Project S.O.A.K.
Submersible Oceanic Aquaculture of Kelp

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ABSTRACT

Sugar Kelp (*Saccharina latissima*) is a sustainable crop that requires zero fresh water, arable land, pesticides or fertilizers. Kelp contains more calcium than milk, more iron than spinach and more fiber than brown rice. It has the potential to make biofuels, locally reduce ocean acidification, and improve water quality by photosynthesizing excess nutrients. Kelp aquaculture in the US is in its infancy and new ways are being developed to grow it offshore. As a result, we designed a submersible frame made out of HDPE pipe for kelp grow out.

In the marine lab nursery, juvenile kelp was spawned on spools, made of twine wrapped around sections of PVC pipe. The seeded twine was transferred to the frame system by unraveling the spool onto the horizontal and vertical frame lines. Design considerations include the capability to withstand drag forces during coastal storms, convenience when submerging & raising to seed/harvest, and efficiency for growing large amounts of kelp in a reduced area. Held in place by two anchors, the frame is located offshore NH near the Portsmouth Lighthouse. Buoys suspend the square frame horizontally about 3m from the surface so the growth remains below the wave motion. This frame design can be implemented for large-scale use or in smaller coastal communities.

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BACKGROUND

I. Sugar Kelp

Sugar Kelp is a common brown seaweed which grows on rocky shores up to 30 meters deep. It grows quickly during early spring and prefers sheltered conditions. Sugar Kelp earns its name because it's sweeter than other kelps, thus used in cooking around the globe. It matures into a single broad frond with a crinkly edge, shown in Figure 1. The frond can grow up to 4m long and 15cm wide [1].

Figure 1: A blade of Sugar Kelp [2].

II. Why Farm Kelp?

Requiring zero fresh water, arable land, pesticides or fertilizers, Sugar Kelp is a sustainable crop rich in iodine, protein, calcium and vitamin C [3,4]. During the photosynthesis process, kelp absorbs nitrogen, phosphorus and carbon dioxide, which are three nutrients we have too much of in our coastal waters. The oceans currently absorb about 1/3 of human-created carbon dioxide emissions, roughly 22 million tons per day! The carbon dioxide in the ocean dissolves into carbonic acid, raising the acidity. Higher ocean acidity means lower calcium carbonate levels, which is difficult for shell forming organisms. This is problematic for New England's fisheries who get a majority of their value from these organisms which include: lobsters, oysters, mussels, etc. When these shelled organisms are at risk, the entire food web may also be at risk. Kelp farms can be beneficial for ecosystems by locally reducing ocean acidification [5, 6, 7, 8].

III. Pre-existing Kelp Farming Techniques

The 'long-line' technique is the primary method of kelp farming currently used around the world (Figure 2). It consists of roughly 400 feet of line extending between two moorings. The line is held 6-8 feet below the surface by intermittent buoys along the length of the line (Figure 3). Multiple long lines can be deployed by making them parallel to each other. The distance between the long lines affects the harvesting of the kelp because the kelp can tangle. The ideal distance found through experiments was 15 feet between each parallel long line; 10 feet resulted in minimal tangling, and 5 foot distances produced less growth in the kelp and resulted in tangling.

Figure 2: Example of a long-line kelp farming system [9].

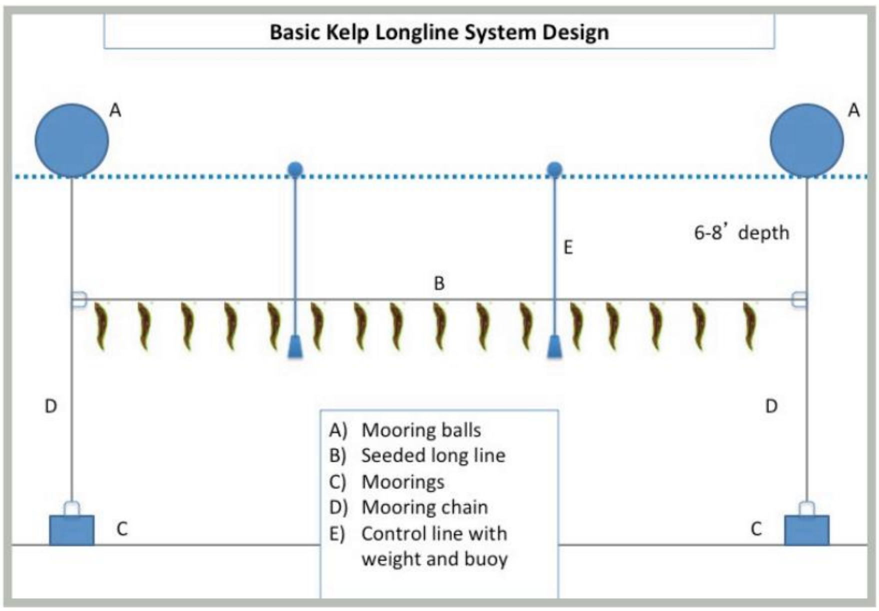


Figure 3: Diagram of long-line kelp farming system [10].

Long-line methods are simple and easy to use. However, they can take up huge areas, making them a less efficient method. Designing a frame structure that can produce large amounts of kelp in a reduced area would be optimal. Smaller site permits would be needed, which is especially beneficial for inshore areas with boat traffic. A design that can be scaled up/down would also be ideal to reach audiences of large-scale aquaculture farming to small coastal communities growing their own food.

MATERIALS & METHODS

I. Design Considerations

When designing an alternative kelp farming system, there were three major considerations: (1) the capability to withstand drag forces during coastal storms, (2) convenience when submerging and raising to seed/harvest, and (3) efficiency for growing large amounts of kelp in a reduced area. The design proposal consisted of a frame with lines stretched across it, suspended horizontally below the water surface. The system should be submerged deep enough to be under the harsh wave motion, but shallow enough for the photosynthesis process to occur.

The frame system design can be seen in Figure 4 below. Green dashed lines indicate the components that were seeded with immature kelp for growth, which include the four horizontal lines stretched across it, the eight vertical lines tied to buoys, and the frame perimeter. Held in place by two embedment anchors, the frame can be raised and lowered by adjusting the horizontal position of the anchors and the length of the vertical frame lines. This will be explained in detail later. Ideally, the design can be implemented for small coastal communities, or scaled up for large-scale production of kelp.

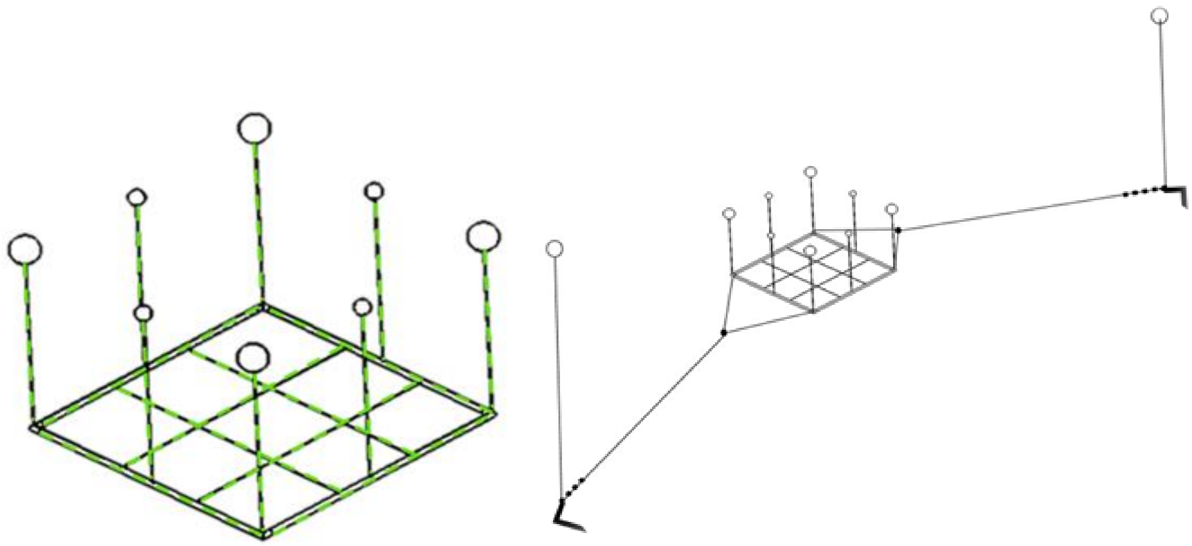


Figure 4: (left) Diagram of the frame indicating the components that were seeded (green dashed lines). (right) The frame system connected to the mooring system, which is composed of two anchors.

II. Site Conditions

The UNH inshore aquaculture site is located off the coast of New Castle, NH near the Portsmouth Lighthouse (shown in Figure 5). A permit was obtained by the NH Fish and Game Department to use the site. There was an aquaculture raft already at the site, called the Integrated Multi-Trophic Aquaculture (IMTA) Raft, which the frame was moored parallel to. The Judd Gregg Marine Research Laboratory, shown in Figure 6, was used for frame fabrication and assembly throughout the academic year (September 2016 - May 2017).

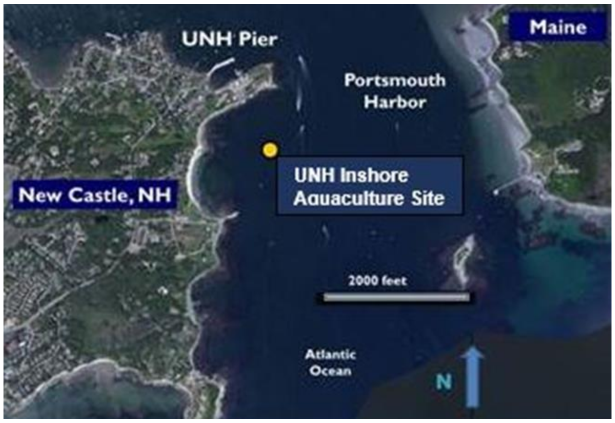


Figure 5: The UNH Inshore Aquaculture Site, located offshore New Castle, NH near the Portsmouth Lighthouse [11].

Figure 6: The Judd Gregg Marine Research Laboratory in New Castle, NH.

The UNH Inshore Aquaculture Site conditions were obtained from graduate student Corey Sullivan's thesis, in which he helped design and deploy the IMTA Raft. Rather than use the daily averages for wave height and period, storm conditions were of interest in order to find worst-case-scenario conditions. January 2016, winter storm 'Jonas' produced maximum wave heights and average wave periods shown in Table 1. The site depth and Piscataqua River max tidal velocities were also taken from Corey's thesis [11]. The flood and ebb tidal velocities are in the same direction because the site is located in a back-eddy on the ebb flow.

Table 1: UNH Inshore Aquaculture Site conditions of interest

Max Wave Height	1.6 m	Max Flood Tide Velocity	0.60 m/s
Avg Wave Period	5.0 s	Max Ebb Tide Velocity	0.15 m/s
Avg Depth	10 m		

III. Calculations

In order to construct a durable frame system that can withstand forces at the site, worst-case-scenario loadings were calculated. As shown in Figure 4, the frame is held in place by two embedment anchors. To ensure maximum durability of the mooring system, calculations were performed with the entire load on a single anchor line. The load, induced by fluid drag around the system, is due to the river current and waves. The force diagram (Figure 7) shows the induced drag force F_D due to the flow, the resulting tension in the anchor line T at some angle θ, and the necessary buoyancy force B to keep the frame at the desired level in the water column.

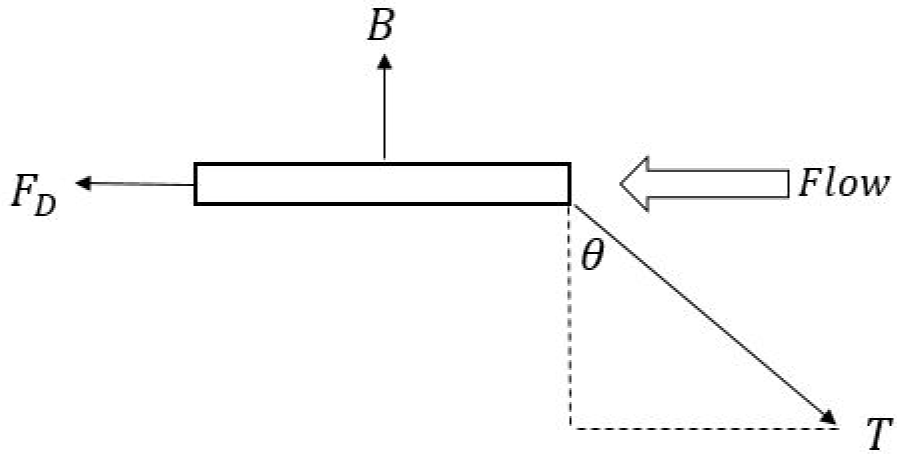


Figure 7: Force diagram of induced drag on a single mooring line.

The drag force, on the two frame lengths and two horizontal lines perpendicular to the flow, as well as the eight vertical lines, was found using the drag equation:

$$F_D = \rho C_D A_P {u_T}^2$$

$\rho = density\ of\ seawater$
$C_D = drag\ coefficient\ of\ the\ structure$
$A_P = projected\ area\ of\ the\ structure$
$u_T = total\ velocity\ of\ the\ flow$

The projected area was calculated for the two frame lengths and two horizontal lines each with an estimated 1 ft of kelp growth. To find the total velocity of the flow, the maximum river current velocity and maximum particle velocity due to waves are summed together.

$$u_T = u_C + u_w$$

$u_C = \max river\ current$
$u_w = \max particle\ velocity\ (waves)$

Where u_C is 0.6 m/s (site conditions Table 1) and u_w was found using the equation for the maximum particle velocity due to waves:

$$u_w = \frac{HgT}{2L}\frac{\cosh(k(h+z))}{\cosh(kh)}$$

$g = gravity$
$T = wave\ period$
$H = wave\ height$
$L = wavelength$
$k = wavenumber$
$h = water\ depth$
$z = depth\ of\ interest$

The wave period, wave height, and water depth were taken from Table 1. The depth of interest z is how much the frame is submerged. As z gets larger, the depth of interest is farther below the wave motion, and the max particle velocity due to waves will be less. The frame is suspended below the wave motion by 8 ft long lines, so z = 8ft = 2.44m.

The wavelength L was found from the dispersion equation:

$$L = \frac{gT^2}{2\pi} \tanh\left(\frac{2\pi h}{L}\right)$$

Which is a transcendental equation, meaning it cannot be solved for with basic algebra (notice the two L's in the equation cannot be grouped). Iterating this equation in Matlab obtains a solution for L, which can then be plugged into the wavenumber relationship:

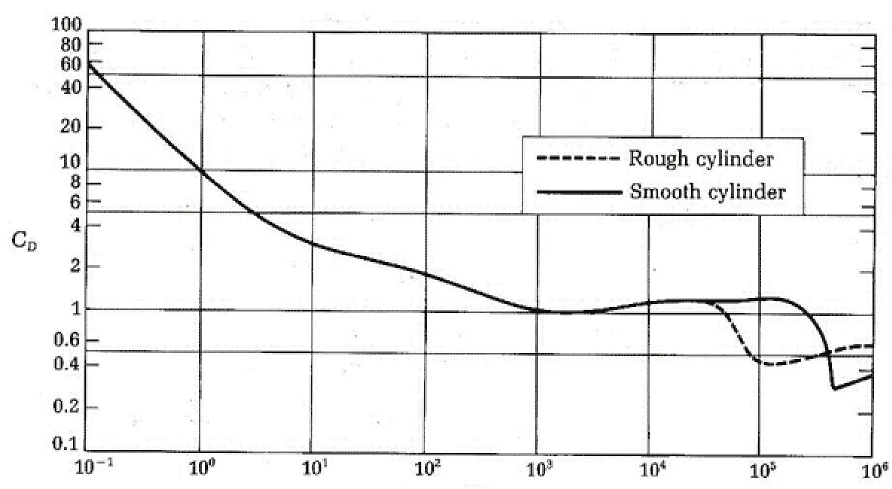
$$k = \frac{2\pi}{L}$$

Plugging these values into the max particle velocity equation produces a resulting u_w value. This can be summed with u_c to get a total velocity u_T value.

To solve for the drag force, the drag coefficient C_D needs to be found. This cannot be accurately calculated so a plot of Drag Coefficient vs. Reynold's Number was used to estimate C_D. Reynold's Number Re was found with the equation:

$$Re = \frac{u_T D}{\nu}$$

$D = characteristic\ length\ structure$
$\nu = kinematic\ viscosity\ of\ seawater$



Knowing Re, the drag coefficient was estimated, with the more extreme curve (smooth), to be approximately 1.2. Now that the drag force can be found, the tension and buoyancy can be found by summing the forces in Figure 7.

$$\sum F_x: T\sin\theta - F_D = 0 \qquad \sum F_y: B - T\cos\theta = 0$$

The angle of the anchor line θ was found using the site depth, and the approximate anchor distance from the frame, which is roughly 100ft = 30.5m. Solving for T, then B gives the tension in the mooring line under the loading and the necessary buoyancy force. Tables containing the values for each calculation can be found in Appendix III: Calculation Values. The final values for F_D, T and B are:

Table 2: Calculated forces.

F_D	T	B
6300 N = 1416.3 lbs	6577 N = 1478.6 lbs	1890 N = 424.9 lbs

Using a factor of safety = 2, the appropriate gear could be purchased (buoys, line, chain, etc.).

IV. Frame Fabrication

Four High-Density Polyethylene (HDPE) pipes were found at the UNH boneyard for the main components of the aquaculture frame (Figure 8 left). The UNH boneyard is an outdoor storage location for extra marine supplies on West Edge Drive in Durham. The pipes had a 4 inch outer diameter and were cut to 15 feet in length. They were slightly bowed from being piled up and exposed to weather. To join the four pipes into a square, four HDPE corners were ordered. The corners were 90 degree elbows with 4 inch outer diameters.

To attach the corners and pipes, an HDPE welding machine was used at the Judd Gregg Marine Research Complex (Figure 8 middle). The machine was composed of: the frame, which had clamps for two pieces to be held in place and a lever that slides one of the clamps horizontally (so as to apply pressure to the join), an extractable milling cutter which is essentially a circular plate with a razor that spins and shaves anything pressed against the spinning plate, and an extractable heating plate that can slide between the two clamped pieces.

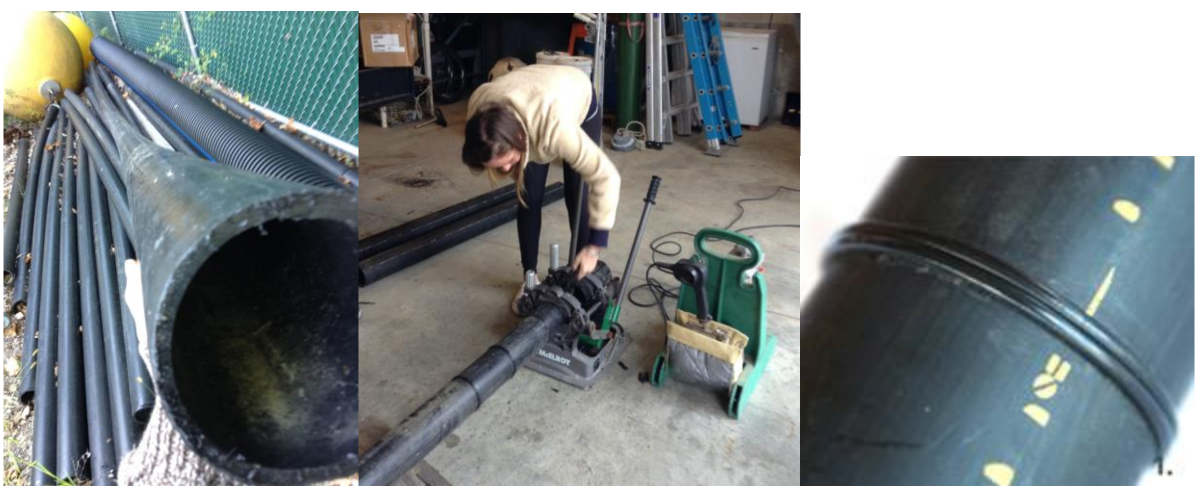


Figure 8: (left) HDPE pipes in the UNH boneyard. (middle) The HDPE welding machine. (right) The band formed when the hot plastic beads back, during the fusion welding process. [12]

To compensate for the warped pipes, the ends were shaved down until the pipe and corner were aligned on the same plane, allowing them to meet perfectly. The corners and pipes were then fused together via fusion welding. Fusion welding entailed heating each end by inserting the heating plate, at 400-450°F, between them and applying pressure. Once each end had melted down, the heating plate was removed and the two pieces were gently pushed together. This pressure to the hot plastic caused it to bead back and form a band at the welded joint (Figure 8 right). Once cooled, the join is as strong as the pipe itself because the bead is on the outside and inside of the pipe.

After all four pipes and corners were fusion welded, forming a large square (Figure 9), holes were drilled through the frame to allow the hollow structure to fill with water when submerged. This is to make the frame neutrally buoyant so that it won't float up into the wave motion. The final dimensions of the frame were 16' x 16' (because a single corner added ½' to the 15' pipe length).

Figure 9: The welded HDPE frame.

V. Mooring System

Using the theoretical forces that were calculated, the appropriate mooring gear could be purchased from New England Marine & Industrial. The mooring system consisted of the following components: anchors, chain, sinking line, shackles, thimbles, pear links, and buoys. Material specifications and pictures can be found in Appendix II. Figure 4 shows the diagram of the mooring system attached to the frame. The bridle lines come off the frame and connect to the anchor line, which goes down to the chain and anchor. From the anchor is a crown line connected to a crown buoy at the surface. The crown line serves to adjust the anchor position. Lifting the crown buoy pulls the embedment anchor out of the seabed, and moving the anchor farther/closer to the frame adds/decreases tension in the anchor line.

To raise the frame to the surface, the anchor should be moved towards the frame, providing slack in the anchor line. Then the eight vertical frame lines can be cinched, so that the frame floats to the surface. To re-submerge the frame, the eight vertical frame lines should be let out and the anchor should be moved away from the frame to restore the necessary tension.

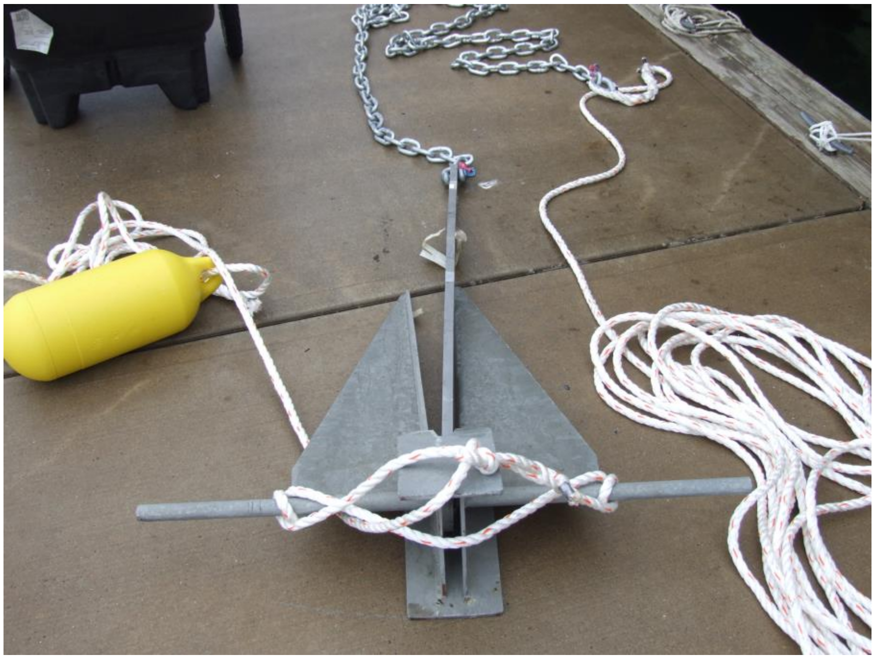


Figure 10: The mooring gear assembled on the dock.

Figure 10 shows the mooring gear assembled on the dock. The individual components were connected using shackles. It was important to make sure all connections were metal-on-metal, because the constant movement of the gear, no matter how slight, can wear out the materials over a long period of time. For instance, if the rope was tied to the metal shackles, it could chafe through, so we spliced the lines with thimbles (shown in Figure 11). Splicing lines consists of unravelling the three-strand line, melting the ends of each strand so they won't fray, then weaving the strands back into the line, creating a loop at the end around the thimble.For the non-metal connections, like the plastic buoys, the rope could just be tied securely.

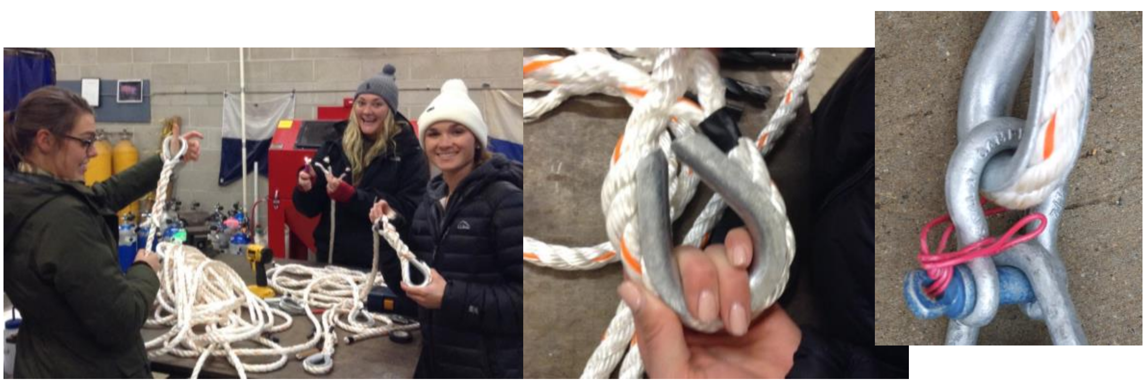


Figure 11: (left) Splicing mooring lines with thimbles. (middle) Close-up of the thimble in the splice. (right) The thimble and shackle connection secured with mousing wire.

The constant motion of the gear also has the potential of unscrewing the blue pins in the shackles. To prevent this, we used mousing wire, which is a copper wire coated in a tough plastic (Figure 11 right). The plastic prevents the copper from being cut through by the metals, while the copper is a strong metal to minimize movement.

VI. Kelp Spawning

The kelp was spawned on spools, which later allowed the immature kelp to be transferred to the frame for further growth. Six spools were prepared by wrapping twine around PVC pipe. A small device was created, to make the process faster, by using a drill to spin the pipe while guiding the twine around it (Figure 12). Sterile latex gloves were worn during this process to minimize contamination. The twine was pushed together forming a cover over the PVC pipe, then tied at the top using granny knots and rubber bands. After the spools were finished being twined, they were wrapped in pliofilm and placed in a freezer until ready for use.

Figure 12: Preparing the spools using a drill to spin the PVC pipe, while the twine was guided onto it.

For the kelp spawning nursery, two 20 gallon tanks were placed in the Judd Gregg Marine laboratory and filled with seawater. The tanks, settling tubes, PVC pipe, twine, and water were all sterilized with 50 mL of bleach. In order to neutralize the bleach, 5g of sodium thiosulfate was added to the tanks. Then a simple chlorine test was used to determine whether the water was safe for use. Figure 13 shows the assembled nursery tank.

Figure 13: The kelp spawning nursery.

Once the nursery was set up, mature sorus tissue was collected from kelp on the UNH pier docks, and brought to the lab where the spawning process began. The healthy sporangia tissue on the mature kelp was cut out and any sections containing bryozoans were thrown away due to contamination. The tissue was then wiped down three times on each side and placed in a 3% iodine bath. It was then placed in a seawater bath, patted dry and folded into a paper towel. Once each piece of sorus tissue was prepped and wrapped individually in paper towels, it was ensured that none of the pieces were touching, in case of any contamination or premature spawning. They were then placed in a refrigerator at 50°F for 24 hours.

Next, the six spools were placed in settling tubes in the sterilized nursery to thaw (greenish-blue tubes in Figure 13). While the spools were thawing in the nursery, two beakers were then filled with seawater and left to reach 60°F to 65°F. The sorus tissue was evenly distributed between the two beakers and left to sit for either 45 minutes or until the water temperature decreased to 50°F while sitting out. During this time, the water progressively turned brown as the spawning process continued (Figure 14). The kelp released zoospores into the water which then externally fertilized, forming sporophytes. The sporophytes are the diploid multicellular phase of the kelp cycle that arise from zygotes [13]. The kelp tissue was then removed, and the remaining spawned water was evenly distributed between each of the six settling tubes. They were then covered with tinfoil and left to sit in a 12 hour dark cycle to allow for attachment.

Figure 14: Healthy sorus tissue during the spawning process

After the spawned kelp had attached to the twine on the spools, the nursery was kept on a 12 hour LED lighting system of light and dark cycles for photosynthesis for four weeks. Every week that month, the spools were switched over to a fresh tank with Provasoli Enriched Seawater Nutrients (PES). Store bought nutrients were initially used on the first batch of spawned kelp in the nursery. However, these nutrients were not sufficient enough for the kelp growth process due to competition with diatoms on the growing kelp. This led us to create our own Provasoli Enriched Seawater (PES) culture nutrients in the laboratory which was used. PES was made with four solutions.

Solution 1:

1797 mL deionized water
12 g of Tris buffer
8.4 g of $NaNO_3$
1.2 g of Na_2 glycerophosphate
0.012 g of Thiamine-HCl (Vit. B_1)

Solution 2: Iron based solution Fe (as EDTA complex; 1:1 molar)

1L of deionized water,
0.700 g of Fe $(NH_4)_2$ $(SO_4)_2$ $6H_2O$
0.600 g of Na_2EDTA

Solution 3: P II metals

1 L of deionized water
1 g of Na_2EDTA (Disodium ethylenediamine tetraacetate)
1.140 g of H_3BO_3 (Boric Acid)
0.049 g of $FeCl_3$ $6H_2O$ (Ferric Chloride)
0.130 g of $MnSO_4$ H_2O (Manganese sulfate monohydrate)
0.005 g of $CoSO_4$ $7H_2O$ (Cobaltous sulfate heptahydrate
0.022 g of $ZnSO_4$ $7H_2O$ (Zinc sulfate, 7-hydrate)

Solution 4: vitamins

25 mL deionized water
0.002 g of Vitamin B_{12}
0.001 g of Biotin

Once the kelp was strong enough, the spools were taken down to the dock and left to grow in the ocean until the structure was ready for deployment.

Figure 15: (left) Store bought nutrients. (right) Making Provasoli Enriched Seawater (PES) nutrients in the lab.

VII. Deployment

Deployment took three days to complete. On March 24th, seven of the 8-ft-long vertical lines were seeded with one spool. To transfer the seeded twine onto the rope lines, one end of the twine was tied to the rope end, then the rope was fed through the PVC pipe. As the rope was pulled through the pipe, the twine unraveled from the PVC pipe and wound around the rope (Figure 16 left).

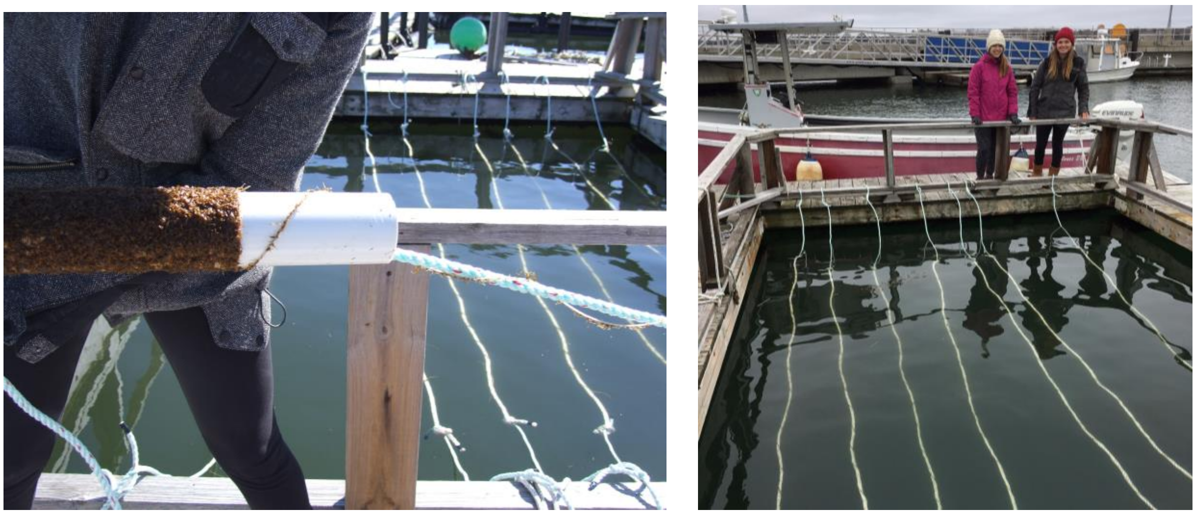


Figure 16: (left) The seeded twine being transferred from a PVC pipe to a vertical frame line. (right) The seeded vertical frame lines tied in the middle of a raft in the bay (Vessel ‘Red Tide’ in the background).

The seeded lines were temporarily tied in the middle of a raft, in the bay, for full access to sunlight (Figure 16 right). Only seven vertical lines were seeded because once a spool has started unraveling, the entire spool must be used. Time prohibited starting any further seeding because a snowstorm was coming in and we wanted to deploy the mooring system. The mooring system was loaded onto the vessel ‘Red Tide’ and deployed at the site. Both anchors were dropped, along with the crown lines, mooring lines, and bridle lines. The bridle lines were temporarily tied to one of the large buoys until the frame could be deployed at a later date. When the anchors were dropped, one of the locations was deeper than expected, resulting in one of the crown buoys being pulled under the surface. The snow was thickening and the wind was picking up, making the water too rough to attempt locating the crown buoy.

On the second day, March 28th, the frame was carried down to the beach. Three, 4 lb dive weights were fastened to each corner with hose clamps, providing 12 lbs on each corner and a total of 48 pounds on the whole frame. The purpose of weighting down the frame is to keep the frame below the wave motion, in case an anchor becomes un-embedded or if one of the mooring lines break.

Figure 17: (left) Attaching buoys and weights to the frame on the beach. (right) A close-up of the dive weights being fastened to the corner of the frame using hose clamps.

While on the beach, six of the eight buoys were attached to the frame. The seventh buoy was used during the mooring system deployment at the site, temporarily holding the bridle lines at the water's surface. A long line was tied to the structure and the eighth buoy. The buoy was thrown out to deeper water in the bay, where a waiting Red Tide caught the buoy with a gaff hook and tied the long line to the boat cleat (Figure 18). The structure was then pulled off the beach and towed to the raft containing the seven vertical lines. The frame was temporarily tied to the side of the raft, until its deployment at the site.

Figure 18: (left) Throwing the buoy (tied to the frame) out to deeper water, where Red Tide could retrieve it. (right) Red Tide towing the frame off the beach.

On the third day, March 30th, the four horizontal lines, remaining vertical line, and one long perimeter line were seeded. They were coiled and placed in water-filled-coolers for transport. Keeping the seeded lines wet during deployment was crucial to avoid desiccation or dramatic change in temperature. The frame was pulled up on the starboard side of Red Tide, tied to cleats, and transported to the site (Figure 19).

Figure 19: Tying the frame to the boat cleats for transport to the site. Water-filled-coolers containing the seeded lines are shown as well.

Red Tide's port side was tied to the IMTA raft, so the frame could be untied from the starboard side. The frame was lifted on top of the IMTA raft and the four cross lines and perimeter line were attached (Figure 20). Water was continuously splashed on the kelp lines while the frame was out of the water. The seeded lines were tied onto the frame and duct-taped, to keep them from sliding along the frame. While duct tape is not a permanent fastener, it was sufficed for the purposes of this project.

The frame was then carefully lifted, placed back in the water, and attached to the mooring system. While switching the bridle lines from the buoy to the frame, the mooring lines appeared to be tangled. This could have been caused by slack in the lines and the current causing them to twist. The bridle lines were attached anyways, and the remaining eight seeded vertical lines were attached the frame and buoys by lifting the frame on the side of the boat and rotating it. Later, divers went out to untwist the mooring lines and add extra line to the submerged crown buoy.

Figure 20: (left) The frame lifted on top of the IMTA raft. (right) The IMTA raft, located next to the Project SOAK frame system at the site.

RESULTS & DISCUSSION

I. The Design

While a long-line technique may be more user friendly, the frame design allows for more seeded lines in a smaller area. The materials used were easy to find, purchase and work with. Although the pipes were warped, shaving and leveling was a simple technique to get the pipe ends to meet the corners.

Site conditions were easy to obtain thanks to Corey Sullivan's thesis, on the IMTA raft. This helped the project get started quickly, because no data had to be collected. However, this created a problem when the average depth measurement at the site, was not the depth experienced during deployment; this caused one of the crown line buoys to be pulled under the surface. It was found that the depth at that buoy's location was about 5 meters greater than expected.

Using a factor safety = 2 with worst-case-scenario loadings ensured the structure could withstand harsh conditions. In addition, all the mooring materials had different working load limits (Appendix II: Material Specifications), so finding worst-case forces with a factor of safety made selecting the gear easier. In the future, it could be helpful to calculate cyclic loadings on some of the gear and the kelp. This could provide estimates for the design's limitations in different coastal environments.

II. Spawning the Kelp

Spawning the kelp was a relatively easy process. However, this year was warmer so it took longer to find mature kelp with healthy sorus tissue, thus delaying the project. Once enough kelp was collected and spawned, the first batch of seeded spools experienced competition with diatoms once they were moved to ocean water. Unfortunately, the diatoms outcompeted the kelp, causing the spools to be of no use to the project. The spawning process takes about 4 weeks, so the project was further delayed, while a second batch of spools was prepared.

It was suspected that the store-bought Proline F2 Algae food was contaminated and contributed to the diatom growth (Figure 15). New kelp was collected and prepared for the spawning process. During this time, Provasoli Enriched Seawater Nutrients (PES) were made in the lab (Figure 15). Through the same spawning process, the second batch of spools attached and continued healthy growth after being moved to seawater.

II. Deployment

During the deployment process, the seeded lines were tied in the middle of a raft to continue growth. While there was more access to sunlight on the raft, it obstructed water flow around the seeded lines. This could have inhibited nutrient flow to the immature kelp. Meanwhile, utilizing the beach to attach the weights and buoys added an extra step, but it was safer and faster than attempting to attach them at the site.

Deploying the mooring system first, made the entire process a series of steps, which allowed time between steps to asses any problems and prep for the next step. This also made coordinating between students in different disciplines (with different schedules) easier.

When transporting the kelp to the site, using water-filled-coolers allowed for the kelp to stay wet. While coiling the seeded lines to place in the coolers, the twine unraveled from the lines and created a messy pile of twine and rope in the water. At the site, the lines were separated and uncoiled causing some of the kelp to fall off the twine, proving this method to be disadvantageous.

Another unforeseen issue occurred while attaching the frame to the mooring system bridle lines. The current was spinning both Red Tide and the structure, causing the two mooring lines to tangle. This wasn't a huge issue for the project because divers would be able to fix it. But, the target audience for this design is the average kelp farmer, who may not have diving equipment or experience.

Once the frame system was fully deployed, kelp growth and structure integrity were observed. The frame has proven to be durable throughout the process of deployment and continues to endure, despite strong currents and waves.

CONCLUSION

Project S.O.A.K was a successful interdisciplinary project incorporating both engineering and biology. A submersible kelp aquaculture frame system was engineered, while the harvesting and spawning of wild kelp was completed for attachment and deployment at the UNH inshore aquaculture site off the coast of New Castle, NH. The kelp growth and structure will continue to be monitored until harvesting season in July. The system has withstood the environmental conditions at the site, and kelp is growing at a healthy rate.

Future kelp aquaculture project goals could include monitoring pH and CO_2 levels with sensors, to investigate the positive impacts of the kelp photosynthesis process on local water quality. Designing a system that incorporates both kelp and mussel farming could also be of future interest. This could show the relationship between lowering ocean acidity (during kelp photosynthesis) and mussel productivity.

APPENDIX I: REFERENCES

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[6] http://ocean.nationalgeographic.com/ocean/explore/pristine-seas/critical-issues-ocean-acidification/

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[10] http://www.readingeagle.com/ap/article/lobster-schlobster-seaweed-is-maines-hot-new-product

[11] All Season Mussel Raft and Fish Cage

[12] http://www.sinvacpiping.co.za/fittings.html

[13] Kelp farming manual

APPENDIX II: MATERIAL SPECIFICATIONS

8 Frame Buoys

- 16" diameter
-75 lbs buoyancy
-hardshell buoy

2 Crown Line Buoys

-7.5" x 20"
-21 lbs buoyancy
-hardshell buoy

2 Sections of Mooring Chain

-20' long
-½" long-link
-hot-galv
-Working Load Limit = 6000 lbs

2 Danforth S3500 Anchors

-Weight = 100 lbs
-Hold Strength = 3500 lbs

8 Thimbles

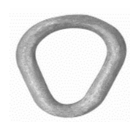
- ½" heavy wire rope

600' coil of Potwarp Sinking Line

-⅝" thickness
-Max working load = 3600 lbs

2 Pear Links

-½" Weldless Sling Link
-working load limit = 2900 lbs
-drop forged carbon steel, galvanized



14 Screw Pin Shackles

-drop-forged carbon steel, galvanized
-12 are smaller = ½"
    -working load limit = 2 tons
-2 are larger = ⅝"
    -working load limit = 3-¼ tons

*All photos taken from: New England Marine & Industrial Website

12 Dive Weights
-4 lbs each

8 Hose Clamps
-galvanized steel
-Home Depot

4 HDPE pipes
-High-Density Polyethylene pipe
-4” outer diameter
-15’ long
-taken from UNH boneyard - marine storage

4 HDPE Corners
-High-Density Polyethylene pipe
-4” outer diameter
-90 degree elbow
-ordered from ISCO Industries

APPENDIX III: CALCULATION VALUES

Known values

g	9.81 m/s	z	2.44 m
T	5 s	ρ	1000 kg/m^3
H	1.6 m	ν	1.31 x 10^{-6} m^2/s
h	10 m	u_C	0.60 m/s

Calculated values

Θ	73.3˚	u_W	0.43 m/s
L	35.96 m	u_T	1.03 m/s
k	0.175 rad/m		

Horizontal line with kelp

D	0.324 m
Re	2.55 x 10^5
A_P	1.48 m^2
F_D	641 N

Vertical line with kelp

D	0.324 m
Re	2.55 x 10^5
A_P	0.987 m^2
F_D	427 N

Frame with kelp

D	0.396 m
Re	3.12 x 10^5
A_P	1.85 m^2
F_D	801 N

Above, the drag forces were calculated for each type of component in the flow. To find the total drag force over the entire structure, the drag forces must be summed:

2 horizontal lines = 2 x 641 = 1282 N
8 vertical lines = 8 x 427 = 3416 N
<u>2 frame lengths = 2 x 801 = 1602 N</u>
Total drag force = 1282 + 3416 + 1602 = 6300 N
F_D = 6300 N

Using F_D in the sum-of-the-forces equations to find T and B gives:

F_D	6300 N	1416.3 lbs
T	6577 N	1478.6 lbs
B	1890 N	424.9 lbs