity is unavailable and solar panels or diesel generator sets are unpractical or undesirable. The ROOWaC could be easily transported to such destinations to provide drinking water to both locals and tourists.

4. Plan

We plan to build a full-scale, fully functional prototype during the CREATE stage. The only difference between the CREATE stage system and the DRINK stage system will be the materials used for the dome and the suction piles. The dome panels and the suction piles for the DRINK stage will be made out of FRP, in order to meet the shipping weight requirements. For the CREATE stage, the dome panels will be made of marine plywood, and the suction piles will be made from steel pipe. This will allow us to save on materials cost and have shorter lead times during the CREATE stage. The thicknesses used in the CREATE stage will be selected so as to provide the same strength as the FRP materials that will be used in the DRINK stage.

As shown in Figure 10, we anticipate being able to have the prototype ready within about 90 days after the DESIGN stage prizes are awarded. This leaves 60 days of float and gives us plenty of time to test and refine the system.

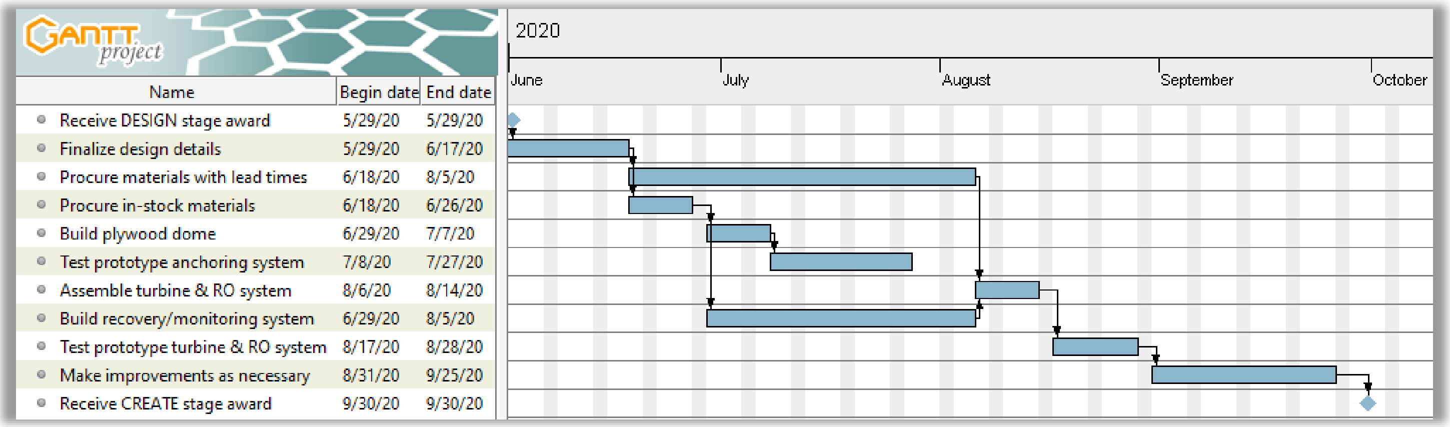


Figure 10. Gantt chart of plan for full-scale prototype construction.

5. Our Team

Wells Engineering, LLC has assembled a strong team of several specialists and undergraduate students in order to ensure that our team will have the ability and capacity to meet the time requirements of the competition.

Key Team Members

Jeremy Wells, PE is a professional engineer specializing in small hydropower. He has a bachelor's degree in engineering and 11 years of experience in engineering design and analysis in the field of water resources. He loves to explore technologies that are being developed in other fields and how those technologies can be leveraged in his own problem-solving. He has provided pro bono consulting on humanitarian water resources projects in Mexico and Ethiopia.

Jeff McNamara is a water treatment expert with over 25 years of experience in the fabrication and implementation of specialized water treatment systems, including reverse osmosis systems and advanced oxidation systems. He has provided water treatment systems for residential, commercial, and industrial customers. He has worked on humanitarian water treatment projects in Africa and the Middle East.

Supporting Team Members

Jonathan Wells provides 3D drafting services to Wells Engineering, LLC and is also a certified SCUBA diver. He will be installing the suction piles for the system testing.

Steve Barker works for Delta Flight Products fabricating and assembling lightweight aerospace components. He will be providing technical input to the fabrication and assembly details for the FRP structure.

Mahalia Butler is a mechanical engineering student at Kennesaw State University. She will be assisting with the deployment and testing of the system.

Jesse Schloesser is a mechanical engineering student at Kennesaw State University. He has co-op experience working for the energy department at Pond & Company. He will be assisting with the deployment and testing of the system.

Shaw Jenkins is an electronics technician and a student at Middle Georgia State University. He will be assisting with the energy recovery and monitoring system.

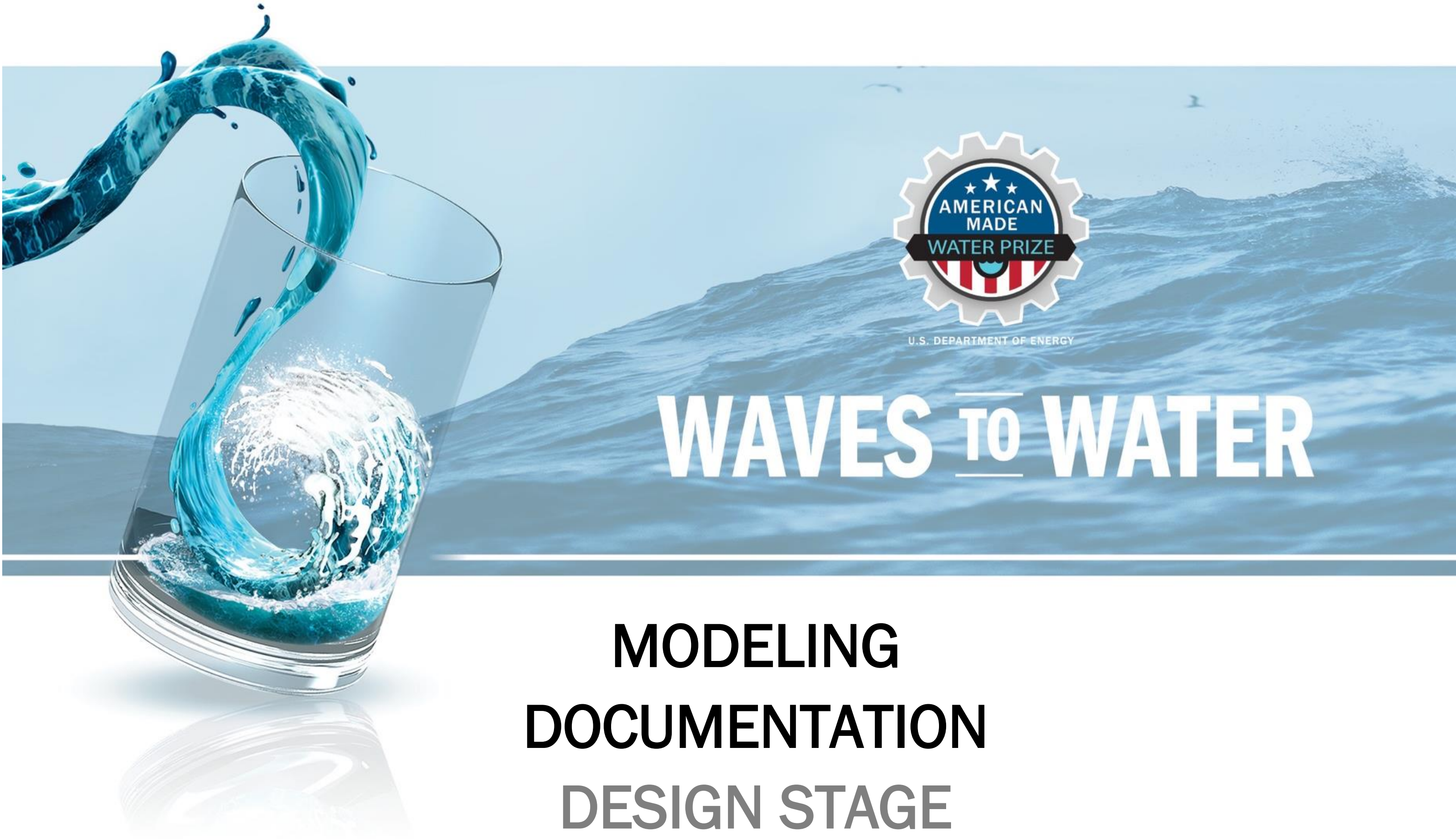
Max Milby is an electronics technician and college student. He will be assisting with the energy recovery and monitoring system.

6. Conclusion

The name ROOWaC comes from the Hebrew word “ru’akh”, meaning breath. The process of air being pushed and pulled across the turbine by the oscillating water column resembles the breathing process of inhaling and exhaling. The Hebrew Bible refers to the “breath of life” that is in all living creatures. The “breath” of the ROOWaC will help to sustain that life, by providing pure water to thirsty people. This innovation by the Wells Engineering, LLC team and our plan to materialize it should be strongly considered for a DESIGN Stage prize.

7. Supplementary Information

TECHNICAL NARRATIVE WORD COUNT: **4,997 TOTAL WORDS**



MODELING DOCUMENTATION

DESIGN STAGE

The ROOWaC Desalinator

By Wells Engineering, LLC

(Reverse Osmosis powered by an Oscillating Water Column)

Team

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Jesse Schloesser | Mechanical Eng. Student | Macon, Georgia, USA

Shaw Jenkins | Electrical Technician | Macon, Georgia, USA

Max Milby | Electrical Technician | Cordele, Georgia, USA

0. Introduction

The ROOWaC system is a desalination system that uses wave energy from an oscillating water column (OWC) to desalinate seawater by forcing it through reverse osmosis (RO) membranes. These two technologies and how they are integrated in the ROOWaC system are described in the Technical Narrative. The purpose of this Modeling Documentation is to describe the modeling methodologies and findings that underpin the characteristics and capacities of the system.[1]

The Prize criteria require that the system be able to produce at least 400 liters of water over the 5-day testing period at a maximum average TDS level of 1,000 mg/L. The shipping weight must be less than 650 kilograms, and the system must take under 48 hours to set up. No more than 500 watt-hours of battery storage can be included, and all energy for desalinating water must come from wave energy. The wave conditions assumed in the modeling are listed in the table below from the Waves to Water Prize Official Rules:

Wave Conditions Table

Sea State	Significant Wave Height [m][2]	Energy Period [sec]	Time for Each Wave Condition [hours] [%]
W1	0.5	6	26.4 (22%)
W2	0.5	10	6 (5%)
W3	1.0	6	33.6 (28%)
W4	1.5	7	26.4 (22%)
W5	2.0	7	26.4 (22%)
W6	3.0	7	1.2 (1%)

The following required **Water Production Results Table** and **Wave Energy Converter Modeling Results Table** summarize the capacities of the system for the given anticipated wave conditions. It is clear from these results that the system is able to meet the technical requirements of the Prize. The subsequent sections of this document will give the details of the modeling methods and assumptions that led to these results. This document will also detail the structural analyses performed to ensure that a sufficiently strong and light structure can be built to the physical dimensions necessary to produce these results.

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[1] Modeling has been defined in the prize rules as any effort to analyze or simulate an intended design by delivering quantified results that are accurate and reasonable.
[2] The significant wave height is the average height of the highest one-third of all waves measured.

Water Production Results Table

Sea State	Avg Intake Rates [L/min]	Avg Desalinated Water Production [L/min]	Avg Desalinated Water Salinity [mg/L]	Avg Brine Discharge Rates [L/min]	Avg Brine Discharge Salinity [mg/L]	Total 5-Day Production [L]	Total 5-Day Salinity of Desalinated Water [mg/L]
W1	0.00	0.00	-	0.00	-	2,897	543
W2	0.00	0.00	-	0.00	-		
W3	0.92	0.28	653	0.64	50,242		
W4	1.49	0.54	550	0.95	54,619		
W5	2.28	0.87	499	1.42	56,068		
W6	3.32	1.33	460	1.99	58,132		

Wave Energy Converter Modeling Results Table

Sea State	Avg Absorbed Power [Watts][3]	Peak Absorbed Power [Watts][4]	Peak Mooring and/or Foundation Loads [N][5]
W1	0	0	3,700
W2	0	0	3,700
W3	156	1,960	3,700
W4	312	2,580	3,700
W5	501	2,580	3,700
W6	783	2,580	3,700

[3] The average mechanical power that is being captured by the wave energy system and translated into mechanical work, for the defined sea state, prior to integration with the desalination system.
[4] The instantaneous peak absorbed power for the defined sea state prior to integration with the desalination system.
[5] The instantaneous peak forces or reaction loads associated with mooring lines, anchor systems, or foundation systems.

1. Modeling Methods and Assumptions

The total water production was estimated for a 5-day test period using the distribution of wave conditions listed previously in the Wave Conditions Table. The following steps were taken to arrive at a calculated total water production:

1) A time-domain model was developed in Microsoft Excel to model wave heights and periods at time steps of one second or less for a duration of 2,000 seconds for each of the six wave conditions.
   a) A Bretschneider spectrum was assumed for determining the distribution of waves in each wave condition. The spectrum is defined as:

   $$S(\omega) = \frac{5}{16}\frac{\omega_m^4}{\omega^5}H_s^2 e^{-5\omega_m^4/4\omega^4}$$

   where ω is the wave frequency in radians per second, ω_m is the most likely frequency of any given wave, and H_s is the significant wave height in meters. Here, significant wave height means the average height of the highest one-third of all waves. The spectrum plot is shown in Figure 1.
   b) A Rayleigh probability distribution was used to determine the percentage of time that a certain wave height will occur in all the waves of that series.[6]
   c) A series of waves was developed for each wave condition based on the Rayleigh probability distributions using Excel's "random" function. A sufficient number of waves was used from the series to make up a 2,000-second model duration for each condition to ensure the statistical average and peak values were adequately captured. Samples from these 2,000-second data sets are provided in Figure 2.
2) Pneumatic power was calculated for each time step.
   a) The Wells turbine sizing was completed by using a hub ratio, open area, and blade cross section that are in between those for two OWC plants for which measured power output data were available; LIMPET[7] and Niigata-Nishi.[8] The outer diameter was sized to optimize the air velocities and RPMs for the average wave height and period of each wave condition. See Figure 6.
   b) The wave surface elevations and physical dimensions of the air chamber were used to calculate the volume of air displaced at each time step in the wave series for each wave condition. See Figure 3(a).
   c) The air flow rate and the turbine dimensions were used to calculate the air velocity at the turbine for each time step. The standard wind turbine equation below was used to estimate the mechanical power in kilowatts that could be transferred from the air turbine to the pump based on the calculated air velocities. See Figure 3(b).

[6] Michel, W. *Sea Spectra Simplified*. Marine Technology, January 1968, page 28.
[7] *Islay LIMPET Wave Power Plant, 1 November 1998 to 30 April 2002*. Queen's University of Belfast.
[8] Takao, M. and Setoguchi, T. *Air Turbines for Wave Energy Conversion*. Intl J of Rotating Machinery, 2012.

$$P = kC_p \frac{1}{2} \rho A V^3$$

where k is a constant for unit conversion equal to 0.000133, C_p is a power coefficient indicating efficiency, ρ is the density of air in pounds per cubic foot, A is the rotor sweep area in square feet, and V is the air speed in miles per hour. [9] C_p values were estimated for the Niigata-Nishi ($C_p \approx 0.25$) and LIMPET ($C_p \approx 0.45$) plants, and the two were averaged for a C_p value of 0.35 for the ROOWaC turbine.

3) The pump flow rate was calculated for each time step.
   a) A flow coefficient (ratio of air speed to turbine blade tip speed) of 0.24, based on the estimated flow coefficients for the LIMPET and Niigata-Nishi plants previously mentioned, was used to determine the RPMs of the turbine. See Figure 3(b).
   b) Since the turbine and pump are directly connected, and since the pump is a positive displacement pump (meaning that it pumps a fixed volume of water per revolution), the RPMs can be used to directly calculate the flow rate. The flow rate was calculated in this way at each time step using the following relationship:[10]

$$\frac{\text{Rated gpm}}{\text{Rated rpm}} = \frac{\text{"Desired" gpm}}{\text{"Desired" rpm}}$$

   c) The pressure was calculated from the power and flow based on the pump manufacturer's formula.[11] It was determined that the formula corresponds to a pump efficiency of approximately 85%. See Figure 3(c).
   d) All data points below a pressure of 550 psi were assigned a flow of zero to account for the pressure regulating valve, which will help maintain the desired water quality.
   e) The pump RPM was capped at a maximum of 5750 to account for turbine "stall" that was reported as having occurred at the LIMPET plant.[12]
   f) Flows at pressures greater than 1,200 psi will be stored in the surge tank to prevent damage to the R.O. elements. The surge tank will be piped with pressure regulating valves to act as an accumulator, so that those flows will be passed on to the R.O. elements when pressures from the pump drop back down below 1,200 psi.
   g) The pump has a pressure rating of 2,000 psi. The flows were capped accordingly to account for the pressure relief valve at the pump, which will be set at 2,000 psi.
4) The permeate (purified water) flow rate and TDS level was determined at each time step.
   a) Several points along the pump curve (flow vs. pressure) were entered into WAVE software[13] to develop a curve of recovery rates (amount of permeate as a percentage of feed rate) and TDS levels for the R.O. elements. See Figures 3(d), 4, and 5.
   b) Friction losses published by the pump manufacturer were included for an equivalent length of 50 feet of ¼" pipe. This conservatively accounts for valves and fittings

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[9] www.windpowerengineering.com/construction/calculate-wind-power-output/
[10] https://www.catpumps.com/sites/default/files/products/pdfs/4DX10ER_E.pdf
[11] Ibid.
[12] *Islay LIMPET Wave Power Plant, 1 November 1998 to 30 April 2002*. Queen's University of Belfast.
[13] 2019 by DuPont de Nemours Inc. Version 1.72.724, Calc Engine Version 01.11.05, Database Version 14.5.

within the piping system.[14] The R.O. elements were modeled with a back pressure sufficient to deliver the purified water to shore through 1,000 feet of ¾" layflat hose, again referring to the manufacturer's published tables for friction losses.[15]

5) Weighted averages were calculated from the 2,000-second models using the specified "Time for Each Wave Condition [hours] [%]". Those values were converted to the appropriate units and entered into the Water Production Results Table and Wave Energy Converter Modeling Results Table.

Key assumptions made in the modeling include:

- Wave conditions given in the Prize Official Rules were assumed.
- A water depth of 5 meters was assumed.
- Seawater salinity was assumed to be 35,000 mg/L sodium chloride.
- A pump efficiency of 85% was assumed as previously explained.
- Friction losses in the piping, valves, and fittings came from manufacturer's tables.[16]
- An intake filter will be provided to filter out suspended solids upstream of the pump. A 1-psi loss was included to account for minimal clogging. This filter will be over-sized to ensure reliable operation and minimize the need for frequent cleanings. The pressure loss is expected to be negligible when the filter is clean.

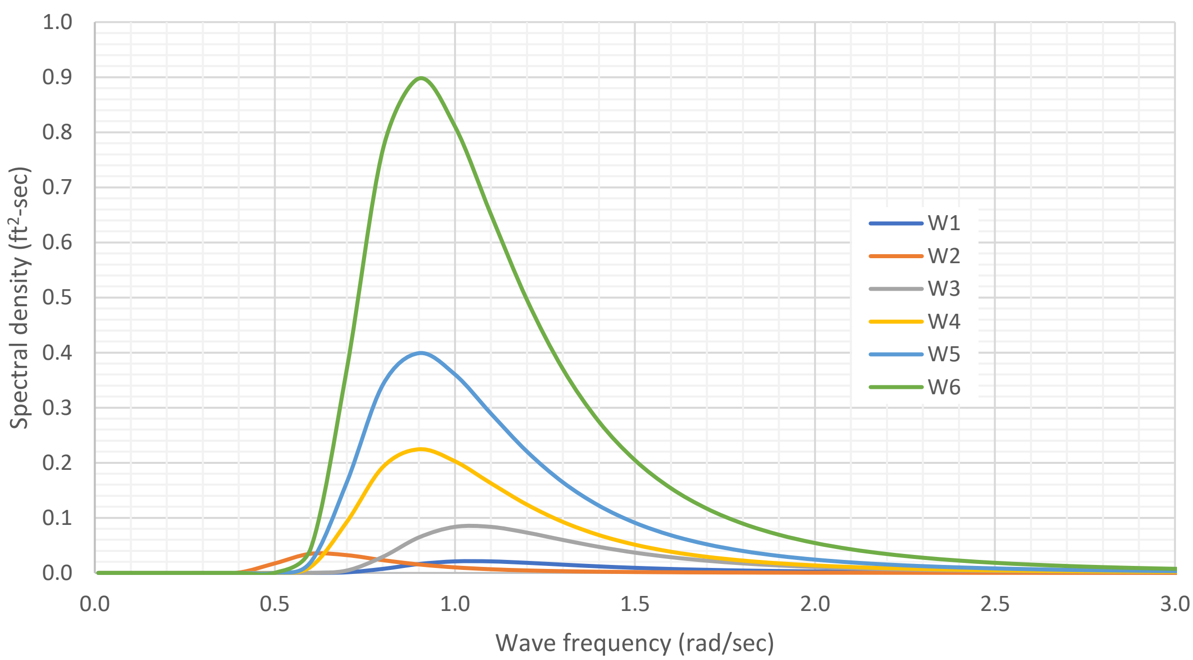


Figure 1. Bretschneider spectrum.

[14] *High-Pressure System Design Guide*. CAT Pumps. 2019.
[15] Ibid.
[16] Ibid.

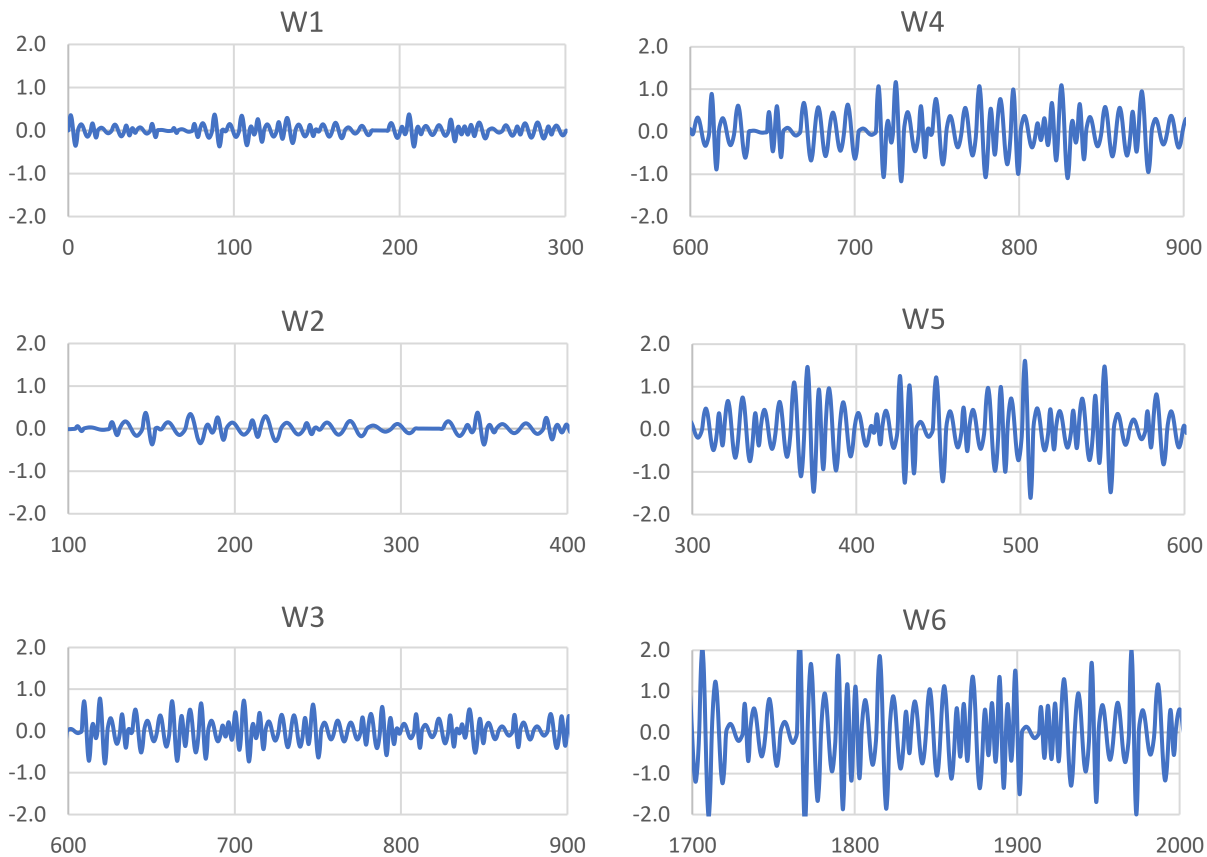


Figure 2. Samples from the modeled sea state data. X-axes are time in sec and y-axes are wave height in m.

2. Modeling Details

The plots below show the key relationships used in the modeling.

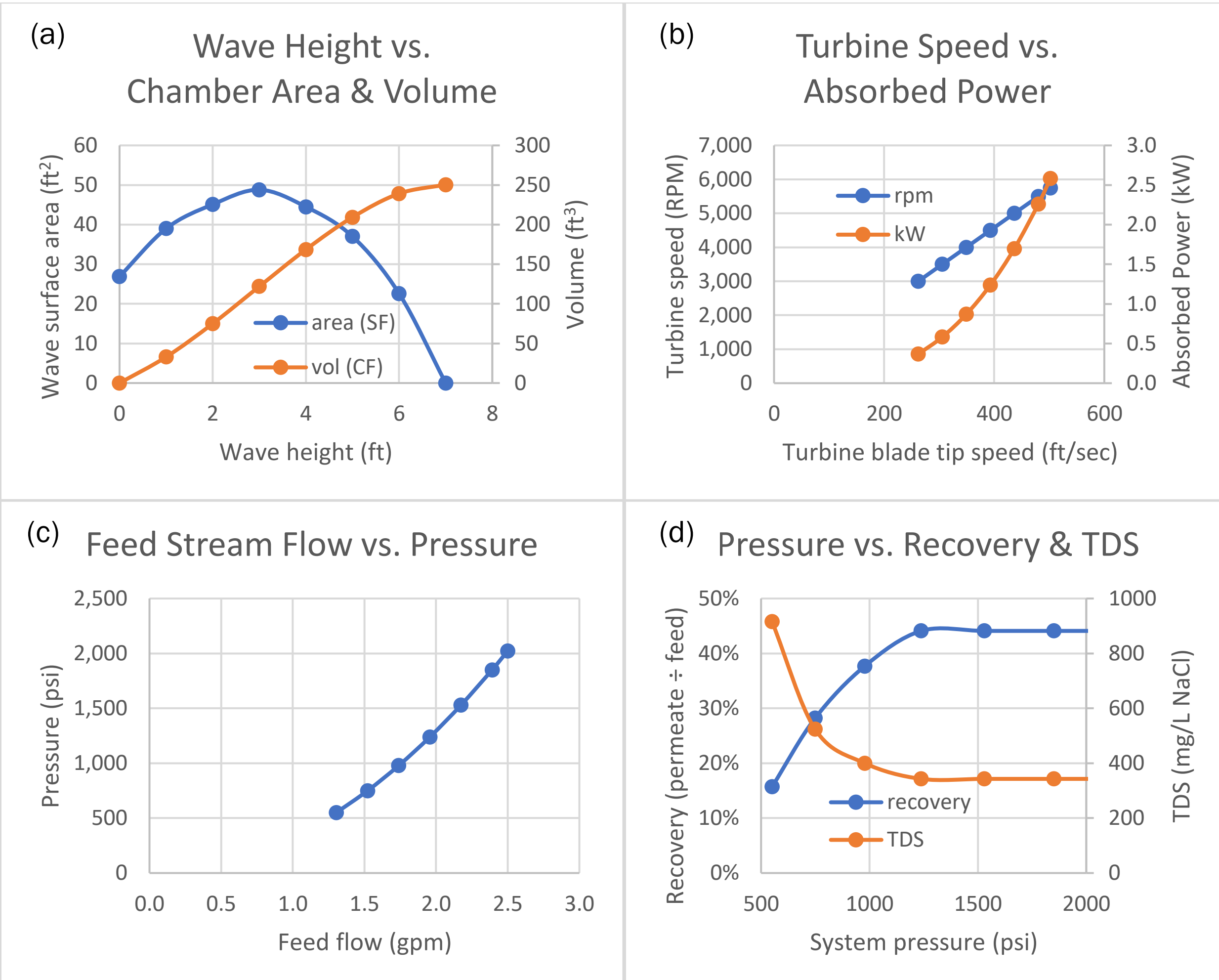
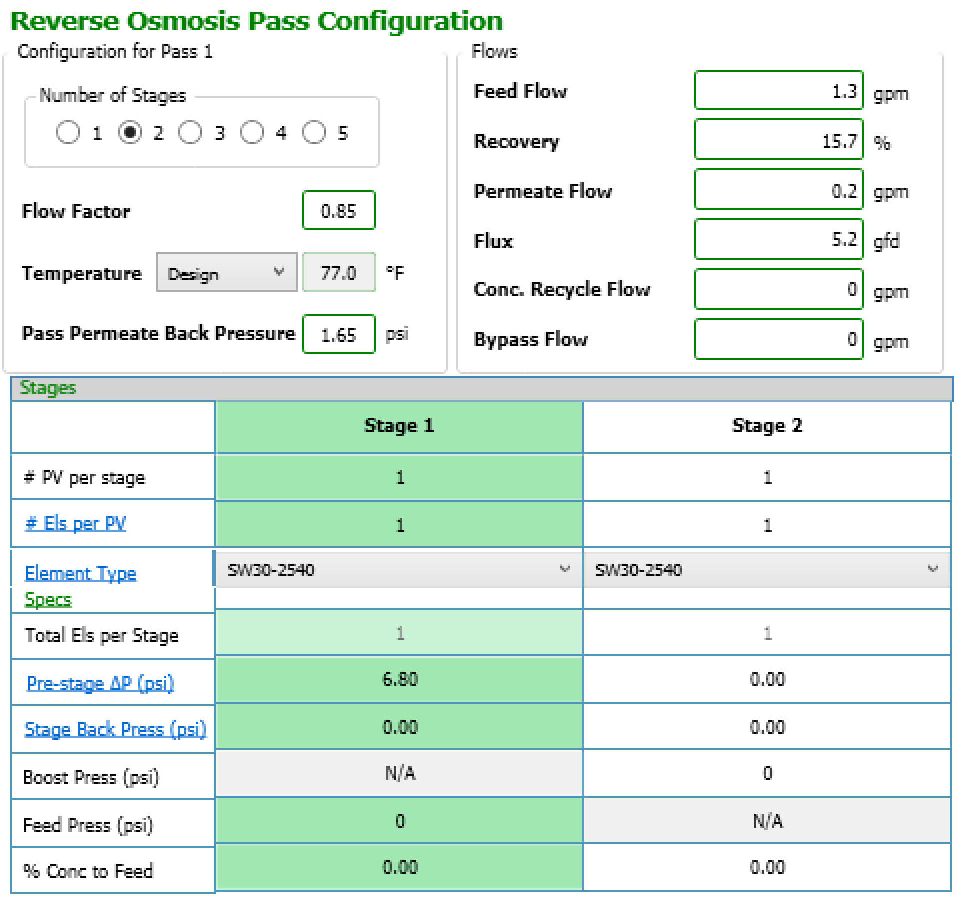


Figure 3. Modeling relationships.

2.1 Reverse Osmosis (RO) Modeling Details

DuPont's Water Application Value Engine (WAVE) software[17] was used to predict the flow rates and TDS levels in the RO system. Screenshots from the DuPont WAVE software RO model are presented in Figure 4 for the case of the minimum system pressure of 550 psi. The WAVE software system schematic is shown in Figure 5.

[17] https://www.dupont.com/water/resources/design-software.html



#	Description	Flow (gpm)	TDS (mg/L)	Pressure (psi)
1	Raw Feed to RO System	1.30	35,000	0.0
2	Net Feed to Pass 1	1.30	35,059	551.1
4	Total Concentrate from Pass 1	1.09	41,403	541.9
6	Net Product from RO System	0.20	915.7	1.7

Figure 4. Sample WAVE software input (top) and output (bottom) for minimum pressure case.

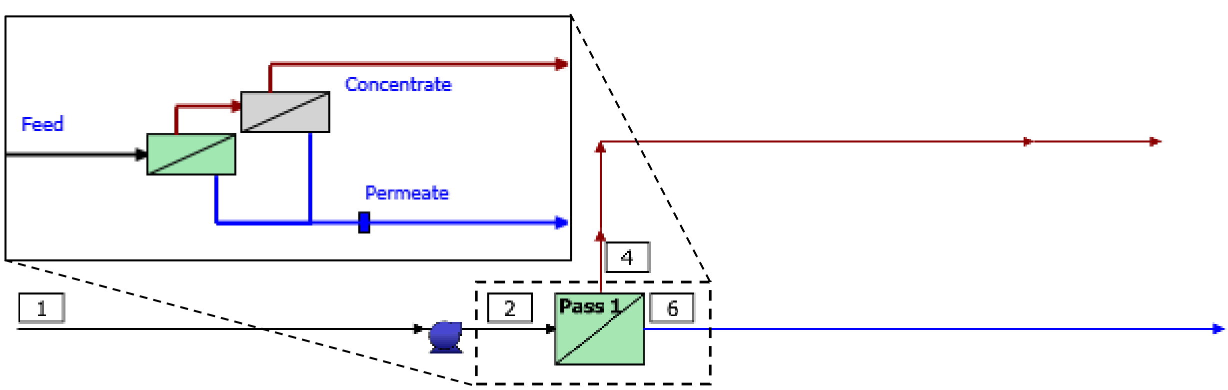


Figure 5. System schematic from WAVE software (numbering corresponds to '#' column in Figure 4).

2.2 Wells Turbine Modeling Details

As explained in Section 1, the power absorbed by an air turbine is a function of air density, turbine sweep area, and air velocity. With a typical wind turbine, the air velocity is equal to the wind speed and is a given, so the only ways to increase power are to increase C_p with more efficient turbines and to increase the sweep area A.

For an OWC application, the air flow rate is given and is based on the wave period and the volume of air displaced in the OWC. The power can be maximized by optimizing the A and V terms. It is obvious, since the V term is cubed in the equation, that increasing the velocity has more of an effect on the power output than increasing the sweep area. The velocity can be increased for a given flow rate by decreasing the sweep area and/or increasing the hub area. Too high of an air velocity however can result in the turbine stalling. The desired shaft rotational speed must also be considered. The Wells turbine for the ROOWaC was designed for air velocities of about 40 to 80 miles per hour, similar to the LIMPET plant,[18] with the sweep area and hub ratio sized to achieve the desired rotational speed for optimal operation of the plunger pump. Figure 6 shows the blade cross section shape, open area, and hub ratio for the ROOWaC Wells turbine and the turbines used to calibrate the ROOWaC model.

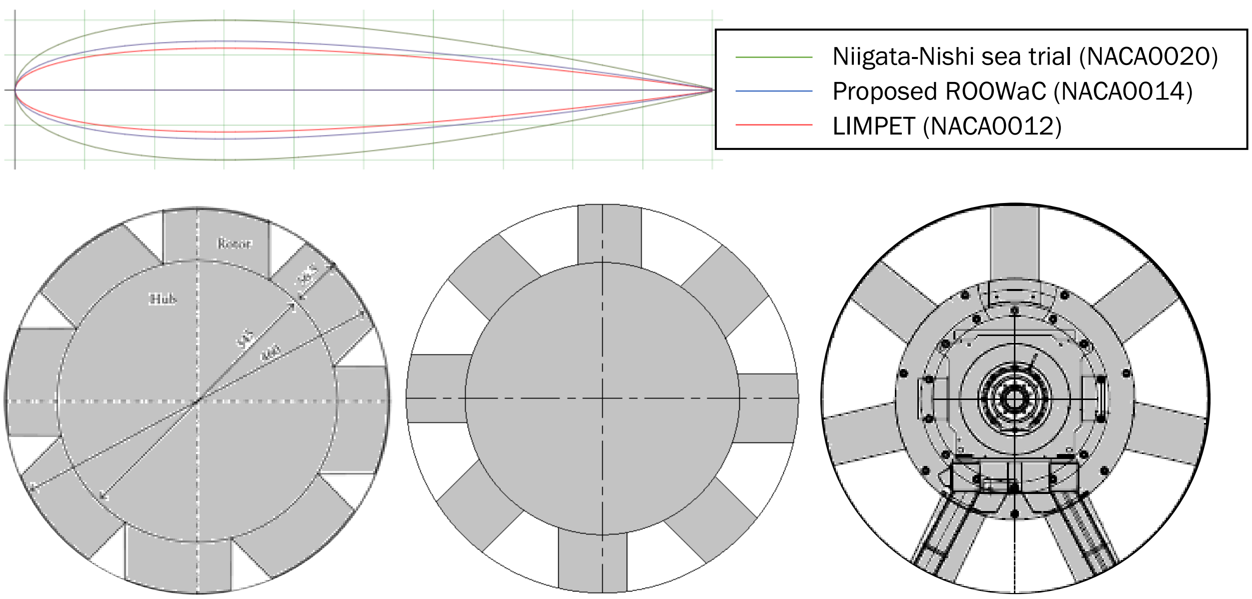


Figure 6. Top: Wells turbine blade cross sections;[19] bottom: turbine open areas and hub ratios for [left] Niigata-Nishi sea trial[20] (~16% open, 0.75 hub ratio), [center] proposed ROOWaC design (~50% open, 0.70 hub ratio), and [right] LIMPET[21] (~65% open, 0.62 hub ratio).

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[18] *Islay LIMPET Wave Power Plant, 1 November 1998 to 30 April 2002*. Queen's University of Belfast.
[19] Shapes generated at http://airfoiltools.com/airfoil/naca4digit
[20] Takao, M. and Setoguchi, T. *Air Turbines for Wave Energy Conversion*. Intl J of Rotating Machinery, 2012.
[21] *Islay LIMPET Wave Power Plant, 1 November 1998 to 30 April 2002*. Queen's University of Belfast.

3. Structural Analysis

Structural analyses were performed of the air chamber structure and the Wells turbine runner to ensure that a sufficiently strong and light structure could be built to the physical dimensions necessary to produce the results presented in the previous sections of this document. The turbine runner was modeled as stainless steel. The air chamber structure was modeled as fiberglass-reinforced polymer (FRP). Static finite element analysis (FEA) was performed using SolidWorks 2018 by Dassault Systèmes.[22] Screenshots are shown below.

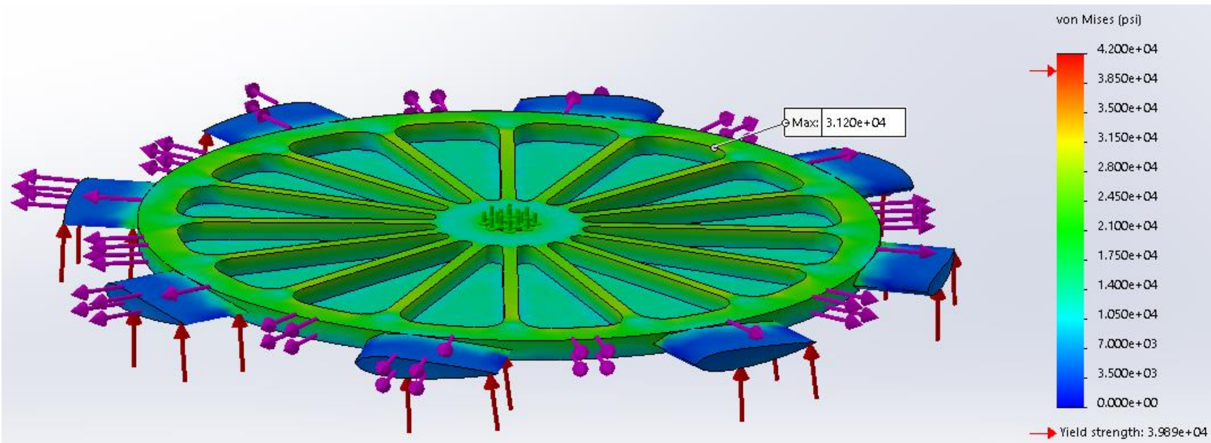

Figure 7. Turbine runner finite element analysis (FEA).

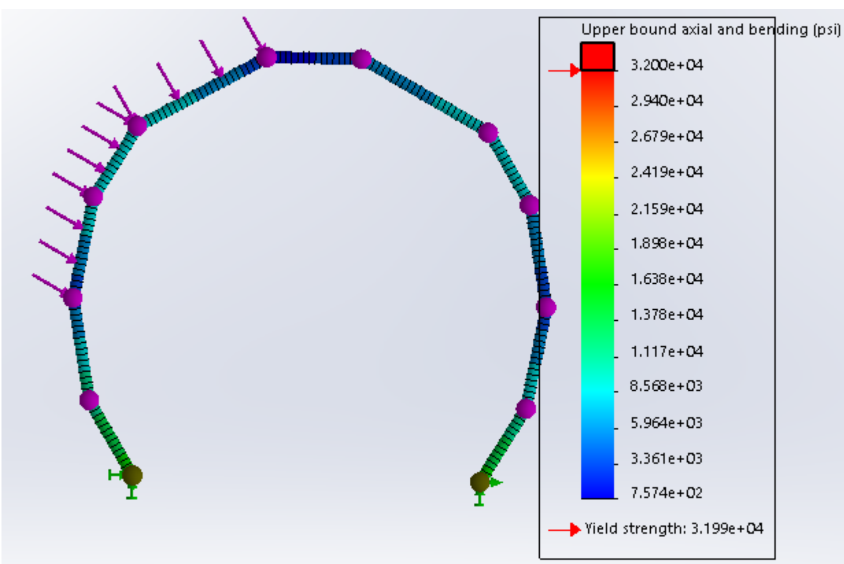

Figure 8. FEA of air chamber structure. This screenshot shows the case of a crashing wave from one side.

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[22] www.solidworks.com

The taut-mooring anchoring method will keep the anchor cables in tension at all times. Thus, the mooring loads do not change significantly between sea states. The free body diagram in Figure 9 shows the estimated total load for the suction piles.

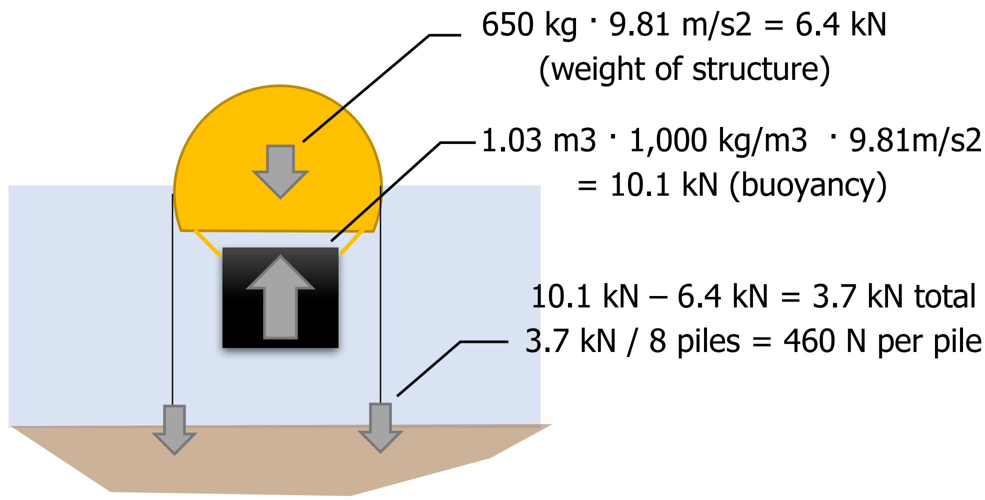

Figure 9. Free body diagram and mooring loads.

The shipping weight of the system was modeled by calculating and adding the weights of all individual components in Microsoft Excel. The shipping weight was calculated to be approximately 641 kg. The dimensions of all individual components were modeled in three dimensions using Sketchup to determine how the system could fit within the specified shipping container. Figure 10 shows a rendering from the Sketchup model.

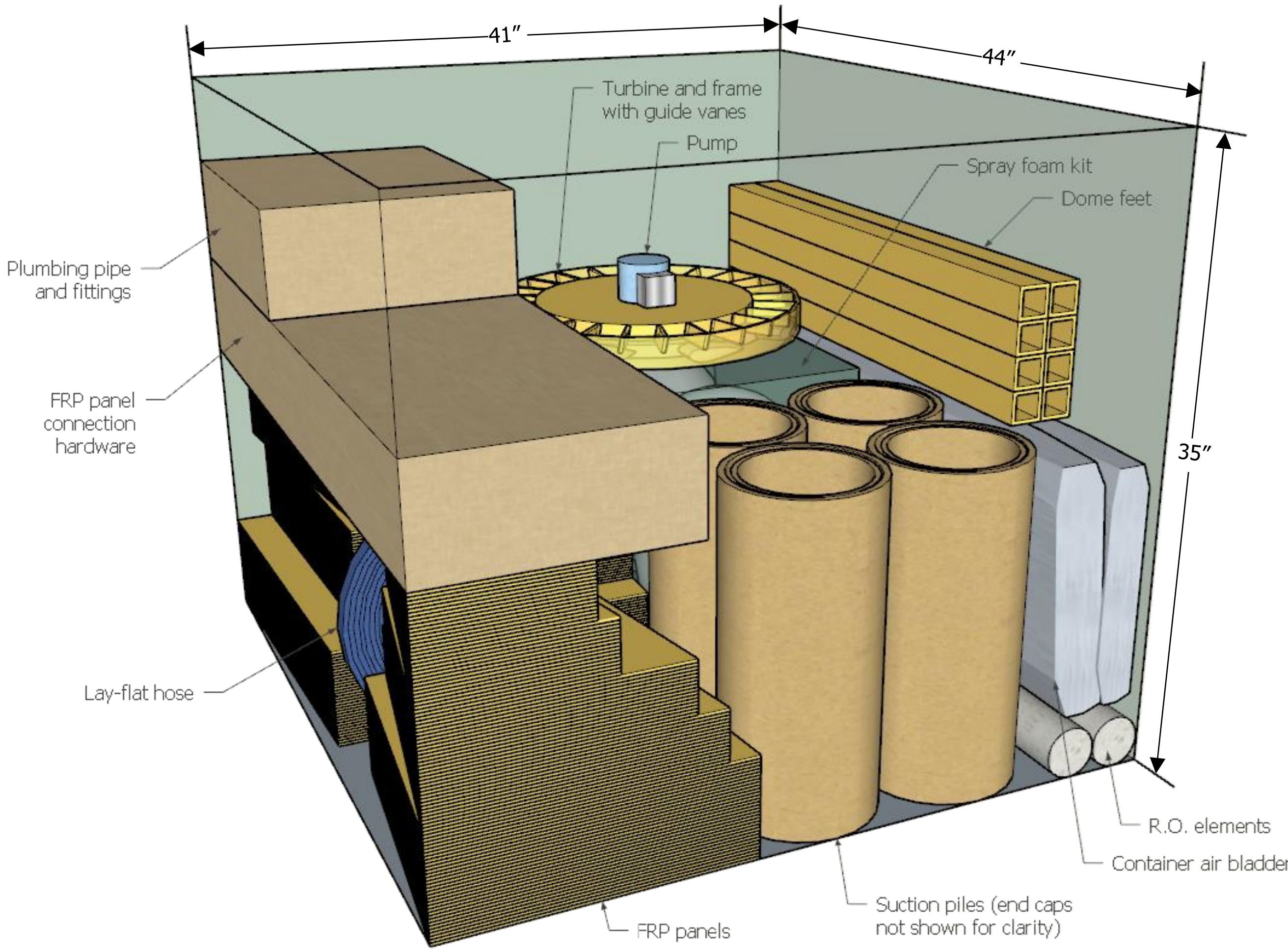

Figure 10. Packaging of the system into the standard shipping container.

4. Adaptability of the System

The system can operate under different wave conditions and different sites without major tuning to ensure operation at a wide variety of locations. The turbine and pump have been sized to be able to handle the maximum rpms that can be reasonably produced by the volume of air inside the structure. Once all of the air is expelled from the system, the turbine will become submerged and there is therefore no risk of overspeed. There is also a natural stalling effect that is inherent in Wells turbine installations.[23] If more power is desired, multiple units could be installed. To increase single-unit power, the turbine and pump can be easily scaled to match the size of an enlarged air chamber.

[23] *Islay LIMPET Wave Power Plant, 1 November 1998 to 30 April 2002*. Queen's University of Belfast.

5. Conclusion

This Modeling Documentation has demonstrated how the ROOWaC system was determined to be able to meet the technical characteristics established for the Waves to Water Prize competition. Specifically, the system is expected to produce the following results:

- Estimated average water quality of 543 mg/L total dissolved solids (TDS)
- Approximately 2,900 liters of produced water volume over the 5-day test period
- Approximate shipping weight of 641 kg

We look forward to the opportunity to prove these expected results during the CREATE stage.

Supplementary Information

MODELING DOCUMENTATION WORD COUNT: **2368 TOTAL WORDS**