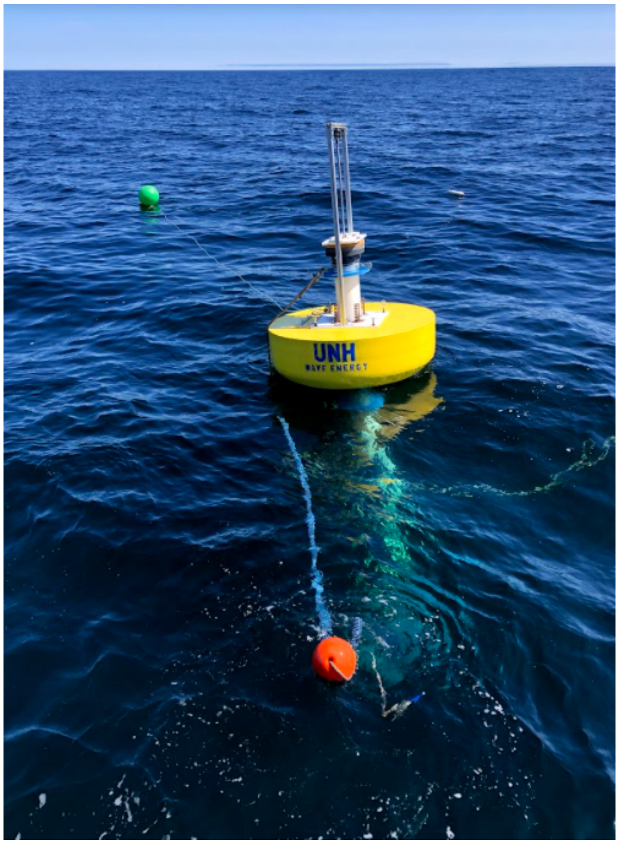
Wave Powered Water Pump



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University of New Hampshire
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TECH 797 - Undergraduate Ocean Research Project

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ABSTRACT

The goal of the project was to finish the construction of a Wave Powered Water Pump (WPWP) from the previous year's work and deploy the system in random seas. The WPWP moves nutrients from a lower depth to the surface in a sustainable way using wave energy to help kelp aquaculture produce at a faster rate. This year the team performed multiple tests in the UNH Chase engineering tank to ensure the system's ability to pump water. Throughout the process of completing construction, the team developed different methods to ensure the WPWP was watertight and that the inner cylinder of the spar was kept from filling with water by testing different options to fill the space with foam. The team deployed and tested the WPWP outside the mouth of the Piscataqua River in New Hampshire in approximately 60 feet of water with the help of the R/V Gulf Challenger. The final system resulted in a flow rate of approximately 2.5 gallons per minute in 1 to 3 foot waves.

ACKNOWLEDGEMENTS

The Wave Powered Water Pump team would like to thank the many people and organizations for making this year's project possible. We would like to thank our advisors, M. Robinson Swift and John Ahern, for their invaluable advice and assistance with fabrication techniques, testing and field deployment. We would also like to thank Capt. Bryan Soares and First Mate Debra Brewitt for ensuring the field deployment went smoothly. This project was also made possible by funding sources from New Hampshire Sea Grant, the Departments of Mechanical and Ocean Engineering here at UNH, and also the UNH Parents Association.

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1. INTRODUCTION

1.1. BACKGROUND

In recent years, biofuels have emerged as a greener and more sustainable way to power the different engines that are in cars, trucks, and even airplanes. More recently, kelp has become an alternative and more attractive biofuel when compared to traditional biofuel sources, such as corn and vegetable oils, due to the irrigation and fertilizers used when farming on land. Kelp is seen as a more sustainable biofuel source since it does not use freshwater (irrigation) and land (habitat destruction) when grown in its natural habitat, the ocean [1].

Researchers at the University of Southern California have been working with private kelp aquaculture farms and have found that when kelp is exposed to nutrients lower in the water column, it can increase kelp's growth rates. These increased growth rates have resulted in up to four times the biomass production. The kelp at these farms have been able to receive the nutrients lower in the water column by physically moving the kelp lines lower into the water column on a daily basis [1].

Instead of bringing the kelp lines to the nutrients, another method could be bringing the deep nutrient-rich waters up to the kelp lines. With the Wave Powered Water Pump (WPWP), these nutrients could be pumped from depths up to the kelp lines higher in the water column in a sustainable way by wave power.

1.2. PREVIOUS WORK

In previous years, the WPWP was UNH's Wave Energy Conversion Buoy (WECB), where instead of pumping water, the buoy was designed to convert wave motion to electrical energy as a wave point absorber. Last year's WPWP team was tasked with converting the previous WECB into a buoy with the ability to pump water.

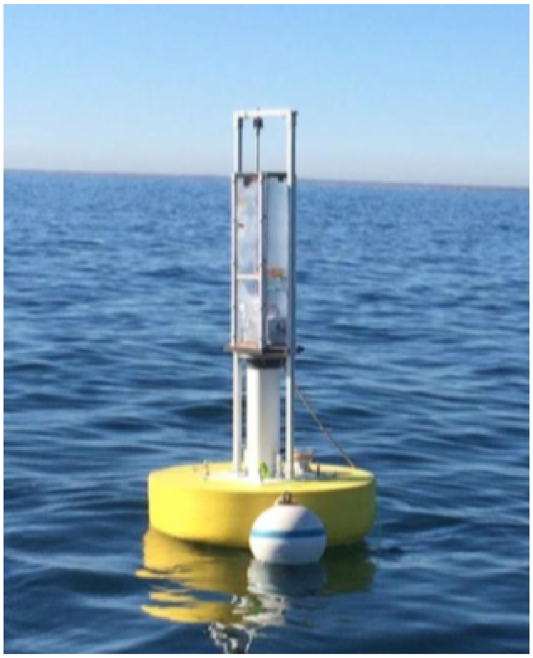


Figure 1: The previous WECB during a field test [2]

After different design considerations for a pump type between a diaphragm pump, piston cylinder pump, and internal piston cylinder pump, the team went with an internal piston cylinder pump inside the main spar. The team was able to convert the previous WECB into the WPWP by removing the electrical components and gutting the 8 inch diameter spar. The team then added a 4 inch piston cylinder situated inside the 8 inch spar, with an aluminum piston head and piston shaft connected to the yellow follower float (see Figure 1) with aluminum bracing.

The team was able to prove the pumping potential of the buoy by deploying it in the Chase Ocean Engineering tank at UNH. The team was able to manually move the spar to pump water during the tank test. However, due to COVID-19 in March of 2020, UNH chose to continue the rest of the year all online, preventing further tank or ocean tests.

1.3. OBJECTIVES

Given the previous work on the buoy, this year's team was tasked with a set of objectives to accomplish over the year:

- Inspect the condition of the buoy
- Finish constructing the buoy & improve the pumping mechanism
- Thoroughly test in the Chase Ocean Engineering tank
- Implement sensors for data collection
- Field test the WPWP in the waters outside of Portsmouth Harbor

1.4. APPROACH

Given the COVID-19 shutdown of the university in March 2020, this year's team started by inspecting the system to ensure all past components of the buoy and water pump system were working properly after sitting idle over the summer. The inspection was done before moving on with finishing construction. After finding the system naturally allowed water into the piston through the piston head quad ring gaskets, we then wanted to fill the empty space behind the piston head with foam and seal any other possible points of leakage. Throughout the process we utilized the UNH engineering tank and tested different methods of filling the cylinder with foam. We also discovered and tackled changes to the hydrostatics of the system, and created a safer way of lifting the system. After the construction we were able to deploy the system at the mouth of the Piscataqua River with the help of the Gulf Challenger. The critical test was how well water was pumped during ocean waves.

1.5. BUDGET & FUNDING

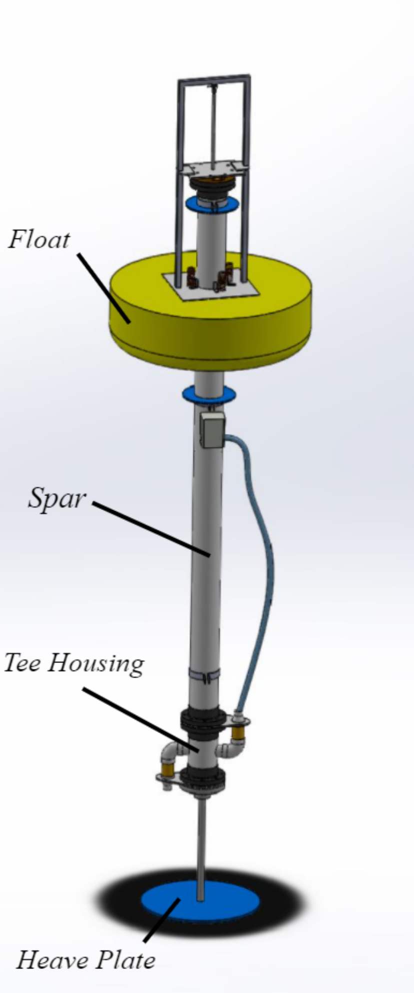
With this year's main objective being to deploy the WPWP, the team had to be able to fund the use of the UNH R/V Gulf Challenger. The team initially received $1000 from New Hampshire Sea Grant for being a part of the TECH 797 course, as well as $600 from the Mechanical Engineering Department. This left the team $378 short of the cost of a full day on the Gulf Challenger.

Finding additional funding proved to be more difficult than initially expected because of many events being cancelled due to COVID restrictions. However, the team was able to write a proposal and received $446 from the UNH Parents Association to cover the use of the Gulf Challenger and the excess fabrication expenses incurred above those originally predicted. The final cost of the fabrications and the budget breakdown can be seen in the Appendix.

2. BUOY DESIGN

2.1. OPERATION

Like many wave point absorbers, the Wave Powered Water Pump (WPWP) consists of a central spar buoy and a wave follower buoy surrounding it, as seen in Figures 2a and 2b. The system is able to pump water because of the relative motion of the float to the central spar.



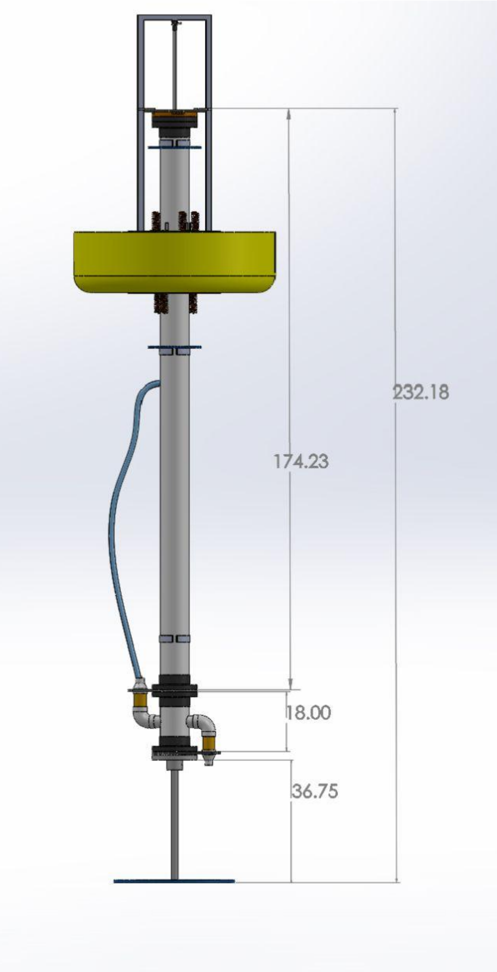


Figure 2a (left): Solidworks modeling of WPWP. The yellow float slides vertically on the spar while following the waves and drives the pump through the gallows/connecting rod assembly at the top.
Figure 2b (right): Dimensions of the WPWP from the top of the spar to the heave plate, as well as dimensions of separate components. All dimensions are inches

As seen in Figure 2a, a heave plate is connected to the bottom of the spar. This heave plate helps keep the spar stationary during wave action, since it does not feel the effect of most waves. As a wave passes by, the yellow float follows on top of the wave crest, and then as the wave passes, descends into the wave trough, all while the spar is relatively stationary.

In Figure 3 below, the motion of the float in relation to the spar is illustrated at the crest and the trough of a wave. In the left illustration, the float is at the top of the upstroke, with the springs at the stopper. As seen in the cross section, the float rises upwards and the spar stays stationary, which also pulls the piston head upwards in the piston cylinder. Due to the check valves on the inlet and outlet of the tee housing, water is pulled into the piston cylinder as the float and piston cylinder rise with the crest of the wave. As the wave passes, the float descends into the trough of the wave while the spar remains stationary, resulting in the piston head to move downwards and push water out of the outlet due to the check valves. This can be seen in the right illustration of Figure 3. Although the float is at maximum upstroke and downstroke in these illustrations (contacting the upper and lower stoppers), the system does not need much relative motion to pump water.

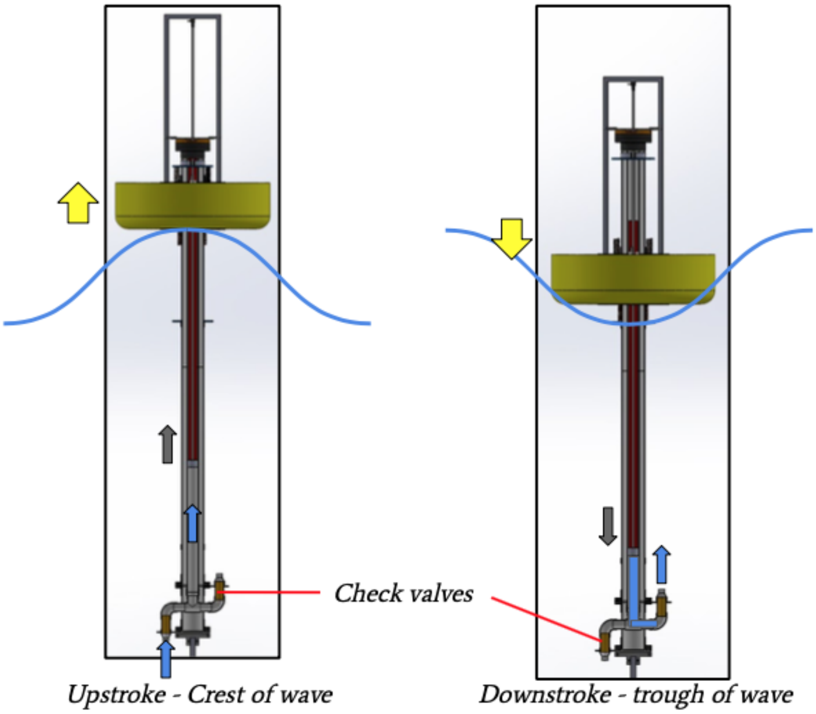


Figure 3: Cross section of the spar in Solidworks showing the internal piston cylinder, piston, piston shaft, and tee housing plumbing at the crest and trough of a wave. Foam spacer is also shown (red).

2.2. COMPONENTS

2.2.1. SPAR

The spar is made of a single length of 8 inch diameter Schedule 40 PVC piping, about 14 feet in length. On either end of the spar is an 8 inch diameter plastic flange. Just below the top flange is a riser clamp which holds the wood stopper to stop the float if forced too far upwards. Five feet down the spar is another riser clamp and stopper, for the lower bound of the float's range. The stoppers are the blue discs seen in Figure 4 below. The internal piston cylinder resides inside the spar, supported by a plastic disc at the midpoint of the spar.

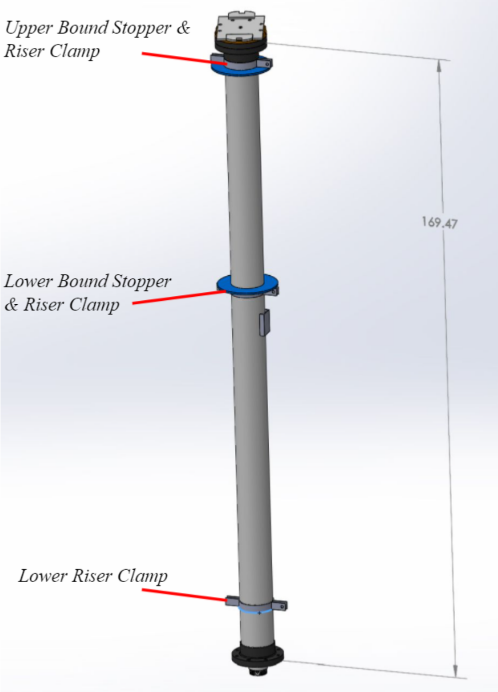


Figure 4: Solidworks modeling of just the spar and its components. The dimensions are in inches

At the top of the spar, there is a plastic disc which stabilizes the internal piston cylinder at top, as well as a metal plate and a spacer ring from an old flange. The final component on the top of the spar is an acrylic guide plate, which grasps onto the aluminum bracing on the float. The piston rod goes through a rubber gasket in the center of the guide plate and into the piston cylinder. All the spacer components are held into place by bolting onto the top flange.

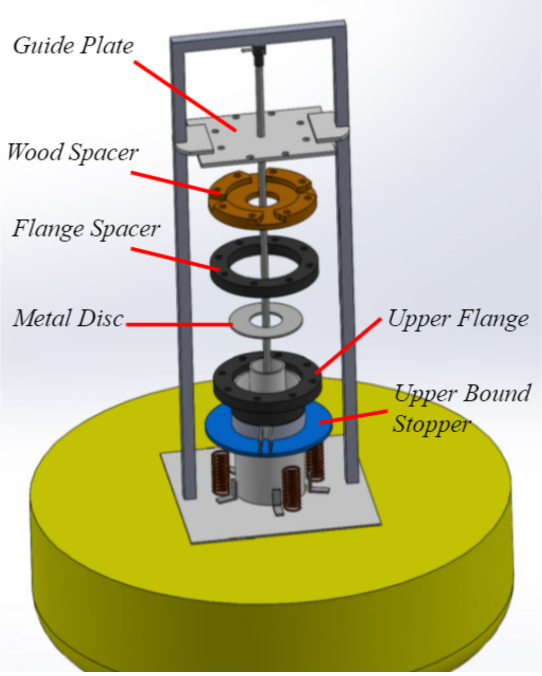


Figure 5a (left): Exploded view of the components at the top of the spar in Solidworks

Figure 5b (right): Top of the spar with all components bolted together

2.2.2. FLOAT

The float is made of Surlyn and the spar goes through its central hole. Connected to the float is an aluminum gallows frame which is through-bolted vertically to the float. The piston shaft is connected at the middle of the crossmember at the top of the aluminum gallows. The whole aluminum bracing, piston shaft and piston assembly moves with the float. The float also has eye loops on its top surface, through-bolted vertically to ensure strength when using the eyes for mooring.

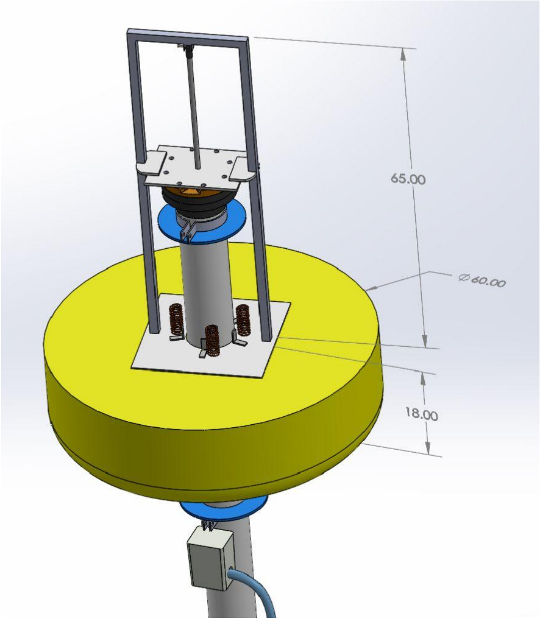
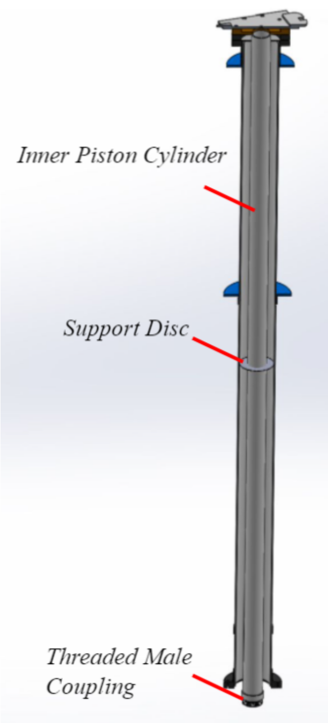


Figure 6: Solidworks modeling displaying approximate dimensions in inches.

As seen in Figure 6 above, the float has a diameter of 5 feet, and is 18 inches tall with a taper inwards towards the bottom of the float. The gallows assembly has an approximate height of 65 inches, just over 5 feet, which is guided by the rectangular guide plate on the top of the spar. The inner hole diameter is approximately 9 inches, enough for the spar to pass through but still close enough to be secure. Also seen in Figure 6 are the springs on top of the float in case the float reaches its maximum stroke (there are also springs located on the underside of the float). These springs bounce off the upper and lower bound stoppers, seen in Figure 6 by the blue discs.

2.2.3. PISTON CYLINDER

The piston cylinder, as seen in Figures 7a and 7b, is two pieces of four inch diameter Schedule 40 PVC pipe, situated in the center of the spar. These two pieces are cemented together with a coupling near the middle of the spar (not shown). The top of the piston cylinder is flush with the vent spacer, and the bottom has a four inch male threaded PVC fitting to thread into the tee housing. The piston cylinder is supported in the center of the 8 diameter spar by a plastic disc with an outer diameter of 8 inches and an inner diameter of 4 inches. This can be seen in the cross section of the spar in Figure 7a below.



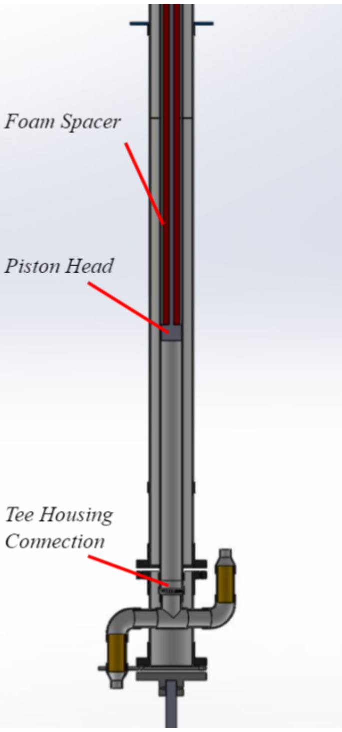


Figure 7a (left): A cross section of the main spar showing the internal piston cylinder, support disc, and threaded male coupling.
Figure 7b (right): A cross section of the spar, internal cylinder, and tee housing. Shown in red is the foam spacer around the piston shaft above the piston head. The threaded tee housing connection is shown seated into the tee.

The piston head and piston shaft reside in the lower portion of the piston cylinder (see Figure 7b). The piston head is 3.97 inches in diameter and has a height of 3.00 inches. It was machined with 3 grooves around its walls for quad rings for sealing. The piston head has a threaded central hole to be screwed onto the piston shaft. The piston shaft is ⅞ inches in diameter, and 14 feet long. The shaft is threaded on both sides to screw into the piston head on the bottom side, and is threaded into a ball joint rod end at the top where it is held in place to the gallows crossmember with a pin (see Figure 8 below).

Figure 8: The ball joint rod end pin connection at the top of the piston shaft, connected to the crossmember of the gallows.

2.2.4. TEE HOUSING

The tee housing is an 18 inch section of the same spar piping, with flanges on each end. The inlet and outlet piping is 3 inch Schedule 40 PVC, which protrudes outwards perpendicular to the 8 inch piping. These pipes protrude near the midpoint of the tee housing. The outlet is directed downwards at a right angle, with a check angle that only allows for water to flow into the tee housing. On the opposite side of the tee housing, the inlet is positioned at a right angle upwards with a brass check valve only allowing water to exit. Both the outlet and inlet piping reduces to 1.5 inches after the check valve, and a female threaded coupling is cemented on the end of the reducer. This allows for a 1.5 inch barb fitting to be threaded into the inlet and/or outlet to connect a 1.5 flexible hose.

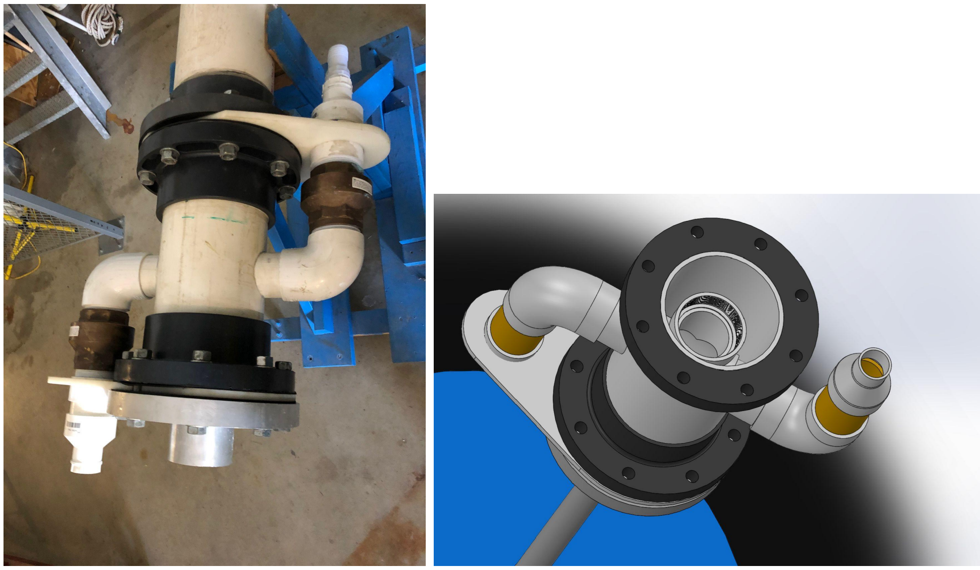


Figure 9a (left): The tee housing bolted to the bottom of the spar.
Figure 9b (right): A Solidworks modeling of the tee housing, showing the PVC tee inside.

Inside the tee housing, the inlet and outlet piping meets in the middle at a Schedule 40 PVC Tee. The inlet and outlet pipes are cemented to the tee, and a threaded female PVC coupling is cemented into the perpendicular 4 inch socket where the piston cylinder can then be threaded in (see Figures 9a and 9b above).

There are guide plates that bolt in between both the upper and lower flanges of the tee housing. These guide plates are made of acrylic and are ½ inch thick, and the section between the brass check valve and reducer passes through a pre-cut hole in them (see Figure 10a below). The top guide plate has a 4 inch diameter hole cut in the center of the flange bolt pattern for the internal piston cylinder to pass through. This also serves as a lower support for the piston cylinder and helps stabilize it. The lower guide plate has thick plastic supports normal to the plate's surface, with semicircles cut out of the top. These support the PVC Tee itself when pressure is applied downwards during the downstroke of the float and piston head. Between each of the flanges and guide plates are gaskets which seal when torqued down properly. These prevent water from entering the main spar, which would result in a loss of buoyancy of the spar.

Figure 10a (left): The lower acrylic guide plate sandwiched in between the lower flange and the metal plate for heave plate attachment, supporting just below the check valve

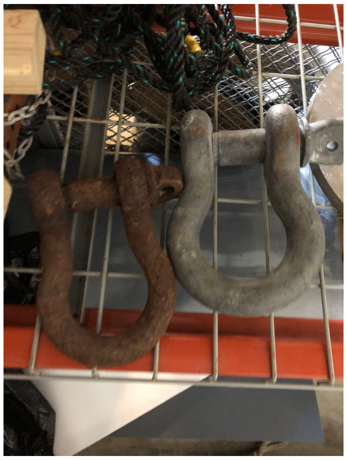
Figure 10b (right): The metal plate under the tee housing. The inner hole in the protrusion allows for the heave plate to be pinned on with a bolt.

At the bottom of the tee housing, there is a thick piece of aluminum approximately 1.5 inches thick and 13.5 inches in diameter which has the same bolt pattern as the flanges to bolt on to the lower flange. In the center of this plate, there is a protrusion with an outer diameter of about 4.75 inches and inner diameter of about 2 inches. This protrudes approximately 3 inches away from the surface of the plate, allowing for an aluminum pipe to be connected for the heave plate and ballast (see Figure 10b).

2.2.5. HEAVE PLATE & BALLAST

The heave plate is a three foot diameter disc made of ¾ inch plywood and painted blue. It is connected to the metal plate at the bottom of the spar by a 3 foot aluminum pipe with a 1.5 inch diameter, which is secured by a floor flange in the center of the heave plate. The aluminum pipe is pinned to both the floor flange on the heave plate and the aluminum plate at the bottom of the spar with nuts and bolts.

Prior to securing the heave plate to the spar, the ballast that was used for the field test were two shackles of different weight. The first shackle weighed 18 lbs, and the second smaller shackle weighed about 12 lbs. These and any other ballasts that the system were tested with can be put around the pipe, and then secured to the bottom of the spar to ensure the weights are secure.



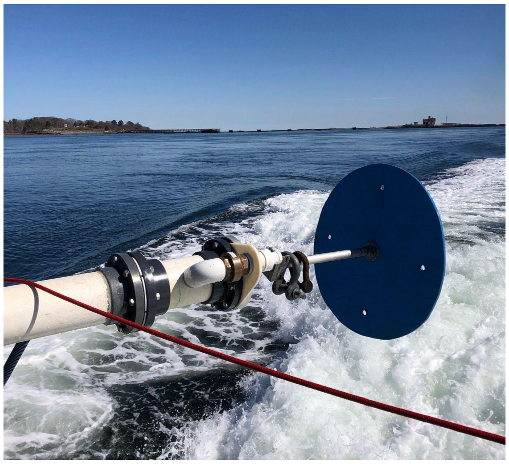


Figure 11a (left): The two shackles used for ballasting during field testing. Figure 11b (right): The two shackles looped around the heave plate pipe after the field test was conducted

3. BUOY UPGRADES

3.1. PISTON CYLINDER FOAM

Due to the nature of the piston head and quad ring gaskets, it was known that water would eventually leak into the piston cylinder. If water were to fill the piston cylinder it would inhibit the piston shaft from having full mobility and would greatly affect the buoyancy of the entire system. Last year's team had purchased Total Boat 2-part polyurethane marine floatation foam that we initially thought could be poured into the spar directly. However, after further research and investigating the system we found pouring the foam would stop the piston shaft`s ability to move up and down the spar.

The solution was to make a mold, as seen in Figure 12a, and create three pieces of foam. These three pieces were going to slide into the piston cylinder and be free floating, taking up approximately 10 ft of the cylinder. The foam that was used was difficult to separate from the mold, which caused difficulties in the mold building process. The final design for the mold was to use an outer cylinder, the size of the outer spar cylinder, and inner cylinder, that was the size of the stainless steel bar. The cylinder was lined with a piece of thin plastic sheeting and mold release was applied. The foam was then able to be pulled out with the smaller inner cylinder still attached reducing the risk of friction within the cylinder.

Figure 12a (left): The original test mold using a small piece of 4 inch PVC and a wooden dowel for the inner hole.

Figure 12b (middle): The final mold design with a 4 inch diameter PVC pipe. The gray plastic sheeting to the left of the mold was put inside the mold to create the gap between the spacer and the cylinder.

Figure 12c (right): The foam spacer created with the molding process.

When we put the foam in the piston cylinder we found the inner cylinder was warped due to the heat released from the reaction of the foam mixture. To fix this we attempted to cut the three pieces of foam into multiple smaller pieces that we were able to drill with a bit and reshape more easily to fit over the piston shaft and into the spar, as seen in Figure 13. After a tank test in the engineering tank, explained further in Section 6, we found the system had too much friction to pump water naturally in a steady wave train. When we took the system apart after the test it appeared as though the many pieces of foam had shifted and the imperfections were likely getting caught as they rotated in the spar. We decided to investigate a pin design, in which a pin would hold adjacent pieces in the correct orientation to prevent this, as well as using Molykote 111 Compound for lubrication. However, the application of Molykote 111 did not seem to make a noticeable difference with the friction problem.

Figure 13: The foam on the piston shaft, cut into small pieces to slide into the piston cylinder.

We discussed the possibility of shaving down the different pieces of foam but decided to try rebuilding the foam instead. We adjusted our foam molding process by adding two sheets of thin PVC plastic on the inside of our 4 inch diameter PVC pipe to add more of a clearance between the foam and piston cylinder walls. We also decided to use a metal pipe in the interior hole to ensure a straight piece of foam was created. After the foam was poured, we attempted to pull out the foam from the mold using a winch by attaching ropes to the exposed section of the mold. The double PVC sheeting on the inside of the piston cylinder increased the difficulty in pulling the mold out, which almost doubled the amount of time and effort it took to pull out. Although the metal rod was inside the foam, it seemed as though the foam still did not come out as straight as it should have.

With these difficulties and our two-part foam running low, pouring two more molds like this seemed to be a difficult task with time and materials running out. We wanted to focus our efforts on the other tasks at hand, so after searching for premade options online, we came across a foam noodle made out of dense, waterproof foam, which had a diameter of 3.25 inches, and an inner hole of just under 1 inch. We inserted a ¾ inch PVC pipe into the hole of the foam noodle, as seen in Figure 14, to slip onto the piston rod, which adds rigidity to the foam and makes it more durable. We cut a 3 inch plastic diameter disc with a ¾ inch diameter hole in the middle to slip onto the piston rod after the foam was installed. The foam and disc were secured with a hose clamp on the rod in order to keep the foam seated on top of the piston head. We used 10 feet of foam in the cylinder to prevent it from stopping the system if the float made a full upstroke. In another tank test this method proved to be successful, pumping water naturally with minimal waves created.

Figure 14: Shows the final pre-fabricated foam noodle used in the final design.

3.2. TOP SPACER

In the initial investigation of the system we also discovered that the top of the spar was not sealed. We wanted to create a way of sealing the cylinder while still allowing water and air to escape the piston cylinder so it could function properly. Our solution was to create a forked spacer design created from ¾ inch marine plywood. The base of the spacer was a solid circle with a center hole to slide over the inner cylinder of the spar. Four other pieces were then cut to form the fork design, as seen in Figure 15a, creating an area for water and air to escape the inner cylinder but keeping water out of the outer cylinder. The pieces were fixed together using epoxy for waterproofing and holes were drilled to match the flange's bolt pattern, to allow the same bolts to be utilized.

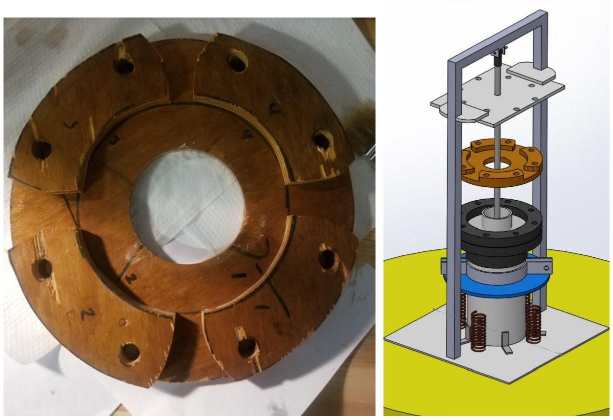


Figure 15a (left): The top wooden spacer after coating in epoxy.
Figure 15b (right): The top spacer in relation to the other components at the top of the spar.

3.3. TEE HOUSING CONNECTION

Throughout the process of taking the system apart and putting it back together we discovered that the piston cylinder was not firmly connected to the PVC tee housing. We were concerned that this was a source of leakage. We wanted to find a non-permanent but watertight connection for the piston cylinder to the PVC tee housing. We used a male and female 4 inch PVC threaded adapter, one cemented to the tee housing and another to the piston cylinder, as seen in Figures 16a and 16b below. This allowed for the tee housing to be taken off as needed, while still preventing the piston cylinder from experiencing excess leakage. The coupling connecting the two internal piston cylinder pieces also causes the piston head to get stuck when trying to remove it from the top of the spar. This choice for connection allows access to the piston head when needed.

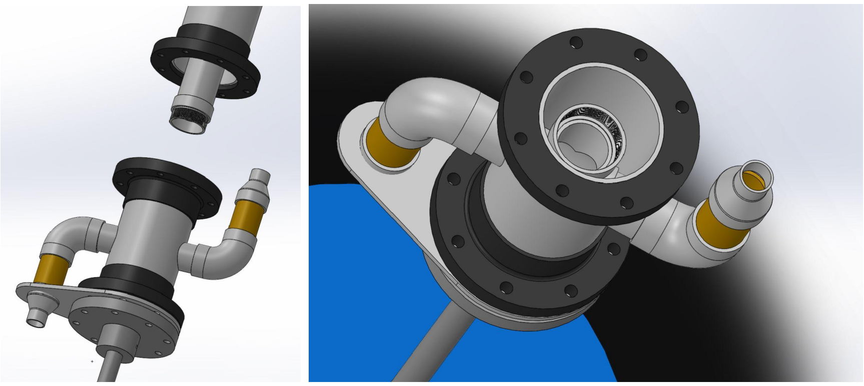


Figure 16a (left): The piston cylinder extending outwards from the spar to be threaded into the female coupling in the tee housing.
Figure 16b (right): The view from the top of the tee housing, with the female threaded coupling

3.4. BRIDLE

Throughout the tank test, described in Section 6, we also found that the WPWP needed to be lifted in a more consistent and safer way when we were on the Gulf Challenger. The final solution was to purchase a 8 inch riser clamp to be mounted between the tee housing and the lower stopper of the float, as seen in Figure 17. We used 2 pieces of thin rubber between the contact points of the clamp and the spar to add friction and ensure the clamp is secure for lifting. Although in the past we have used 3 straps to hoist the buoy, we decided 2 straps in the correct position would allow for easier lifting and less clutter of lines. With the help of John Ahern, we were able to find the center of gravity of the buoy with the float on the lower stopper and the heave plate attached. Using a 7 foot strap to the top of the spar and a 6 foot strap to the new riser clamp approximately two feet above the tee housing, the buoy lifted with a slight angle upright, which was desired for keeping the float in place. We were eventually able to find a 7 foot and 6 foot section of rope with thimbles on each end in the High Bay to use for the field testing.

Figure 17: The WPWP being lifted in the UNH High Bay with the final strap lengths and clamp location.

4. INSTRUMENTATION

4.1. FLOW SENSOR & CASING

For the field test we wanted to integrate data sampling to have tangible data for how well the WPWP worked. We used a 1.5” Digiten Flow Sensor with an Arduino Uno to collect the data.

The Digiten Flow Sensor produced an analog voltage. To turn this into readable data we fed the voltage read out into the Arduino, with our onboard code a live read out of liters per minute was produced. To set the flow sensor/arduino up for deployment we utilized a 9V battery and micro SD module. After final testing the flow sensor logged liters per minute every second and could log for 7 days.

For the deployment we wanted a housing to keep the sensor components dry while still allowing water to flow through the sensor. To do this we adopted a pressure casing from a previous project found in the UNH High Bay. We cut two 2 inch holes into the sides and used a 2 inch tap to thread two bulkhead fittings into the casing as seen in Figure 18. These fittings have 1.5 inch female threading on the inside of them, allowing us to thread the flow sensor in between them. With some thread sealant, the connection between the flow sensor and fittings appeared to be watertight after the initial leak test. The old hole on the lid of the casing was also plugged with a piece of acrylic and back filled with epoxy.

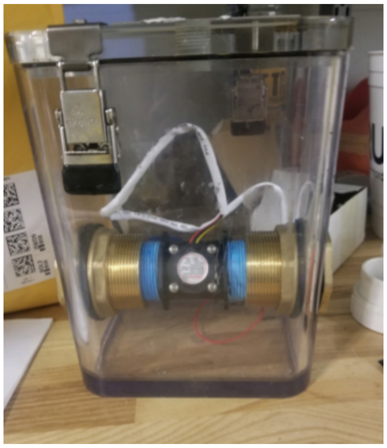


Figure 18: The pressure housing created with the Digiten Flow Sensor.

We placed the housing at the bottom stopper at the top of the spar as seen in Figure 19. We ran a 1.5” flexible hose from the outlet of the WPWP to the inlet of the flow sensor and another hose from the outlet of the sensor to the surface of the water to observe water movement.

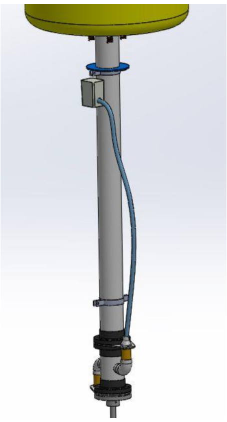


Figure 19: Solidworks modeling of the outlet tube and the flow sensor attached right below the lower stopper.

4.2. WAVE PRESSURE SENSOR

We decided to also integrate a pressure sensor so that the flow rate had a wave height and period associated with it. To do this we borrowed a RBR Duet from Prof. Lippmann. To make sure the sensor was properly calibrated we performed a simple tank test in the High Bay. We lowered the sensor 1 meter at a time to the bottom of the 6 meter deep tank. Comparing the test data to the predicted pressure and observed depths it was concluded that the duet was calibrated and ready for deployment. We deployed the sensor 10ft under the surface near the WPWP as seen in Figure 20.

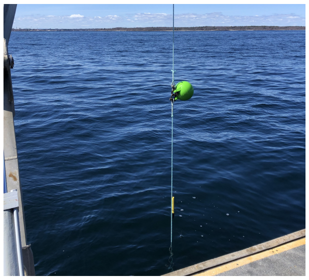


Figure 20: The RBR Duet pressure sensor deployed 50 ft from the bottom and 10ft from the surface.

5. HYDROSTATICS

After adding to the system we discovered the hydrostatics were affected and that the waterline was not in an ideal location. The goal was to allow the spar to float so that the foam float was statically midway between the two stoppers at the top of the spar. To analyze the system the team took the float off of the spar to weigh all of the parts separately using a load cell.

Figure 21a (left): The load cell used to weigh the spar, float, and tee housing

Figure 21b (right): Weighing the float with the load cell utilizing the gantry crane in the High Bay

Component	*Weight*
Float + Gallows Assy	171.55 lbs
Spar + Tee Housing + 18 lbs ballast	246.3 lbs

Table 1: Weights of the two main floating bodies of the system

With these weights, a hydrostatic analysis was performed to investigate the water line of the spar. Using assumptions such as the uniform volume of the spar and negligible volume from the heave plate, the equation below was used to calculate the waterline:

$$W = B = \rho g(\pi r^2)h_{wl} \tag{1}$$

Where ρis the density of water, *g* is acceleration due to gravity, *r* is the radius of the spar, $h_{wl}$is the height of the waterline, and *W* is the weight of the spar. The height of the waterline was found to be close to what we wanted, however water entering the piston cylinder complicated the analysis. During tank testing, we experimented with different weights in the engineering tank. We found that we needed to add 18lbs at the heave plate for an optimal waterline of the spar, at least in freshwater. We added a large shackle from the High Bay onto the heave plate to achieve this as seen in Figure 22.

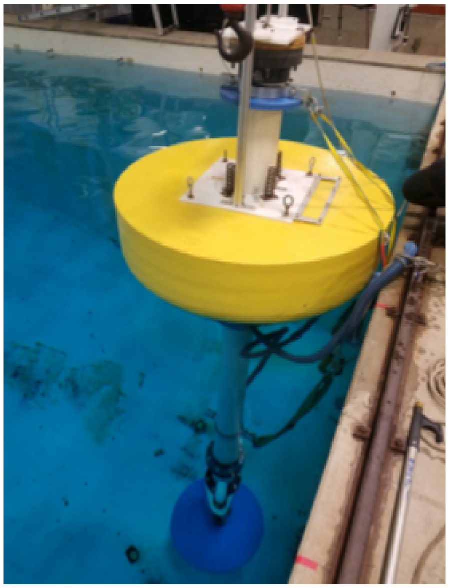


Figure 22: 18lbs on the heave plate to adjust the waterline in the ideal location.

6. TANK TESTS

Throughout the process we did several tank tests using the UNH engineering tank in the High Bay of Chase. Our project was stored in a cage of the High Bay and was stored on stands with wheels so we were able to push the WPWP to the tank, coordinating with other teams to move their equipment out of the way as well. We always put the WPWP in the tank with the outlet hose attached to the tee-housing the heave plate attached. To lift the system into the tank we used the crane above the engineering tank.

Tank Test 1: 11/6/20

Our first tank test was with the foam inserted and the top spacer on the system. Last year's team had left a rope bridal held together with a knot system. We decided to use straps that we found in the High Bay instead in hopes that it would be safer. When we first put the WPWP in the water it laid on its side and it was difficult to move upright, so we found a 45lb weight in the Highbay that we tied to the bottom of the heave plate.

Once it was upright in the tank we tried to pump water by jumping up and down a float that was in the tank. The yellow float of the WPWP and the spar moved together as one system. We then tried to move the piston manually, which we were able to do successfully. It proved that the system could pump water but there was too much friction for the piston to move freely.

When we tried to lift the WPWP out of the tank it became clear that the cylinder had filled with water and we had to let the system hang and drain for a decent amount of time.

Tank Test 2: 1/14/21

Over taking the system apart we did a second tank test without anyfoam to confirm that the system pumped water naturally as last year's team described. We found that it was able to pump water but the waterline did not look where it should have been which led us to start analyzing the hydrostatics and the system still filled with water which led us to do a leak test.

Tank Test 3: 3/23/21

The third tank test was to test our final foam solution of pre-ordered foam. To lift it into the tank we had our new clamp, so we tested different locations and strap lengths to find the equilibrium point.

Once the system was in the water we first tried to pump the piston using a pulley method off of the crane, however we only lifted the whole WPWP out of the water instead of pumping water. We tried to jump up and down on a float in the engineering tank as we did in the previous test and saw that we were able to pump water with a minimal wave train.

The waterline looked to be far too low however, so we tried several different weights at the bottom of the spar, incrementally taking more weight off until the spar looked roughly at the right height.

Tank Test 4: 4/2/21

The fourth tank test was to test the hydrostatics with the pressure casing and 18lb weight at the heave plate. We found that the hydrostatics looked almost perfect, but we did have a concern about the stability, as it was still laid on its side when first put into the water.

6.1. Leak Test

The more testing we did on the system the more obvious it became that the system was experiencing a major leak. We decided to test for possible leaks by filling the inner cylinder and tee housing with water. To make this possible we removed the piston head and lifted the top of the buoy, adding pressure to water in the tee housing. The water was added from the top of the spar. We did not find anything major which led to a conclusion that most of the leakage is going around the O-rings on the piston head. This was something we were already accounting for and the reason foam was being added to the piston cylinder. We did however also find a small leak around the gaskets on the tee-housing that we discovered need to be very carefully applied and tightened.

7. FIELD TESTING

7.1. MOORING CONFIGURATIONS

Two mooring configurations were employed for the field testing of the WPWP. One system was for the WPWP itself, and the other was for the RBR Duet for wave pressure recording. These configurations were designed with a temporary field deployment in mind (same day deployment and retrieval).

The WPWP mooring configuration, as seen in Figure 23, used a 200 lbs deadweight, consisting of barbells that were in the open storage area behind Chase. A length of chain was connected through the barbells in order to connect it to the main mooring line. The main mooring line was a 150 foot length of nylon rope with thimbles spliced in on both ends. The main mooring line ran from the deadweight up to a surface buoy, where a 25’ tagline was attached, as well as the 30’ pendant for the WPWP itself. The pendant going from the surface buoy to the WPWP was shackled to one of the eyes on the top of the float to ensure the spar’s waterline would not be affected when tension was applied to the rope from currents, wind or waves. A tagline was also added to the lifting bridle for the WPWP to aid in retrieval, since the bridle’s hook-on point would be below the waterline.

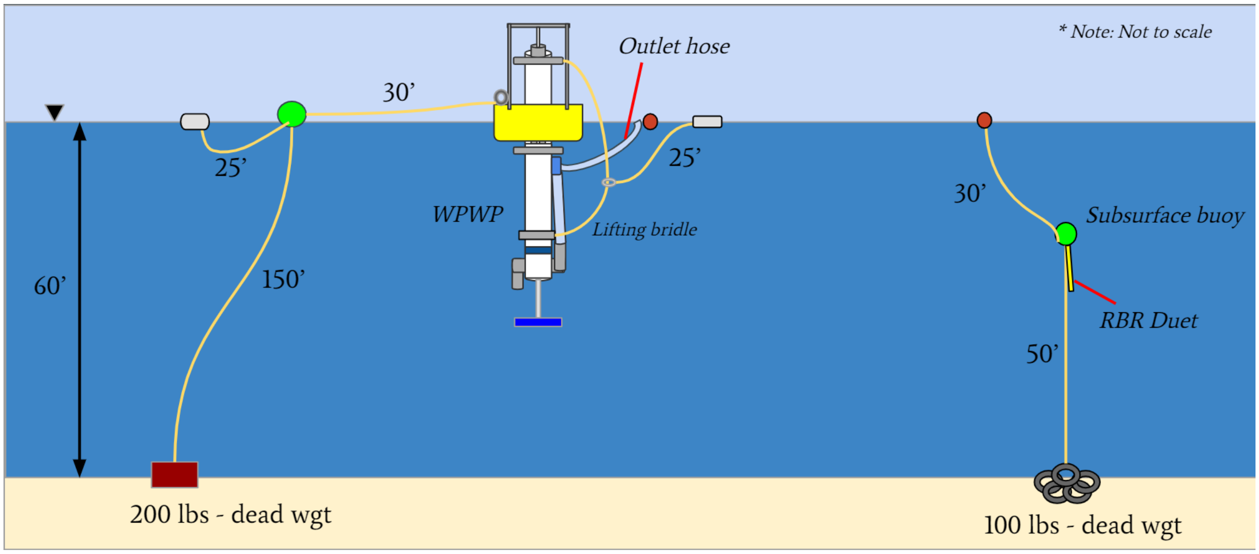


Figure 23: Mooring diagram configuration

As seen in Figure 16 above, the mooring configuration for the RBR duet consisted of a deadweight of 100 lbs, made of five shackles connected to a link of steamer chain. A short loop of chain was wrapped around the chain link to connect to the 50 foot length of nylon main line. This main line had thimbles spliced in on both ends, and the other end was shackled to the subsurface buoy. The RBR Duet CDT sensor was zip-tied onto the main line four feet below the subsurface buoy. A 30 foot tagline was shackled to the subsurface buoy up to a surface float for retrieval.

All lines in these configurations utilized thimbles spliced into the rope on both ends except for the tagline to the WPWP surface buoy and the line from the subsurface buoy to the surface buoy.

The WPWP had an output hose going from the output of the tee housing into the flow sensor casing, and then another hose attached to the output side of the flow sensor housing, and up to the surface. This way, the flow sensor would be able to record data and the team on board would also be able to observe pumping water with the hose on the surface.

7.2. DEPLOYMENT

In preparation for a field test of the system, the team contacted the captain of the R/V *Gulf Challenger*, Capt. Bryan Soares. In December 2020, dates were reserved for early April deployment: April 5th, and April 8th. The team decided to deploy on April 8th, 2021. John Ahern was able to assist the team during deployment. Capt. Bryan Soares and First Mate Debra Brewitt were the *Gulf Challenger*'s crew during the field test.

To get the system to the UNH Pier, John Ahern reserved the UNH CCOM truck and a dual axle flatbed trailer for the days of potential deployment. On the morning of April 8th, the system was loaded onto the trailer using the buoy's lifting bridle and the forklift in Chase. The blue wheeled stands that supported the buoy in the Chase High Bay were used by removing the bottom wheeled part, and placing the wood stands on top of the trailer, as the buoy was forklifted up and put down on the stands. To aid in lifting, the buoy was also tied and secured to the bottom stopper to make sure the float did not move around during lifting or transport.

Figure 24: The WPWP loaded onto the flatbed trailer before departure, hitched to the UNH CCOM truck

Once the buoy was resting on the stands on the trailer, heavy duty ratchet straps were used to secure the buoy for transport. As seen in Figure 24 above, three yellow ratchet straps were used for holding down the buoy. Two of the straps were placed above the stands and the third was put around the float, making sure to not cause too much bending of the spar. The deadweight anchors for mooring were also forklifted onto the trailer with a wooden pallet, and were strapped down beneath the middle of the spar. The CCOM truck was loaded with the mooring lines, output hoses, floats, shackles, heave plate, weights, zip-ties and extra tools for the field testing (see Figures 25a and 25b).

Figure 25a (left): All the mooring lines, floats, heave plate, etc. to be loaded onto the CCOM truck.

Figure 25b (right): The deadweight moorings on a wooden pallet strapped down to the trailer.

With everything secure, the team departed for the UNH Pier and backed the truck to the crane at the end of the pier for the buoy to be loaded onto the R/V *Gulf Challenger.* Prior to hoisting the buoy with the crane, the heave plate was attached to the bottom of the spar, along with two shackles: the usual 18 pound shackle, and a 12 pound shackle to accommodate for the different density of seawater. The buoy was loaded onto the vessel by putting the top of the spar towards the bow angled to the starboard, and the heave plate hanging off the stern. The aft gates on the vessel were removed to accommodate for this. While on board, the float rested on the deck, and one of the wooden stands had to be utilized to support the bottom of the spar. The float was then ratchet-strapped down to the deck of the vessel to ensure the buoy was secure while underway.

Figure 26a and 26b: The WPWP situated on the deck of the R/V Gulf Challenger

After the WPWP was on board, the two deadweights were hoisted on deck with the crane, and the rest of the mooring equipment and tools were brought aboard by the team.

With all necessary equipment on board, at approximately 12:10pm, the *Gulf Challenger* departed from the UNH Pier heading for the mouth of the Piscataqua River. Capt. Bryan Soares recommended deploying the buoy in 60 feet of water approximately one and a half miles northeast from the “2KR” nun buoy at the mouth of the river (see Figure 27). The wave conditions that day consisted of swells less than a meter high with relatively long periods, and some surface chop, which allowed the team to get to the location smoothly.

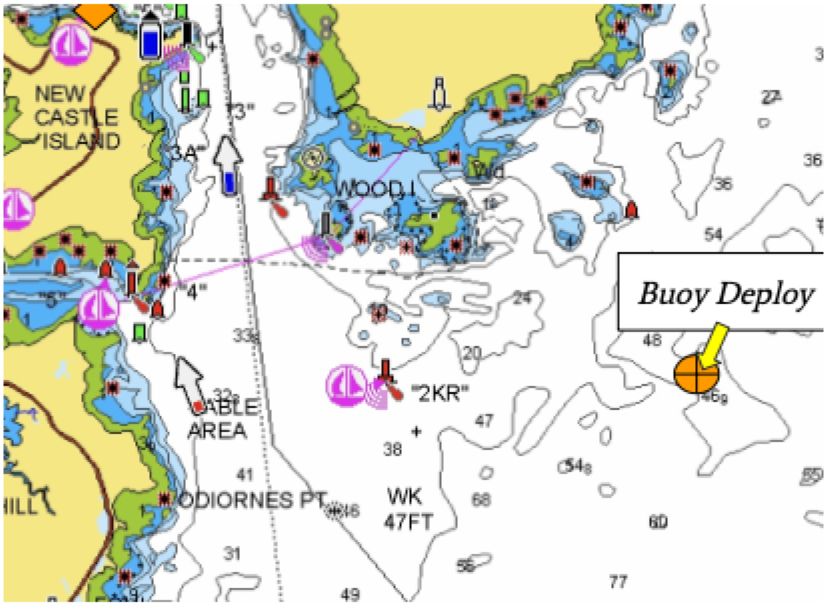


Figure 27: Map showing the mouth of the Piscataqua River. The orange diamond in the top left corner represents the UNH Pier. Note the "2KR" nun buoy at center

Once at the recommended deployment location, the first equipment rigged up and deployed was the WPWP mooring system. The team planned on first deploying the mooring system, then launching the WPWP away from the mooring system, and finally slowly towing the buoy to the mooring system where the pendant from the surface buoy could be shackled onto one of the eyes on top of the float. The vessel's A-frame crane and a quick release borrowed from Kingsbury Hall was used to safely drop the deadweight and deploy the WPWP. Once the surface buoy and main line was all payed out, the 200 pound deadweight was dropped into the water using the quick release at approximately 12:41pm.

Capt. Bryan Soares then moved the *Gulf Challenger* to a safe location nearby for the team to deploy the WPWP. The WPWP was hoisted up by the vessel's A-frame crane, and although it took some adjusting to get it off the deck and into the water, it was deployed using the quick release at approximately 12:54 pm (see Figure 28a). The WPWP was launched with the pendant shackled to one of the float's eyes in order to tow it over to the surface buoy. This pendant was then tied to the port cleat on the A-frame of the vessel, and slowly towed over. Once towed over, the vessel's boat hook was used to grab the surface buoy's tagline and shackle the pendant from the top of the WPWP float to the surface buoy. The WPWP was now fully deployed.

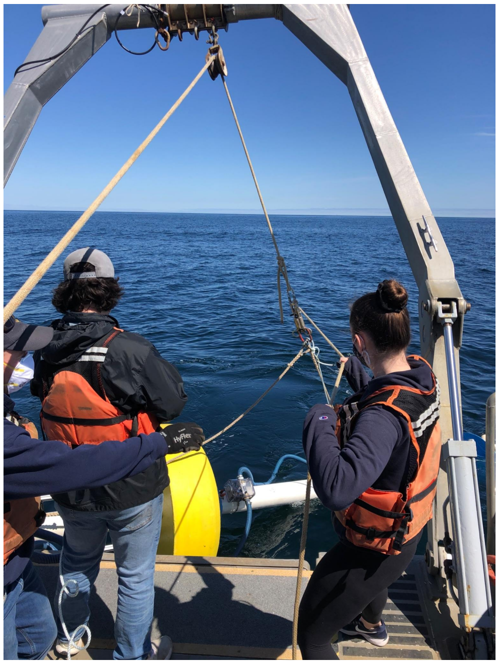


Figure 28a (left): Dakota pulling on the quick release to deploy the WPWP
Figure 28b (right): John Ahern hooking the tagline to connect the WPWP to the green surface buoy.

At first, the WPWP did not sit upright while in the water. In previous tank tests, the team had to manually upright the system at first, and then it would maintain a stable position. The team decided to deploy the RBR Duet and its mooring system in the meantime and see if the WPWP would right itself (see Figure 29a).

For deploying the RBR Duet, Capt. Bryan Soares moved the vessel about 100 yards south of the WPWP's position. The team readied the mooring system by shackling the 50 foot mainline to the 100 pound deadweight anchor, and then shackling the mainline to the subsurface buoy. The RBR Duet was zip-tied onto the mainline a few feet below the subsurface buoy to ensure it was in 50 feet of water, offsetting the length of chain connected to the deadweight. The tagline was then attached to the subsurface buoy and the team began paying out the line. Once the line was all payed out, the deadweight was lifted with the crane and was dropped in the water with the quick release at approximately 1:08 pm.

Figure 29a (left): The WPWP initially resting on its side when first deployed
Figure 29b (right): The RBR Duet (yellow) zip-tied a few feet below the green subsurface buoy. Picture was taken during retrieval

Although the WPWP seemed to be slowly righting itself, the team wanted to manually right it since it was still laying on its side. With all equipment in the water, the team asked Capt. Bryan Soares if he would be able to back up to the WPWP so the team could right the system. After reversing up to the buoy, the team successfully was able to right the buoy at approximately 1:18 pm, and the float immediately began moving with the surface waves. Once righted, the system stayed in a stable upright position. The team planned on observing the system's motion in the random seas for about thirty minutes, allowing for enough data to be collected.

Midway through the deployment, the team timed how long it would take to fill up a five gallon bucket with the outlet hose for a direct measurement of flow rate. Capt. Bryan Soares was able to back the vessel up to the buoy and kept the vessel positioned by the WPWP. John Ahern hung off the stern of the boat with a five gallon bucket and the buoy pumped water into the bucket (see Figure 30b). Dakota timed the duration, and it was approximately two minutes and twenty seconds for the bucket to be filled despite minor wave action.

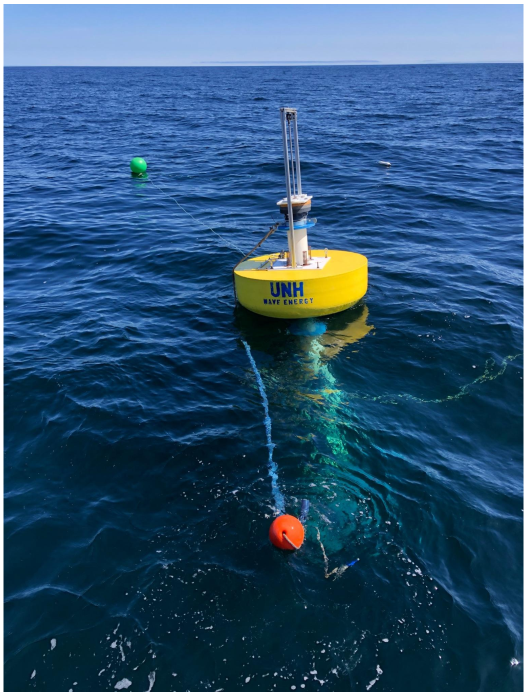


Figure 30a (left): The WPWP after righting it manually
Figure 30b (right): John Ahern hanging off of the stern of the Gulf Challenger, filling up a five gallon bucket with the output hose of the WPWP

7.3. RECOVERY

After observing the WPWP and conducting the bucket fill test, the team began retrieval of the RBR Duet mooring at approximately 2 pm. The tagline was hooked and tied to the winch line where Deb and Capt. Bryan started winching the mooring system with the A-frame crane. Once the subsurface buoy came up, John Ahern tied a horizontal rope from the cleats on either side of the A-frame through the mooring's mainline thimble to suspend it and allow for the winch line to be moved to the main line to complete retrieval. The RBR Duet was removed from the mainline, and the deadweight was successfully retrieved.

At approximately 2:20pm, the team then moved to retrieve the WPWP and its mooring system. The tagline attached to the bridle was hooked and then was pulled upwards to tilt the buoy on its side to access the bridle lifting point. Retrieval of the WPWP proved to be more difficult than deploying it, even with the absence of the quick release. Once hooked up to the WPWP's bridle, the mooring pendant was unshackled from the float, and the team had to try to adjust the buoy to position the top of the spar going into the boat. Due to how long the WPWP is, the team was having trouble getting the aluminum crossmember up and under the A-frame. To make the system as short as possible, John Ahern was able to tie the float to the bottom stopper riser clamp while alongside the stern. This gave enough clearance for the top of the aluminum bracing to pass under the A-frame when the A-frame was positioned as outwards as possible.

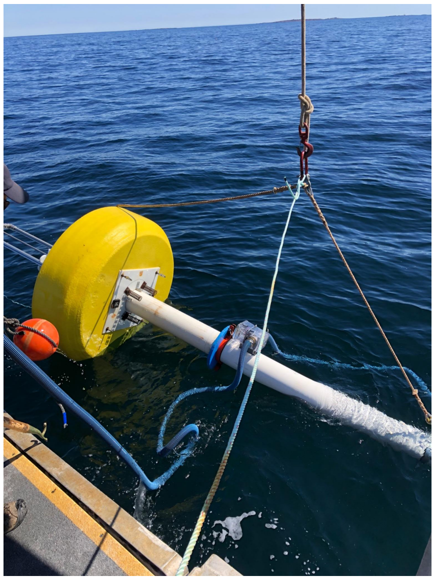


Figure 31a (left): The horizontal rope across the A-frame allowing for the winch rope to be transitioned to the main line.

Figure 31b (right): The WPWP prior to lifting, with the crane hook attached to the bridle. Note the float is fully extended, prior to John securing it to the bottom stopper.

Once the WPWP was hoisted aboard with the crane, it was put back into the same position. However, the rear stand had to be slid in up and under the spar as the lower riser clamp was lifted lightly by the crane. Once situated, the float was tied down with ratchet straps to secure the system. The team then went back to the surface float, hooked it, and attached the main line to the winch rope. Deb and Capt. Bryan then winched the deadweight aboard, successfully retrieving all components deployed.

At approximately 2:50 pm, the team headed back in towards the UNH Pier. The R/V *Gulf Challenger* returned to the pier at approximately 3:10 pm, and the team began unloading the vessel. The deadweights were hoisted by the crane up to the trailer first, and then the WPWP was hoisted up onto the trailer. The stand used on the vessel was tied to the spar and hoisted up with the WPWP in order to put it directly onto the trailer (see Figure 32a). The team then carted the mooring lines, buoys, tools, and any other equipment on board up to the CCOM truck.

Figure 32a (left): The WPWP being hoisted up to the trailer with a stand attached
Figure 32b (right): The WPWP and deadweights strapped down for departure back to UNH

The WPWP and deadweights were strapped down and secured in the same manner as earlier. The team then departed the UNH Pier at approximately 3:45 pm. After safely arriving back at Chase, the WPWP, deadweights, and all components used in the field test were sprayed down with freshwater. The moorings were unloaded with the Chase forklift and placed back into the Chase outside storage area. The WPWP was then unloaded using the forklift as well, and was carted back inside. The team brought the mooring lines, buoys, and tools into the High Bay and John Ahern returned the trailer.

7.4. RESULTS & DISCUSSION

Our analytical data from the flow sensor was unfortunately corrupted due to water leaking into the pressure housing. However we did collect an approximation during the field test, timing how long it took to fill a 5 gallon bucket directly above the water surface. With that measurement the WPWP pumped approximately 2.5 gallons of water per minute. Based on the way the data was collected, this measurement could be on the lower side of the pump's abilities. This could be due to the extra head that the pump had to overcome when the output hose was in the air pumping water into the bucket. Also, the pulling on the outlet hose could have had a negative effect on the pump's abilities as well, and the vessel could have disrupted the wave field.

The pressure data from the RBR Duet sensor showed that the average wave height was 0.6245 meters. When comparing this result with the data from the UNH Jeffreys Ledge data on April 8th at the time of the testing, which reported an average wave height of 0.8404 meters, the recorded pressure data seems reasonable. This discrepancy could be due to the near shore location of deployment when compared to the buoy at Jeffreys Ledge. The average period from the Jeffreys Ledge data for the field testing date and time was 6.65396 seconds.

Although the recorded wave pressure data showed a long period of smaller swells, there was also a mix of wind-driven chop. While observing the WPWP on the mooring, the team noticed that the system did seem to respond to the longer period swells, although not as noticeable as the wind-driven chop. The system seemed to respond well to chop, and even small chop produced relative motion. The float was very responsive to many different wave types. Due to the heave plate not being very deep in the water column, the spar may have been moving a bit with some of the taller swells.

8. CONCLUSION

This year's team was able to finish fabrication of the WPWP and successfully pump water in random seas. The main fabrication step completed was filling the empty space above the piston cylinder of the spar with foam to prevent water from accumulating there, without inhibiting the functionality of the system with too much friction. Other steps included creating a top spacer to allow for venting of air and water from the piston cylinder, a waterproof connection between the spar and tee housing, and a new bridal and lifting method.

The team proved that the WPWP pumped water both in the UNH engineering tank and in random seas during a deployment near the mouth of the Piscataqua River. A rough measurement showed the system pumped approximately 2.5 gallons of water a minute with 0.6245 average wave height in 1 to 3 foot seas.

8.1. FUTURE WORK

This year we were able to prove that the system works in random seas. We were however unable to collect exact measurements of the flow. Data collection for the flow would be a next step for the WPWP to fully gauge its abilities.

Through deployment we also discovered that the WPWP may need to be more stable. The system initially laid on its side when first deployed in the water, the concern is that if a large enough wave knocked the WPWP back onto its side it would be unable to correct itself back to the upright position.

Another improvement could be to develop an easier and safer method of retrieval. Deployment went smoothly, however when retrieving the WPWP it lifted parallel to the A-frame, making it difficult to turn and move back on the Gulf Challenger.

The final step in the future would be to integrate the WPWP into an aquaculture farm and observe if it makes a difference to the nutrient levels and production of the farm.

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[2] Ell, S., Harris, A., Leibundgut, W., Passaretti-Fina, S., Sanders, K., Ullrich, M. (2020, April 24). *Wave Powered Water Pump*. Department of Ocean Engineering, University of New Hampshire.

APPENDICES

Budget

Expenses	Cost ($)
R/V *Gulf Challenger*	1978
Arduino Flow Sensor	26.99
Arduino/Arduino elements	21.96
SD Card	7.49
Threaded PVC Couplings	13.94
Molykote 111 Compound	17.01
Foam (3 pcs)	20.20
8 inch Riser Clamp	47.67
Brass Fittings	79.98
Total	2213.24

Source of Support	Amount
New Hampshire Sea Grant	1000
ME Department	600
UNH Parents Association Grant	446
Personal Funds	167.24
Total	2213.24