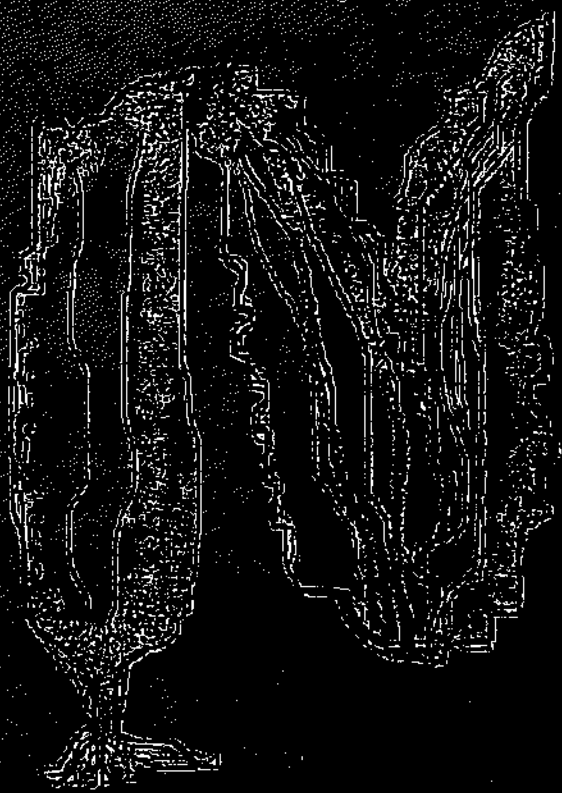
Kelp Open Ocean Aquaculture



Tech 797-Ocean Projects

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Abstract:

Whether it be high fuel prices, climate change, or other reasons, many humans are beginning to look for some type of renewable energy as a solution to the imminent fossil fuel shortages. Many believe that ethanol made from corn could be a solution. However, others argue that we could not feasibly grow enough corn for both our rising fuel and food needs. But what if you could grow a crop with high sugar content, a key component needed in the production of ethanol, in an area which takes up over 70% of the Earth? What if the crop could grow two feet per day if in the right climate? What if a solution to our energy crisis was kelp?

Through design, modeling, and testing it was determined that starting a kelp farming operation was an economically unstable undertaking. This cost analysis accounted for materials needed to build the farming structures, laboratory chemicals for germinating and growing live kelp plants, as well as other costs associated with running a business. The summary included assumptions of the initial costs necessary and the length of time needed to recoup the initial investments and begin to turn a profit. Through this summary it was determined that growing kelp as a business venture does not seem profitable enough to suggest a kelp farming industry.

Introduction:

Although kelp has been harvested from the ocean for thousands of years, the industry of commercial kelp farming is fairly young. Seaweed aquaculture is believed to have originated around the 17th century when fish farming was becoming popular and it was discovered that kelp was growing on the lines and fences that contained the fish farms (Tamura, 1966).

Kelp has many uses and is a highly versatile crop for this reason. Although fish, crustaceans, and shellfish still currently play a larger role in the aquaculture industry, the cultivation of seaweed is none the less alluring, and has the potential to be a profitable industry. For example, between the years of 1993 and 2002, the seaweed market grew by an estimated 26% to approximately 6 billion dollars (McHugh, 2003; FAO, 2004).

The uses of kelp include but are not limited to: food, fertilizer, and medicine. The growth of seaweeds for human consumption traditionally has taken place in Japan and China (Kawashima, 1993; Tseng, 1993, 2001; Ohno and Critchley, 1997; Critchley and Ohno, 1998). However, as the need for bio fuels and alternative sources of energy increase, a high energy source such as kelp could prove to be a valuable resource, and research is being conducted on using the kelp biomass as a source of energy.

Large investments have been made researching fuels such as biodiesel and bio-ethanol which are traditionally based on seeds and fruits of plants. However these fuels alone are not capable of solving the world's pollution problems and still less capable of meeting growing energy demands of the world. For this purpose, second-generation biofuels are needed. These are made from feedstock based on the whole plant and biomass, which would theoretically be an efficient use of kelp (Noweck, 2007). Experts believe that biomass could satisfy one-third of world energy demand (Miiller-Langcr, 2006; Faaij, A, 2006) and this is why more research projects are being launched worldwide for the purpose of developing commercial biomass-based processes. Kelp open ocean aquaculture fits the type of commercial project that would greatly benefit from this type of biofuel research and development.

Harvesting kelp that grows naturally along a coastline can be detrimental to the local ecology, upsetting the natural ecological balance. Growing kelp in a manner designed specifically for harvest, such as growing kelp on lines in the open ocean, would not only be an easy way to grow and harvest large amounts of kelp in a small area, but also would be more ecologically sound. By the early 1950's, it was hypothesized that a scientifically supported culturing technique, consisting of caring for and growing spores in a lab before transplanting them into a farm, would result in successful commercial production. (Scoggan *et al.*, 1989)

Harsh weather conditions, and mixes of species harvested in the wild causes variable quality of marketable *Saccharina latissima*. The placement of a structure to serve as a farm would benefit the growth and ultimately the profitability of kelp. *S. latissima* is the type of kelp that grows in northern waters such as those located off the gulf of Maine. Prior cultivation tests have been completed on four different structures in northern European waters. These tests were the primary source of our research because although kelp has been successfully harvested in many parts of the world, northern wind, light, temperature, and current conditions are drastically different then the location of the successful seaweed culturing economies of the south pacific and off the coast of China. One of the positive reasons to pursue kelp farming in northern waters is that plants exposed to high current velocities or to wave action tend to have narrower branches and blades as well as differ in thickness and length, but positively these morphological changes, which are responses to increased water motions, have the potential to reduce drag forces and enhance plant toughness. Plants with exposed-habitat characteristics are less susceptible to damage or destruction by rapid currents and wave variations then kelp plants grown in sheltered habitats (Gerard, 1987). These characteristics are desirable because of the turbulent nature of the waters in the Gulf of Maine, and the subsequent loading on the plants that would be growing in a somewhat unnatural environment.

The basic design and purpose of a kelp farm are plants which are grown on lines that are anchored to the ocean floor. This allows the kelp to be harvested without floating away, however due to the layout of kelp farms and depending on size, harvesting can be one of the greatest challenges. The density of kelp growth is the reason that there have been difficulties in the planning and harvesting of kelp farm. Depending on the magnitude and location of the farm, kelp can be harvested in a variety of ways, from hand picking by divers to a more economical process involving automated machinery and boats. This has been a problem for planning out kelp farms in the past and was one of the main focuses of our research. The attempts of Buck and Buchholz were analyzed and studied as crucial characteristics of our design were developed.

Four different cultivation systems designed for offshore use: these included the longline, the ladder, the grid, and the ring. The ladder and grid constructions were oriented parallel to the main direction of the tidal current. The ladder and grid constructions were very similar to each other in that the ladder was simply a series of grids. The longline consisted of a 50m long, horizontal carrier rope anchored by a 4 metric ton twin mooring system. Its purpose was to fasten culture lines perpendicular to the water surface, while being kept in place by a concrete weight. The weights on the culture lines were insufficiently heavy, and were tossed across the carrier line effectively removing the young *S. latissima* by friction and causing them to become entangled with each other (Buck and Buchholz, 2004).

The ladder construction was 60m X 10m in size and was positioned horizontally 1m below sea surface by using a combination of concrete weights oriented around the structure perimeter, and air filled buoys at the surface to keep it afloat. The weights on the ladder proved to be potential breaking points on the structure and the buoys at the corners were very unstable and had to be exchanged (Buck and Buchholz, 2004).

The ring construction had a total diameter of 5m and consisted of a polyethylene tube with a 10mm thick wall and a diameter of 110mm that was welded to rings. The rings were weighted down by a steel cable (30mm in diameter) inserted into the tube. Carrier ropes, which would hold the kelp spores, were suspended radially and 80m of culture line could then be fastened like cobwebs on each ring. The ring needed to be lifted by a land based crane and towed into the harbor (Buck and Buchholz, 2004). This proved to be quite inefficient due to the inability to raise and lower the structure on the growing site.

The grid system that had been used previously off the Isle of Man and in Brittany, off the coast of Great Britain, measured 60m X 30m and was submerged at a depth of 1.2 m below surface (Perez *et al.*, 1992, Kain, 1991). The frame was made of "Herkules" rope, commonly used by commercial fisheries, and is heavier then the surrounding seawater, which reduced the risk of breaking where weights were attached. The grid proved to be more stable then the ladder structure, but during this test, the structure was destroyed by the crew of a yacht who ignored the official signs, and became tangled in the ropes, effectively ruining the structure. (Buck and Buchholz, 2004)

Although the ring probably is the best design documented presently for off-shore use, however, a major flaw is the fact that to harvest, the entire structure needed to be towed by a land based crane out of the water. In order to convert this off-shore design for large scale and for open ocean use, some sort of crane on a boat would need to be used. This would prove to be financially more expensive and laborious than a design that would be a permanent fixture, meaning that only the lines would need to be removed and replaced with harvesting, not the whole structure as in the ring design. Also, harvesting with a grid-type structure could be done with a standard fishing boat and little cost would be incurred for specialized equipment. After studying the tests on these different structures, our group decided to pursue a square shaped grid-like structure, but researched and developed alternative methods for raising and lowering the structure.

Design Criteria:

Design of Structure:

The current design was chosen after weighing several different criteria ensuring that the farm would be a rational undertaking. Basically, the kelp farm needs to have the ability to grow kelp efficiently, allow the kelp to be easily harvested, and be relatively economical to construct. A great deal of consideration was given to prior attempts at growing kelp, as have the designs of several of the OOA fish cages, before making the current design to hopefully overcome the flaws in these previous attempts.

We decided on the current design because it seemed to fit our design criteria the best, and we believe it would be feasible to construct a kelp farm in this manner. The basic growing platform would consist of a 50ft x 50ft square constructed out of 4" PVC pipe. There would be 25 growing lines spaced at 2 foot intervals running parallel to each other going from one side of the square to the other. This structure is designed to be raised and sunk utilizing an airlift system that will counteract a pendant weight. The entire system is then designed to be attached to one of the existing grids at the OOA test site off the Isles of Shoals. Figure 1 below is a rough sketch of the current design, illustrating the basic design of the structure.

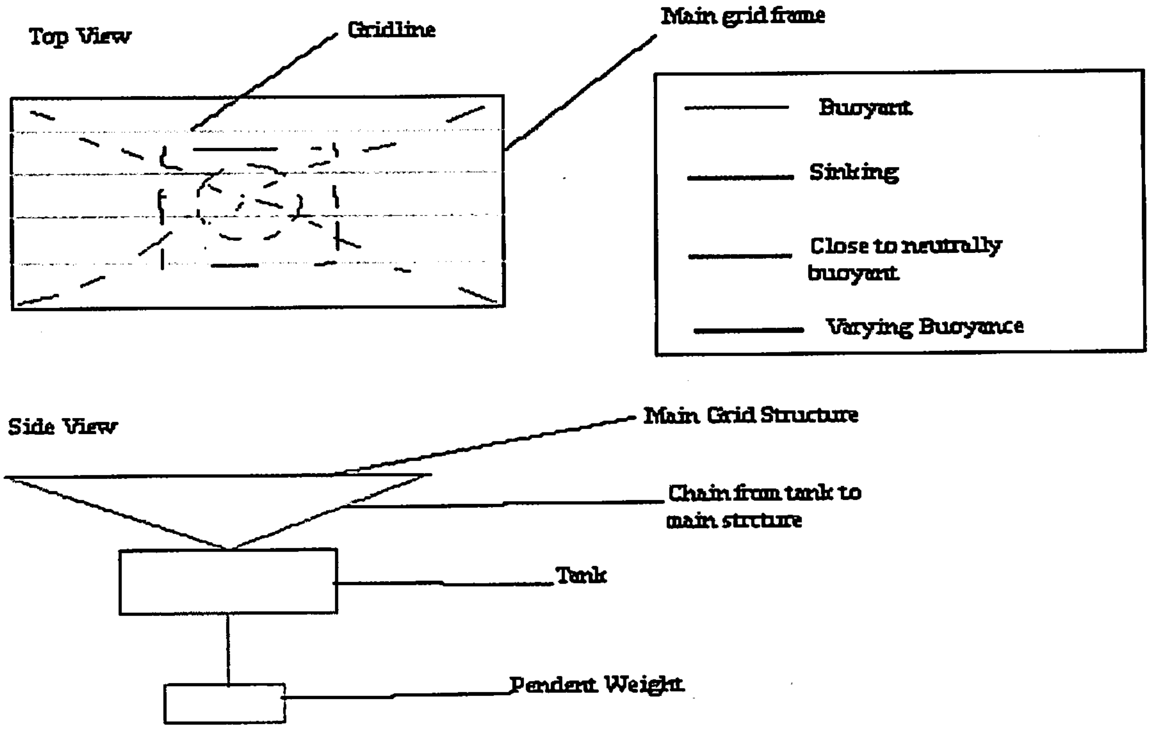

Figure 1
Schematic of chosen design. Notice how the different colors represent the different levels of relative buoyancy, and how they would ultimately affect the raising and lowering of the structure.

Within each one of these main components, the airlift system, growing surface, and pendant weight, several considerations needed to be made when designing each sub component. In terms of the growing surface, it needed to be quite buoyant, so it would not sink, but its buoyancy could be counteracted by the weight of the pendant weight. By using hollow PVC pipe, which in it's self is of quite low density, and allowing it to be sealed from allowing water to enter, the entire growing surface would naturally float. The square shape was chosen to normalize the lengths of the lines used for growing the kelp, as well as allowing the kelp to be harvested more easily. With the current square design, the lines that would hold the kelp could be harvested by detaching one end of the line, and tying it to an already seeded line. Then the line to be harvested would then be pulled from the opposite end of the structure and, as it is being removed, replaced with a new line. This eliminated the need for highly specialized equipment like hydraulic haulers and cranes that proved to be a problem with previous kelp cultivation attempts.

In terms of material considerations, the main grid structure will be made of Polyvinyl Chloride (PVC) piping. PVC is the best choice because it is relatively inexpensive to buy and replace (should the structure be damaged by a storm) and is impervious to being broken down by saltwater. The low density of the PVC, and its being in pipe form, allows the ends of the long pieces to be capped, and, when filled with air, allows them to float. This is of particular importance in the current design because the growing grid must naturally float above both the pendant weight and lifting apparatus to prevent tangling, and to keep the kelp at the optimal height for growing. The pressure vessel on the full-size structure will be made out of steel, with welded seams and mooring connections. Rather than fabricating an entire pressure vessel, it was decided, and deemed feasible to convert a large propane tank into the airlift pressure vessel. This is different than the vessel used on the tested model, however, at the scale that the model testing was done at, it was impractical to use a steel pressure vessel because the scaled dimensions of the vessel would have been difficult to construct.

A fair amount of consideration was given to the construction of a pendant weight to use for the full-scale farm. In the scaled model, a piece of steel pipe was used simply to provide some weight to illustrate the action of the lifting mechanism. The actual pendant weight will have the problem of imbedding itself in the bottom wherever the farm is to be deployed. A traditional anchor would definitely provide the necessary mass to sink the farm and keep it from moving too much on the bottom, but may imbed it's self into the sediment, making retrieval an issue. Naturally, it is difficult to test the amount imbedded of pendant weight systems, both in the lab and in the field, thereby making actual analysis of the pros and cons of each different type of weights difficult. Therefore much of the reasoning behind the decision made is purely qualitative. Since the need to actually have the structure anchored was deemed unnecessary, a flexible anchor could be used that would not imbed its self in the mud. It was then decided that a piece of heavy-duty steel anchor chain would allow ample weight to sink the grid, but at the same time not being as susceptible to imbedding or hanging on the bottom such as the problem with traditional anchors and mooring blocks.

In terms of deciding on the type of lines on which to grow the kelp, several important variables such as diameter, material composition, cost, static, and dynamic characteristics needed to be considered. The manner in which the kelp is being grown is inherently a two-stage process, in which the kelp is first "seeded" on a very long piece of relatively small diameter line which is spooled onto a piece of PVC pipe, then, once the kelp shows signs of being stable enough to be introduced to a larger line, the smaller line is wound onto a larger diameter line allowing the maturing kelp plant to adequately anchor itself. Although kelp is able to attach to virtually anything, in order to ensure that it is able to attach its self and not be swept away, it is best to use a line that is wound relatively loosely and is inherently fibrous. This allows for the roots of the kelp to easily entangle themselves into the fibers of the rope, and create a solid anchor point. To do this, several different thicknesses and common types of rope were tested to determine their elongation and stiffness characteristics. Through this experiment, it was concluded that 5/16" neutrally buoyant potwarp was the best choice for the chosen design. The delineation of the procedure used to test these ropes, including the descriptions of the instrumentation and results used can be found in the results section, and in appendix 1.

For selection of the structural ropes that would connect the growing platform to the airlift tank, pendant weight, surface mooring buoy, and ultimately a grid similar to the OOA test grid at the Isles of Shoals, 4" braided nylon line was chosen. These were chosen because they allow for a huge factor of safety in terms of the ability to sustain long-term wear and tear that could be associated with line of this diameter. This, coupled with the testing results obtained by the group that showed that nylon line had the most elastic properties (SEE results, appendix 1), thereby making it ideal in a dynamic mooring-type environment, where the lines will be subject to impulse loading due to wave and tide motion.

Design of a pressure vessel:

A pressure vessel is a closed, rigid container designed to hold gases or liquids at a pressure different from the ambient pressure. A submersible pressure vessel must be designed around the constraints of the atmosphere it will be submerged in, as well as the performance requirements that it will be designed to uphold in the chosen environment. For use in the kelp farm there are three design considerations that must be accounted for when the pressure vessel is designed so that it may be effectively employed. The buoyancy, pressure, and materials factors are all critical areas in the design of the pressure vessel air tank used to change the buoyant nature of the farm (either to sink or float the farm). The material factors include how the material will respond to the corrosive properties of sea water, how economically feasible the material is in the build and possible hazardous effects the material could have on the ocean environment in which it is submerged.

The issue of how the vessel will respond to the pressure both inside and out is can be based upon mathematical formulas and is quite crucial to the design. If the pressure vessel cannot withstand the pressure of its ambient surroundings (in this case seawater, with a steep depth-pressure gradient), the vessel will succumb to the force on the outside of the vessel pointing radially inward, and will be deformed, causing it to have less volume or, even worse, will implode, thereby ruining the vessel.

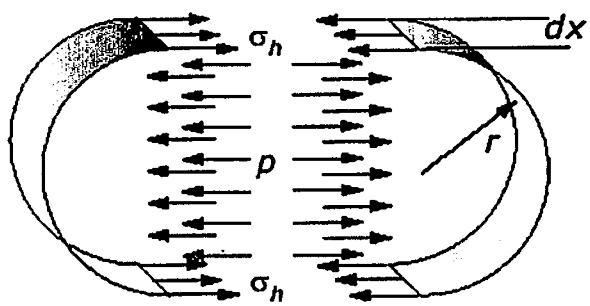

Figure 2
Forces on the inside of a simple pressure vessel

The pressure vessel must be able to withstand the water pressure at about 20 meters depth in the ocean which is about 304 kilopascal (44.09 psi). This is the minimum pressure that the design of the tank can be made to be able to resist, but since the design should include a generous factor of safety, the chosen vessel should be able to withstand upwards of 250 psi. This pressure is within the specifications on the converted propane what would be used on the final design. For a pressure vessel it is important to take into account the principle of Boyle's Law which states that the pressure and volume in a tank must equal a constant. Therefore, this vessel must have enough structural rigidity to overcome the resultant forces due to this principal since the structure cannot afford to reduce in volume, which would entail collapse. Since our design will require a constant volume and a varying pressure the pressure vessel walls have to be rigid enough to overcome the ambient pressure that is forcing the walls of the tank to want to collapse. With the design of the tank chosen the material that is chosen is steel because of its strength and availability. The propane tank that was chosen for the pressure vessel is therefore a logical choice since it is made of steel, which has a high modulus of elasticity (at 207 GPa) therefore lending itself well to the design criteria.

Buoyancy is the most critical aspect of the design of the pressure vessel. The buoyancy of the tank in the design will be tested for its functionality and it will need to be able to withstand the pressure applied to it. The buoyancy design depends on the variances in the density properties of the complete structure, including pendant weight and farm. The buoyancy of the pressure vessel is determined by the formula that the mass of the vessel as a whole (the combination of air and water) must be less than the mass of the volume of water the system displaces. The pressure vessel is required in the structure because it has the ability to balance the difference between buoyancies of the pendant weight and the floating grid of the farm structure. The pressure vessel needs to be able to reach a buoyant enough force to overcome the negative buoyancy force the pendant weight on the ocean floor. Essentially, a balance between potential buoyant force from adding air, and negative buoyancy due to the weight of the pendant weight needs to be correlated. Since steel is inherently denser than seawater, if the tank was full of seawater it would naturally sink, thereby making it necessary to balance the amount of air and water contained in the tank to allow the pendant weight to rest on the bottom, and effectively sink the growing grid to the effective depth.

This particular tank must be retro-fitted since it is original design had only one port of fluid entry and the current design criteria requires two, one port for air and one for water. To lower the structure, water would be pumped into the tank (using the fire hose on the boat), thereby displacing air while lowering the net buoyancy, allowing the structure to ultimately sink. Then, to raise the structure to the surface, compressed air from an air compressor would be pumped into the tank, displacing the excess water, and reversing the sinking process. This presents an issue though of how to force air in so water will be forced out of the tank and to the surface where it can be purged from the system. The second problem is being able to force water back into the system for re-sinking. To overcome these problems the tank will have to be modified one step further. The tank modification on the second hole in the top will need a hose that goes from the port on the top of the tank down into the interior of the tank. This hose will enable water to travel down past the air pocket that will always exist at the top of the vessel when filling the tank with water.

Since the pressure vessel will be in the ocean and the water being exchanged in and out it will be salty, the corrosive nature of saltwater on the tank must be accounted for. Since the tank is made of low-carbon steel, which is susceptible to intense corrosion issues, zincs should be added to the outside of the tank, and be replaced through regular maintenance. The theory behind using zincs is that the corrosive seawater will dissolve the softer zincs before corroding the steel. Another method to combat the corrosion of the saltwater is to apply a coating of paint, much like that on a car. If the tank is coated correctly the metal portion of the tank will not be exposed to the seawater or at least a much greater surface area will be covered. The coating we will use will be a spray coating (similar to paint) that is designed for water. Since the coating is less expensive and more readily re-applied then other coatings (such as a ceramic layer) it makes the most sense to coat the structure in that. The fittings for the air pipes will be made out of stainless so that the can resist corrosion without the use of a secondary coating agent.

Another two reasons for choosing to purchase a tank made of steel is that it is both economical and repairable. Using a pre-fabricated steel propane tank saves the const of fabrication of a custom tank, and using relatively inexpensive steel helps to curb costs further. The steel will allow for easier repairs and also reduce the price of repairs compared to other more expensive metals. Steel can be welded therefore when a crack propagates or any other defect occurs the tank can much more easily be repaired. Since none of the aforementioned factors present any problems ecologically, there should be no ramifications ecologically through putting it in the ocean.

The tank below in figure 3 represents the type of tank that would be used in the final design. It will be able to meet all of the requirements in terms of pressure, corrosion resistance, and cost.

Figure 3
Vertical propane tank.

Design of the re-stringing device:

Kelp is a very fragile plant in the beginning stages of its development. Kelp plants can be killed when it is being transplanted from the laboratory spool onto the rope line on which it will grow. There are two major problems that make this transplanting of the sapling kelp plants tricky. The young kelp plants are small at this transfer time and this means that the root system is small. Since there are small roots the kelp cannot strongly attach itself to the laboratory spooled grow lines and therefore the kelp is able to be detached if not handled with care. If the kelp were to become detached it would become unusable because it cannot easily be reattached to the line. Another problem with kelp transfer is if it is exposed to direct sunlight while still in the juvenile stages of its life, it will perish.

The kelp harvesting device has to be able to keep the kelp in shade or shade the kelp as it is being wound off the spool and on to the rope. To shade our design we will be using one of two designs. The design choice will be determined by the boat that is being used to harvest the kelp. The boat will be a fishing boat in order to the limit the capital investment. If the boat is a smaller vessel where deck space is more available then below deck space then the design will be placed either under a collapsible tent or a tarp. This design will allow the shading item to be removed from the deck when not in use. The second possible way to shade the kelp would be to place the stringing device below deck and run the line out of the cabin of the boat and into the water. This method is only possible on a larger boat where the rope threading device will not completely overwhelm the space. Larger fishing vessels or other commercial boats would be the more likely choice for this method.

The device that will transfer the young kelp to the rope for the ocean growth period must be fast, efficient and simplistic. It must be simplistic to limit problems as well as be able to be moved on and off the deck with less connections and setup. The device design is one that allows for ease of use and uses its own motion to drive other aspects of the design. The design consists of a gear driven cylinder. The device will revolve around a rope in the center in which the kelp on the spool will be threaded onto. The rope is pulled through two gears that are tightened on the rope using a spring. This set-up will force the gears to spin when the rope is pulled through them. This spinning motion of the gear will drive another gear that is interlocked with a third that is connect to a shaft with a gear on the other end. This shaft driven gear is a cone shaped forty-five degree gear that is interlocked with another gear of a forty-five degree angle so that they form a ninety degree angle. This will cause the motion created by pulling the rope through the gears to be able to be translated parallel to the rope. This second gear is connected to another shaft that is parallel to the rope. This gear is the gear that will drive the inner cylinder of the threading device. This threading device consists of two cylinders. The inner cylinder is suspended inside the outer cylinder using pipes that have a clearance of only a few micro meters. This very small clearance will allow friction of the inner cylinder plus two pegs at 180 degrees around the cylinder from each other will force the pipes to spin. One of the pipes in extended out with a cap so that the spools can be mounted on the longer tube. This longer tube will be forced around the rope since the rope will be running in the center. As the cylinder spins around the rope the spooled kelp saplings will be spun onto the rope. These ropes will be placed into the kelp structure that is then sunk below the water to grow the kelp. The cylinder setup has some similarities to a clothes dryer. The outer cylinder is held stable similar to the case of the dryer. This setup will allow the inner part of the threading machine to spin around the rope while the outer cylinder is held fast to coil the laboratory lines around the growing lines.

Construction of a scale model for testing:

To test the decisions made in formulating the final chosen design for the farm, a scale model was created to help assess any potential problems that might occur at the full-scale size. Testing for the dynamic behavior of the structure under storm-like conditions would take place in the wave tank located in the Chase Ocean Engineering building at the University of New Hampshire. Since the depth of the wave tank is roughly $1/20^{th}$ of that at the current OOA site, then the scale model, and all of its' components, should roughly correspond to that scale, in order to ensure that all tests would scale accurately and an accurate representation of the real situation could be accurately modeled.

To construct the main growing grid, it was difficult to find PVC pipe that was exactly $1/20^{th}$ of the diameter that would be used in the final structure (4"), so the smallest size readily available (3/4") was used. Having this discrepancy in scaling is of minor concern, however because the scaled dimension is larger than it would ideally be, the forces due to the flow of water in the dynamic wave environment would be ensonified with the larger dimension, presenting a worst-case scenario. This can be demonstrated in the mathematical model shown in appendix 2.

To the square grid, small eyebolts were attached for fastening the scaled growing lines. For the scaled growing lines, 50lb test braided Dacron fishing line was used. This was chosen because it was almost exactly to scale in terms of diameter, was easy to see when testing in the tank, and is low in stretch compared to regular monofilament fishing lines. A photo of the finished scale grid, complete with growing lines can be seen in Figure 4 below:

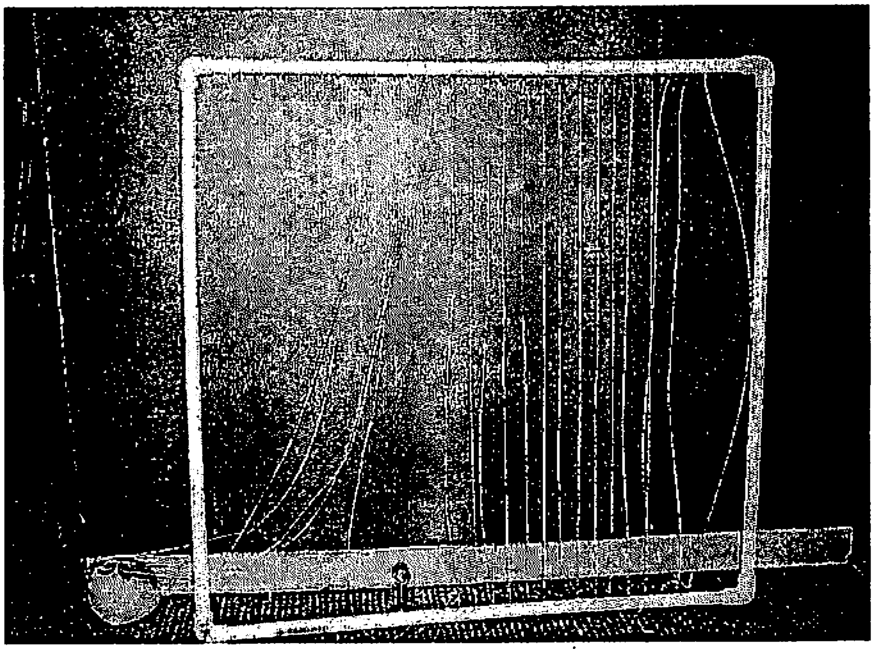

Figure 4
Scale growing grid complete with scaled growing lines.

To attach the growing platform to the airlift tank, pendant weight, and to the surface buoy, lobster pot bait bag line was used as it is 1/8" in diameter, which is slightly less than the 1/20 scale of the 4" braided line to be used for tethering the structure in the full scale model. This was attached using knots; however it would be spliced in the full scale model. Since the marker float for the system would have little functional bearing on the testing that was done, it was omitted from the scale model testing, and the tethers (mooring line and water/air pipes) were simply held by hand.

Explanation of Mathematical Model:

The major calculations performed before construction dealt with drag and buoyancy forces. These were considered the two major issues, since the structure would be sunk deep enough that wave forces would be negligible.

The issue of drag force in the ocean is much different than that on land. When a telephone poll can withstand a one hundred mile per hour wind gust one can not understand why a bridge piling can withstand only five knots of current. The reason is density. The density of air is almost one thousand times less than that of salt water. This makes the five knots closer to a wind gust of six thousand miles per hour. Thus the drag forces which the aqua farm would encounter were the main concern.

To calculate the drag forces which could be expected on the aqua farm, equation 1 was used.

$$Drag_{force} := 0.5 \cdot \rho_{water} \cdot current^2 \cdot A_{cross} \cdot C_{drag} \qquad (1.)$$

"Dragforce" is the drag force which acts on the object. "ρwater" is the density of the medium, sea water in the case of the aqua farm. "current" is the velocity of the medium, or current around the structure. "Across" is the cross sectional area which is subjected to the current. Since the aqua farm presented is square, the chosen side was not an issue. "Cdrag" is the drag coefficient of the structure. This is a scalar value which can be looked up in predefined tables. To make the calculation easier it was assumed that the drag coefficient was constant. This assumption was made assuming it would cause negligible loss in the total force.

Using equation 1, the drag force on the entire aqua farm structure was calculated two different ways. First, the drag force was calculated by assuming the entire structure was a solid rectangle. This would allow for an estimation of the drag forces to be quickly calculated to determine an order of magnitude which could be expected for the full calculation. To do this, a constant drag coefficient was used along with an above average current speed to determine the drag forces for an extreme case. When the solid rectangle was used, the calculated drag force on the structure was found to be approximately 9.2 kilo-newtons.

The second way the drag force was calculated was by calculating the drag forces on each of the ropes and then calculating the drag forces on each of the sides and adding them together. The method and current speed used to find the drag on each of these components was the same as the solid rectangle method, however, the drag coefficient was changed to account for the change in geometry. Calculating the drag using the second method which accounted for the geometry of the structure yielded a drag force of approximately 9.16 kilo-newtons. This is close to the drag forces calculated using the solid rectangle approach which strengthens its validity.

Knowing that the structure will have approximately 9.2 kilo-newtons of drag force acting on it, the amount of force that the support lines will have to support is now known. This will help to determine the types of materials the support lines can be made of as well as their relative thicknesses to assure that the structure will not pull away due to current imposed drag forces.

Next the buoyancy of the structure was calculated to determine the amount of weight which would need to be added to sink the structure below the surface to prevent wave damage as well as ship traffic disturbance.

Buoyancy is the force which makes an object float while suspended in a liquid. This force is proportional to the volume of that liquid it displaces. To calculate the buoyancy of the structure equation 2 was used. This is the standard equation used in buoyancy calculations.

$$Force_{buoyancy} := \rho_{water} \cdot (Volume) \cdot gravity \qquad \boxed{2.}$$

"Forcebuoyancy" is the calculated buoyancy force, "ρwater" is the density of the medium, "volume" is the calculated volume of the structure, and "gravity" is the acceleration due to gravity.

When equation 2 was used, with the assumption that the kelp was close to neutrally buoyant, a buoyancy force of approximately 25 kilo-newtons was calculated. This was then compared to a buoyancy force assuming the structure was a solid rectangle. When the buoyancy force was calculated for the solid rectangle, a value of approximately 34.5 kilo-newtons was calculated which strengthened the validity of the first calculation.

This buoyancy force must be overcome to make the entire structure sink. By sinking the structure, the entire farm is no longer subjected to wave forces or boating traffic which can cause unnecessary damage to the structure. To determine the weight necessary to sink the structure, the mass of the entire structure was calculated.

Bio-fouling or the growth of plants and animals on the support lines and structure was then accounted for. This was assumed to add approximately 500 kilograms to the entire structure. When this was added, the total weight of the structure was calculated to be approximately 1700 kilograms.

The final mass which would need to be accounted for was the mass of water which would be used to fill the floatation tank. This mass was found to be 1890 kilograms which when added to the rest of the masses for bio-fouling and the structure brought the total downward force of 16,500 kilo-newtons.

When this force was subtracted from the buoyancy force a final "pendent" weight was found. The pendent weight is weight that is added to the structure to help make sure that the aqua-farm sinks. This weight may be added as a single mass hanging below the structure or as added mass in the sides of the structure, or even a combination of both. From the calculations it was determined that 850 kilograms of mass would need to be added to the structure to assure that it sinks.

To perform scaled force tests on the modeled kelp farm, scaling analysis was performed keeping the Froude number constant. Since the model was built on a 1 to 20 scale, the scaling value λ was found using equation 3. This provided a scaling factor of 20.

$$\lambda_{scale} := \frac{Length_{proto}}{Length_{model}} \qquad (3.)$$

Using this value of λ, a model testing velocity was found. The testing velocity was found by equation 4, and was the velocity that the models had to be pulled at to allow for scaled drag forces to be calculated.

$$V_{model} := \lambda_{scale}^{\frac{-1}{2}} \cdot V_{prototype} \qquad (4.)$$

When this equation was used, a velocity of 0.67 meters per second was found to be the velocity which the model must be tested at.

To scale the forces from the model test to full scale, a ratio of λ^3 was used. Unfortunately, a dynamic test on the model could not be performed because of problems with the test wave tank.

Kelp Cultivation:

Background material:

Lane *et al.* in their examination of kelp families write that there are 30 genera within the Laminariales with 40 species recognized along the coast of North America. The North Pacific region has twice that number of species resulting in more diversity. (Lane *et al.* 2006). Among these 40 species found in North America our project has chosen to work with *Saccharina latissima*, a species native to the Gulf of Maine.

Lane *et al.* found through sequencing numerous kelp species in the order Laminariales that *Laminaria saccharina* should more accurately be classified in the genus *Saccharina* (Lane et al. 2006). Lane *et al.* reclassified *L. saccharina* as *Saccharina latissima* (Linnaeus, C.E. Lane, C. Mayes, Druehl et G.W. Saunders). The general morphology of *S. latissima* (Figure 5) is similar to most kelp containing a holdfast, connected to a stipe from which a single blade grows. The center of the blade contains the sorus which when reproductively mature which release spores. When mature the sorus is a raised darker brown section that may already be separated from the blade (Merrill *et al.* 1991).

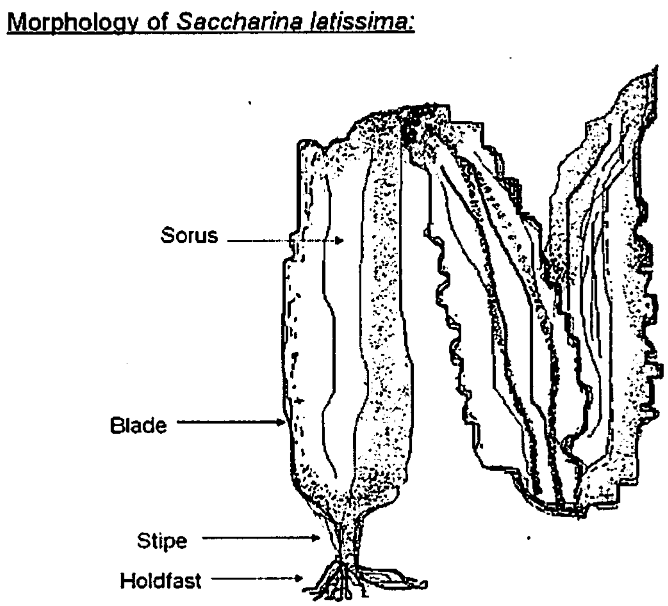

Figure 5
Morphology of Saccharina latissima

Reproductively mature sporophytes release haploid male and female zoospores from the sorus. These zoospores are motile, able to swim depending on light exposure and temperatures (Fukuhara *et al.* 2002). These zoospores can swim for 5-10 minutes in 15-20°C but swim up to 48 hours at 5°C (YSFRI, 1989). Fukuhara *et al.* sites that no zoospores were observed after 48 hours and there was 20% reduction after 24hours (Fukuhara *et al.* 2002). Zoospores settle and germinate to male and female gametophytes. The gametophytes mature until the spermatozoids are released into the water where they fertilize eggs from mature oogoniums and form the zygote (YSFRI, 1989). These zygotes grow into 7-celled seedlings and continue to grow into young sporophytes and thus complete the lifecycle.

Methods and Materials

The following procedure is an adaptation of Charlie Yarish's protocol and the *Bull Kelp Cultivation Handbook* by Merrill, J. and Gillingham, D.M. (Merrill *et al.* 1991). This protocol was perfected over the course of the fall semester with a total of six attempts at spore collection. Although the first three attempts were unsuccessful in seeding lines each attempt helped in the learning process. Some of the factors that were changed in the protocol include temperature consistency, exposure to light, bryozoans contamination and removal, time reemerged in seawater and cleaning of the seeding lines. Appendix 10 lists all cultivation attempts and Appendix 7 shows pictures from the perfected protocol.

For cultivation of *Saccharina latissima* mature plants were collected from floating docks in Prescott Park, Portsmouth, NH (Figure 6). The sori were cut out from the rest of the plant blade, rinsed with filtered seawater and wiped with a paper towel to remove contaminants and debris. The sori were then soaked in a diluted iodine solution (5mL 10% iodine in 1L filtered sea water) for 30 seconds. The sori were then rinsed in filtered seawater, wiped dry and stored in seawater damped towels in a cooler during transportation. All collection and disinfection steps were preformed on site.

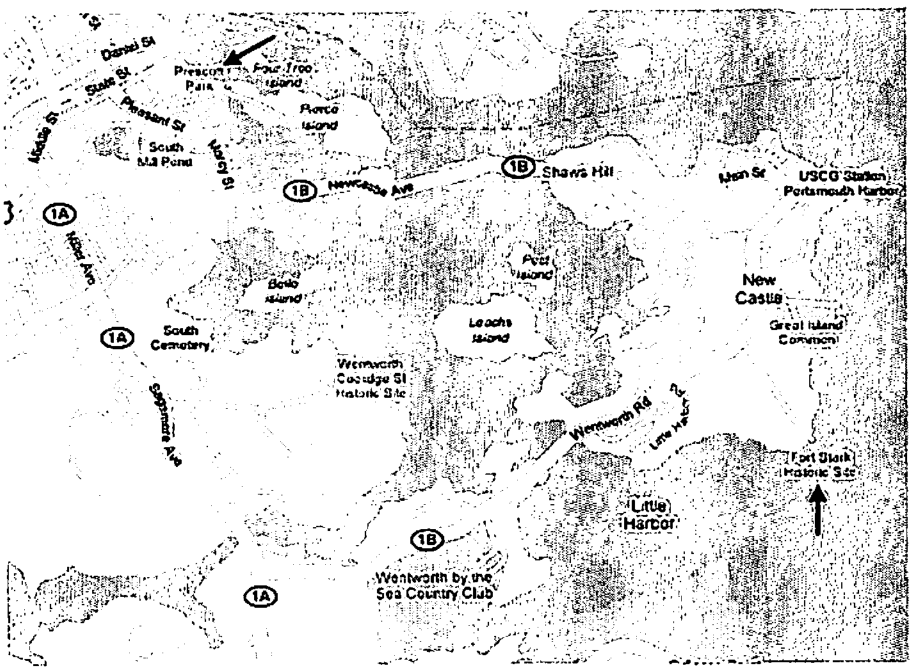

Figure 6

Map of sample sites: Prescott Park and Fort Stark

Upon arrival at the laboratory the cleaned sori were stored in the dark at 4°C overnight (about 10-12 hours). After incubation the sori were rinsed and then immersed in filtered seawater at 10°C for 4-5 hours with limited light exposure. Release of spores caused the water to turn a light to dark brown color. Spent sori were then removed and the mixture was added to a 5 gallon bucket containing PVC pipes with the seeding lines, filtered seawater and gentle aeration. The PVC pipes were 2 inches in diameter with culture line wrapped around for a total length of 10 inches. The culture line was braided nylon seine twine size 12 from Memphis Net & Twine Co. Inc. and resulted in 1275 inches (106.25 feet) per PVC pipe. The lines were presoaked and rinsed with distilled water prior to seeding. In one attempt half of the lines were presoaked in diluted liquid NOx and then rinsed in distilled water to further remove contaminants. There was however no difference in spore settlement and the extra cleansing was discarded due to the possible detriments of the detergent residue. The spores and lines were allowed to incubate in the 10°C cold room for 24 hours without light. Glass slides were included in this procedure to help with monitoring spore development.

After the 24 hour incubation period the PVC pipes and slides were removed and placed in a 38L tank with filtered seawater. Each tank received gentle aeration, germanium (IV) oxide (to reduce diatoms) and 0.5X West and McBride's Modified ES Medium. The spores received lights from 2 fluorescent light bulbs from both sides of the tank for 8 hours a day. The slides were monitored for changes in the lifecycle of the kelp and the water was changed weekly. After the spores were 6 weeks old the light level was increased to 3 fluorescent bulbs per side of tank.

Results

The lifecycle of *S. latissima* was closely monitored during the spring semester. Due to limited contamination and better seeding almost the entire lifecycle was recorded. The lifecycle figure from the *Culture of Kelp (Laminaria japonica) in China Training Manual* provided the most detailed drawings of the different stages. Also during the most successful cultivation (started in January) zoospores were observed swimming in seawater after being released from the sori. A table listing all collection attempts can be found in Appendix 10 and a completed lifecycle diagram in Appendix 8.

Discussion

One problem encountered in the collecting spores was the contamination by bryozoans and other contaminates. Saier *et al.* found a significant reduction in spore release in *Laminaria longicruis* relative to bryozoan coverage (Saier *et al.* 2004). Saier *et al.* found about a 100-fold decrease in spore release in blades with complete coverage of bryozoans and with an increase in spore release with less bryozoan coverage. There was also a peak in bryozoan area coverage in the fall months, September and October. In response to the poor spore release due to bryozoan the iodine solution surface disinfection step was added (Merrill *et al.* 1991). The iodine solution proved to be gentler on the surface of the kelp than scrubbing but more effective in killing contaminates. The final attempt to collect spores in January resulted in the kelp samples with the fewest bryozoan colonies and the greatest spore release.

Fukuhara *et al.* showed that the release of zoospores in *Laminaria japonica* occurs mainly at night (Fukuhara *et al.* 2002). Fukuhara *et al.* also showed that low light levels and low water temperatures increase the time zoospores actively swim. It was shown that with time zoospores will cease to swim and will float, an advantage if caught in water motion in the water column. These results help to verify that in our protocol spore release increase when light exposure was limited and water temperature remained at 10°C. Fukuhara *et al.* data also helps to emphasis the importance of aeration while inoculating the seed lines with spores.

One unforeseen difficulty in culturing *S. latissima* in the laboratory was maintaining a constant temperature. Due to numerous cold room malfunctions several of the cultivation attempts were expose to temperatures outside normal acceptable ranges. During Thanksgiving break the cold room reached temperatures greater than 20°C for an unspecific amount of time, killing most of the kelp. This spike in temperature promoted growth of zooplankton such as diatoms that feed on the sporophytes (Figure 7). Although it was not observed temperature fluctuations can also influence the plants ability to photosynthesize and grow. Davison looked at the effect of temperature on photosynthetic metabolism in S*accharina latissima.* Davison found that temperatures 0°C and 5°C had adverse effects on plant photosynthesis and that plants developed a tolerance at temperatures from 10-20°C (Davison, 1987). This data supports growing the plants at 10°C but shows the detrimental effects of higher temperatures. It should be noted that all literature has suggested using germanium (IV) oxide to inhibit diatom growth. The *Culture of Kelp (Laminaria japonica) in China Training Manual* discusses *L. japonica* tolerations to temperature stating that "gametophytes will cease ovulation when seawater temperature rise much above 21-22°C" (YSFRI, 1989). With this knowledge of *S. latissima* sensitivity to temperature, it is easier to explain why the first few attempts at spore collection were so unsuccessful.

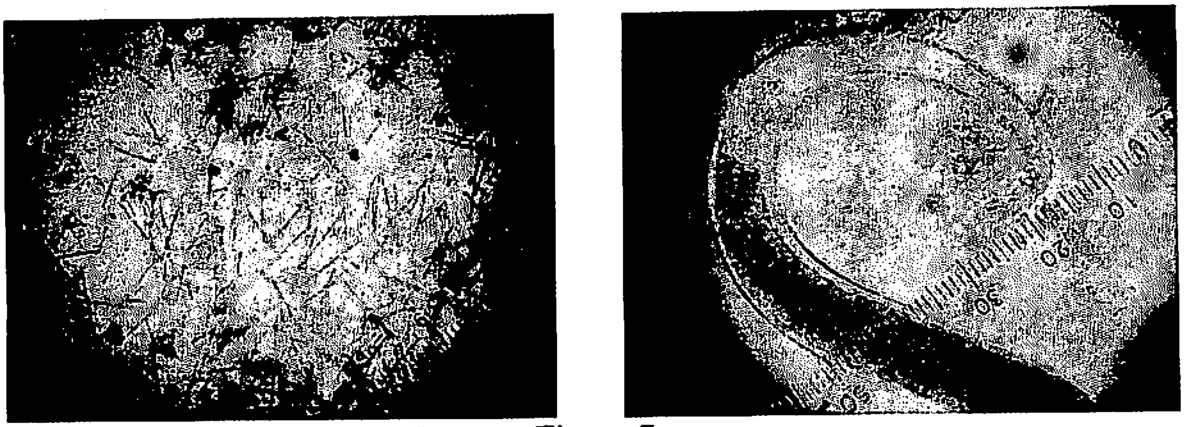

Figure 7
Example of contamination by different plant species, left and worm eating plants, right. (both under 400x magnification)

In general it is recommended that sporophytes be transferred to an ocean site once they reach 1-2mm in length. Although not applicable in this experiment it is also reconvened to move the plants to a protected bay etc. where they can become accustomed to natural conditions for about a week. Allow for the kelp to grow this additional week in nature increases their size and helps to increase their survival rate. In agreement with growing kelp to this size was Carney *et al.* who looked at bull kelp restoration in natural habitats in the northwestern waters of Washington state (Carney *et al.* 2005). In their experiment the transplantation survival of microscopic sporophytes (0.5-1mm) and juvenile sporophytes (<15cm) were compared. Carney *et al.* found that the juvenile sporophytes had a 10-30% greater survival rate than previous research with transplants of larger sizes. Carney *et al.* also noted that grazing gastropods were the greatest cause for stipe breakage and eventual plant death. Although not addressed in this experiment the influence of grazers on kelp survival should be considered in future out-planting attempts. Even though growing *S. latissima* in the laboratory setting can be a challenge, we have proved that it is possible. We have also developed a complete protocol for cultivating native S. *latissima* in the New Hampshire region.

Results:

Line Testing:

Static Rope Analysis:

To choose a type of rope to use as growing lines out in the ocean, tests were performed on three different diameters of potwarp and nylon ropes. These two tests helped to determine how the ropes would respond to constant forces such as current as well as dynamic forces.

To understand how the two types of rope would respond to dynamic and static loading, both a linear variable differential transformer and a piezoelectric accelerometer, were used. The linear variable differential transformer, LVDT, was used to measure the length of rope which had been stretched due to the static loading, while the piezoelectric accelerometer was used to measure the dynamic response of the ropes under load.

A LVDT is a long pin like instrument which contains a metallic core which is displaced. This metallic core creates a magnetic field which, when moved, creates a voltage differential that can be measured. A diagram of the LVDT internals can be seen on the following page in figure 8.

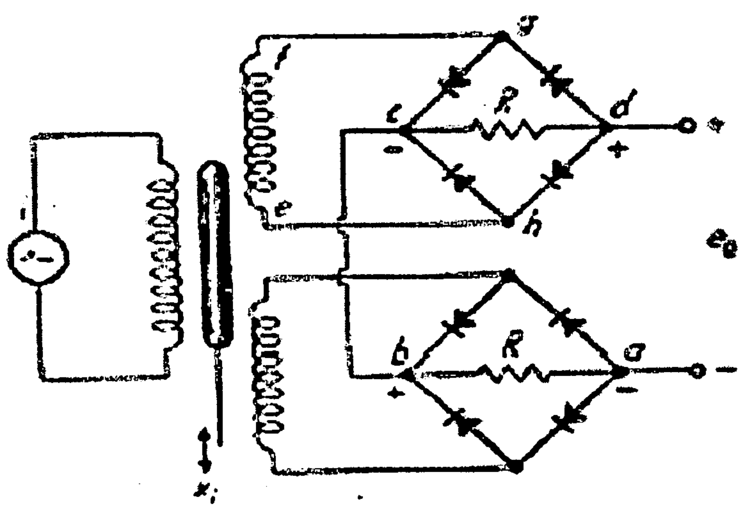

Figure 8:
Set-up of a LVDT.

As the tip of the LVDT was compressed, the core was displaced, and an output voltage was measured via an oscilloscope. The diagram below shows both a compressed (loaded) and an uncompressed (unloaded) LVDT.

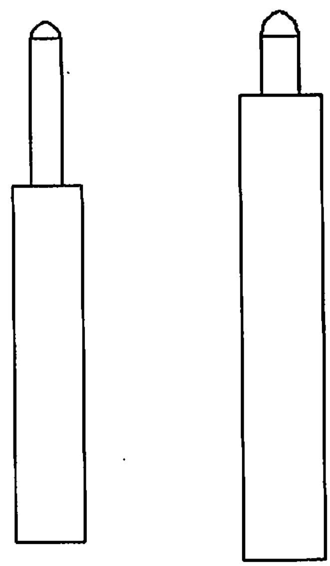

Figure 9:
The figure on the left shows an unloaded LVDT while the figure on the right shows a fully loaded LVDT.

Using the LVDT along with its found sensitivity of 9.9492 volts per inch displaced, a change in voltage was found which was proportional to the elongation of the rope. Below in tables 1 and 2 measurements of output voltage and corresponding displacement for various weights on each of the six ropes tested can be found.

Table 1: Output voltage and corresponding displacement values for specified forces on Nylon ropes.

	3/16" Nylon		1/4" Nylon		5/16" Nylon	
Force	Output Voltage	Elongation	Output Voltage	Elongation	Output Voltage	Elongation
lb	V	(in)	V	(in)	V	(in)
0	19.6	0	19.6	0	19.5	0
2	19.5	0.03811551	19.4	0.0201021	19.5	0
4	19.15	0.17151978	19	0.0603064	19.3	0.02010212
6	18.5	0.41927058	18.4	0.1206127	19.1	0.04020424
8	17.8	0.68607914	17.8	0.1809191	18.9	0.06030636

10	17.2	0.91477218	17.3	0.2311744	18.6	0.09045953
12	16.7	1.10534972	16.7	0.2914807	18	0.15076589
17	15.6	1.52462031	15.4	0.4221445	17.1	0.24122543

Table 2: Output voltage and corresponding displacement values for specified forces on Potwarp ropes.

	3/16" Potwarp		1/4" Potwarp		5/16" Potwarp	
Force	Output Voltage	Elongation	Output Voltage	Elongation	Output Voltage	Elongation
lb	V	(in)	V	(in)	V	(in)
0	19.6	0	19.5	0	19.5	0
2	18.8	0.08040848	19.2	0.0301532	19.35	0.01507659
4	18.1	0.15076589	18.8	0.0703574	18.55	0.09548506
6	17.1	0.25127648	17.9	0.160817	17.5	0.20102119
8	15.7	0.39199132	17.1	0.2412254	16.7	0.28142966
10	15	0.46234873	16.2	0.331685	15.8	0.3718892
12	14.2	0.54275721	15.5	0.4020424	15.1	0.44224661
17	12.2	0.74377839	13.9	0.5628593	13.25	0.62819121

Using the elongation found by the LVDT and the length of rope which was analyzed, percent elongations could be found for each weight. The maximum of these values was then determined to be the final percent elongation factor which could be then used to analyze the entire rope.

Using the force applied to the rope and the length of displacement, the overall rope stiffness could be found. Again the average of all the tests performed was found and used as the overall rope stiffness. Table 3 shows the found percent elongations and stiffness for each rope tested.

Table 3: Percent elongations and stiffness for each rope tested under static conditions.

	Percent Elongation	Stiffness (lbf/in)
3/16" Nylon	1.52	44.68
1/4" Nylon	2.14	43.73
5/16" Nylon	1.46	98.32
3/16" Potwarp	2.36	22.18
1/4" Potwarp	2.75	32.13
5/16" Potwarp	3.47	27.87

Dynamic Rope Analysis:

To analyze the ropes response to a dynamic loading situation, a piezoelectric accelerometer was used. A piezoelectric accelerometer uses a quartz crystal or a ceramic material insert which is deflected proportionally to the vibration of the system. This deflection is output as a voltage on an oscilloscope which can then be analyzed. The piezoelectric accelerometer employed to determine the ropes dynamic properties, used an external amplifier to modify the signal such that it could be output via an oscilloscope. Some piezoelectric accelerometers can have an internal signal amplifier to alleviate the need for an extra component.

For dynamic properties, the piezoelectric accelerometer was used to help determine system responses to step inputs. When the weights were hit, a second order system was captured via Flukeview. These plots were then analyzed and natural frequency and damping ratios were found.

To assure that the natural frequencies of the different ropes did not equate to the wave frequency, a dynamic step response for each of the different ropes was analyzed. From these step responses, damping ratios were found. Table 4 shows these values for each of the ropes.

Table 4: Damping Ratios of the ropes tested.

	Damping ratio
3/16" Nylon	0.0705
1/4" Nylon	0.0736
5/16" Nylon	0.0817
3/16" Potwarp	0.0361
1/4" Potwarp	0.0632
5/16" Potwarp	0.1271

After completing the tests, 5/16" potwarp was chosen. This was because it had a high stiffness and high damping ratio. This would allow it to stop vibrating quicker after a dynamic load while still allowing it to prevent deformation. From an economic standpoint, potwarp is also less expensive then nylon cementing potwarp as the chosen material.

Tank Test:

The tank test was designed to figure out how the farm, tank and pendant weight would perform when placed in practical scenarios. The tests that were performed were used to determine the time that it took the structure to ascend through the water column, the amount of water that needs to be removed from the tank in order to float the tank and the numbers that correspond to areas that might cause problems in the use of the structure in commercial applications. These tests were able to show us some of the problems that could occur.

The first area we had a problem with was filling the tank so it would sink. The tank was not able to be filled by submerging it as we had originally planned to do. We found that the tubes were long enough to be able to reach far enough down into the pool to fill the tank. The tubes would be bunched at the top of the water and caused the tank not to fill. To elevate this problem in the tank we drew air out of the tank so that the water would be drawn in. This would not solve this same problem on a commercial scale. To correct this problem on the commercial scale the tank can be pre-filled using a pump which will allow the tank to sink when placed in the water. The tube can then be submerge to lower it further.

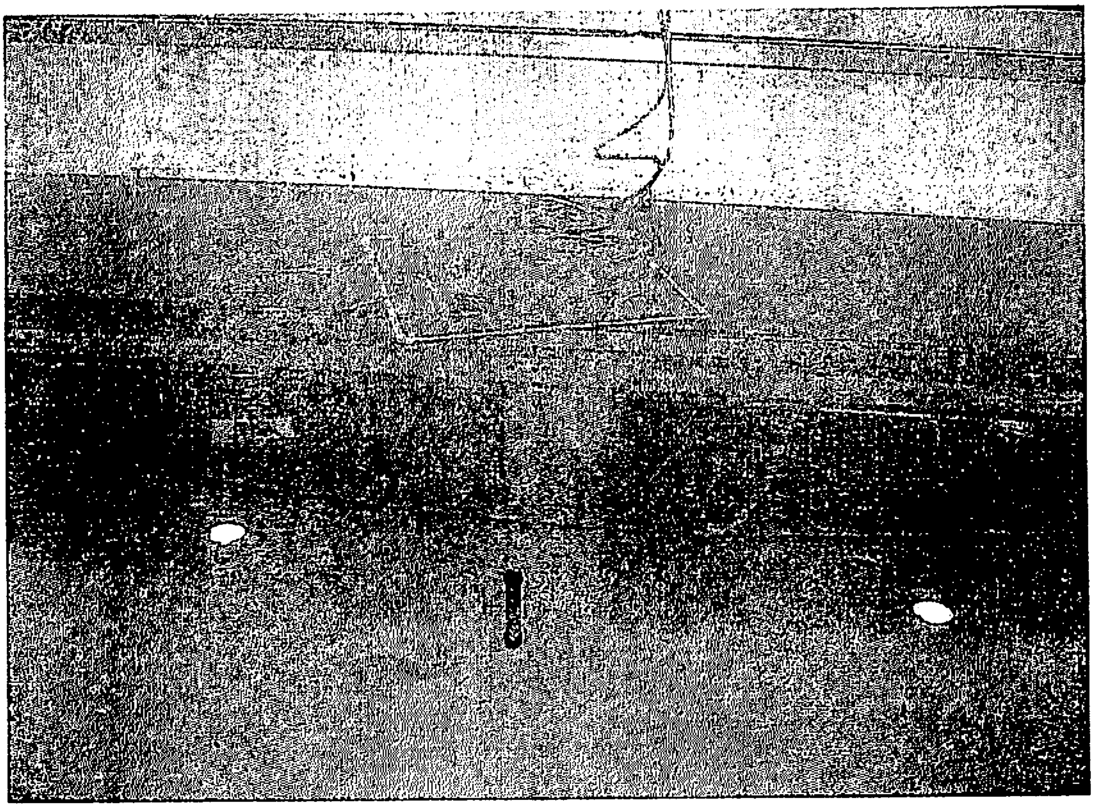

Figure 10
Submerged in tank during testing.

When the first test was performed we were able to determine that the tank had enough buoyancy to counteract the weight of the tank and farm. The air compressor filled the air tube to force water out of the tank. This allowed us to see how the tank responded to the water drop and subsequent buoyancy. With this test we were able to determine that the tank rises at a relatively steady rate. The pendant weight was then attached to the tank and the test was preformed again. From this test we were able to determine that sinking and rising was possible with the pendant weight attached and that pendant weight could be attached with slack which is representative of how the pendant would have to be attached in large scale situation since the pendant weight slack will set the depth of the structure.

The third test helped to determine how the farm and tank would respond if the tank was emptied too fast because too much water was emptied out of the tank. When the tank was emptied out too fast the tank rose up and into the structure but only seemed to nudge the farm before it was countered again by the pendant weight. This would not be a problem on the large scale because the pendant weight would not have slack as it did in the tank and therefore the tank would not be as likely to crash into the farm as was in the tank. The tank then was emptied all the way to see how it would respond. The tank rose up through the ropes of the farm and showed that problems could be caused by empting the tank to quickly.

The next tests were used to determine the physical numbers associate with the tank. In the first of these test we determined the amount of water that had to be forced out the tank in order to raise the farm to the surface. Though this number is not helpful by itself but in conjunction with a couple more tests it was determined that the amount of the water to raise the structure was reproducible which lead to the assumption that this was a scaleable measurement. This makes sense since buoyancy is driven not only by the displacement of water but all the components as compared to their mass. The next tests that were performed were used to determine how much water would have to be emptied out to run the structure into the danger zone. This allowed a range to be determined for the amount of water that could be safely evacuated for proper performance without concerns of raising too quickly. The range that was determined was about 10 percent extra removal of water without negative effects. This needed to be determined so that it could be understood how the regulations on raising the tanks needed to be placed.

Economic Analysis Results:

In this section, the economic feasibility of kelp farming will be explored as a function of startup costs, maintenance, and longevity. A complete spreadsheet of the cost analysis can be found in appendix 7 and will be referenced in this section extensively. All price quotes were taken from retail distributors, and the part numbers, along with the quantity and prices can be found in the economic analysis appendix 7 and the parts list appendix 6.

Ideally, kelp farms could be constructed at minimal cost, while having minimal maintenance to allow for a short payback period. However, one of the major problems with cultivating kelp, is the amount of money needed for the chemicals necessary for starting kelp seedlings in a laboratory before they can be planted on a farm. These costs are fixed, and are a linear function of how big and how many farms are planted; in short, the more kelp that is to be grown, the more chemicals ultimately are needed. This is also true of expenses such as boat fuel, facilities, and personnel. Fuel was assumed to nominally cost $150 per trip, and, was quite negligible compared to the overall cost of maintenance and sustainability. In terms of facilities and personnel, it was assumed, that those involved in kelp farming would already have access to the necessary facilities (boat, cold room, etc.), and that they would not incur any additional personnel other than themselves. Thus, the costs of these items were not taken into account, although calculations could be augmented to account for this.

The startup costs for constructing kelp farms, according to the design criteria chosen by the team, were quite large. The connection lines, pressure vessel, and pendant weight chain were the biggest expenditures and accounted for nearly 66% of the total construction costs of the structures. However, both the pressure vessel and the pendant weight should require the least amount of maintenance and would require replacement far less often than other, more expendable pieces of the farm.

In terms of the structure of the economic model that was developed, the entire model is a function of the market price of the kelp, and the percent of the gross going to maintenance of the farms. As with any natural resource, the market price for kelp would fluctuate due to supply and demand, as would the maintenance costs due to storms, fatigue of load bearing members, corrosion, and biofouling. So, essentially, as the market grew stronger, and maintenance costs were kept lower, the more economically feasible farming kelp would get. For example, figure 11 below represents the overall profit margins for farming kelp assuming a market value of $2.00 per kelp plant, and 20% of the annual gross being put back into the farms as maintenance.

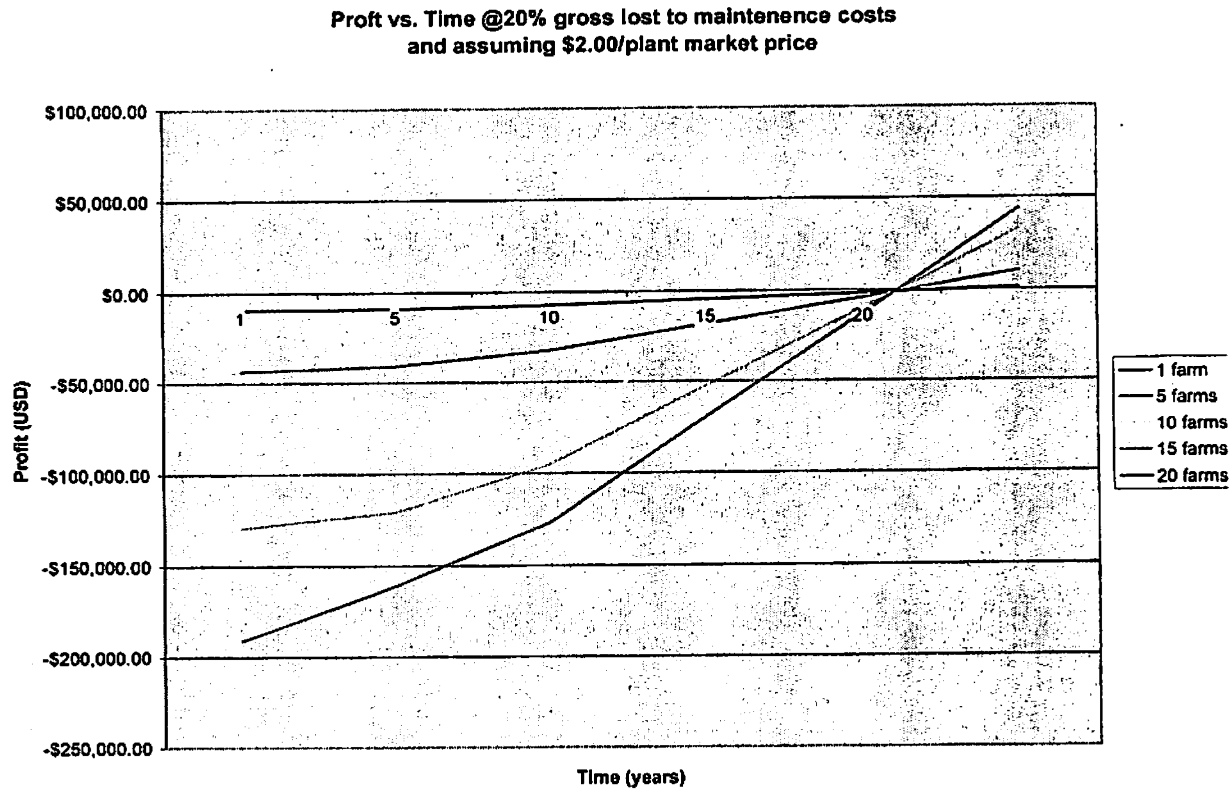

Figure 11
Graph of total profit over a 20 year cycle for kelp farms consisting of 1-20 growing platforms.

This graph shows the break even point for any number of kelp farms between the 15 and 20 year mark, based upon the $2.00 assumed market price, and 20% maintenance allowance. Nominally, an operation employing 20 farms, over a 20 year period, under these maintenance and market conditions would net $44,028.60, which averages over the 20 year cycle to $2,201.43 per year. These numbers prompted the group to investigate the actual market value of a kelp plant. In this calculation, the wet vs. dry mass of the kelp plant needed to be compared, as the market value for kelp is often for the dry product. The average wet/dry mass ratio was 8:1, and, by our calculations, the average weight of a full grown kelp plant was found to be 295g dry. Since the most recent market value for kelp was $2800 per metric ton, the average kelp plant is worth $0.83. When adjusting the graph above, to correspond with the new market price, the farm becomes completely economically unstable.

Conclusion/Summary:

After researching past efforts to design and build open ocean kelp farms, it became clear the difficulty in this type of venture was harvesting the plant. The larger the structure is made the more efficient the growing becomes. However, this poses a problem since the larger the structure becomes the more difficult it is to move it. Many previous efforts relied on taking the entire structure to shore where it was then harvested. With the larger structure, transporting to shore is not an efficient method. By floating the structure to the surface harvesting can occur. It was determined that harvesting while keeping the farm in the ocean was the best approach. Since the structure is connected to a mooring grid its lateral movement is minimized. By making the rope attachments easily changeable, the lines can be changed and pulled quickly. This allows for easy harvesting and quick turn around time. Using these types of strategies, harvesting the kelp becomes easier with a larger more efficient growing farm.

Another major obstacle found with kelp farming was replacing the growing lines. Since the kelp has to be grown in a laboratory until it has reached 2-3 millimeters, stringing it onto the growth lines had to be done carefully as not to destroy the small plants. This problem was resolved with the theoretical design of a stringing device. This allowed for the kelp to be transported to the ocean site on the laboratory spools. This is much easier storage and prevents damage to the young plants. Once at site, the stringer winds the laboratory lines around new growing lines. Since the young plants can not be subjected to direct light this must occur at night or under cover. Once the lines are restrung, the float tank is sunk and harvesting of the old lines can commence when back on shore.

After modeling a business specializing in off shore kelp farming, the potential profit does not seem lucrative enough to support an independent venture. The high initial investment paired with a slow payback period suggests that if kelp aquaculture were to become a true business venture, either the government would have to raise the price of the plant to help out farmers or a large company would have to be willing to wait a few years to begin turning a profit. Although ethanol made from corn may not be the answer to a potential energy crisis it does not seem like many businessmen will turn to kelp aquaculture as a future moneymaking venture.

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Appendixes:

Abstract

The purpose of this lab was to determine the dynamic and static characteristics of two different types of rope of 3 different sizes. These ropes would be used in a kelp open aquaculture farm and would be subject to forces from various currents and natural elements. For our purposes, a total of 6 ropes were tested. Ropes of 3/16", 1/4", and 5/16" were tested for two different materials, potwarp and nylon. The goal was to determine using an LVDT the dynamic properties of damping ratio and natural frequency and the static properties of elongation and stiffness. Through the results of our tests, the optimal choice rope for the needs of our kelp farm, both in material and diameter will be found.

Methodology

To measure the static and dynamic properties of the rope for the kelp farm two instruments were used. The first instrument was using a Linear Velocity Differential Transducer (LVDT) to measure the displacement that occurred when weights were placed at the rope ends. The second instrument was to use a piezo-electric accelerometer. The response data from the piezo-electric accelerometer can be used to find the dynamic properties. These methods were used to test 6 different ropes of potwarp and nylon.

The LVDT setup required a power source and the oscilloscope. The power supply was setup to output a voltage supply of 30.0 volts to the LVDT. The LVDT must then be connected into the oscilloscope. The LVDT was connected such that the output was floating and not grounded. This was done by using both channels of the oscilloscope. Channel one was connected to the positive output of the LVDT, and channel two was connected to the negative output of the LVDT. Both of the scope channels were connected from the negative terminal of the power source. The oscilloscope was then set up by making the channel with the negative input of the LVDT inverse and then using the feature of being able to add the channel inputs. This causes the two channels to create a single input. The LVDT needs to be set in digital mode and setup to measure the output voltage for the first part.

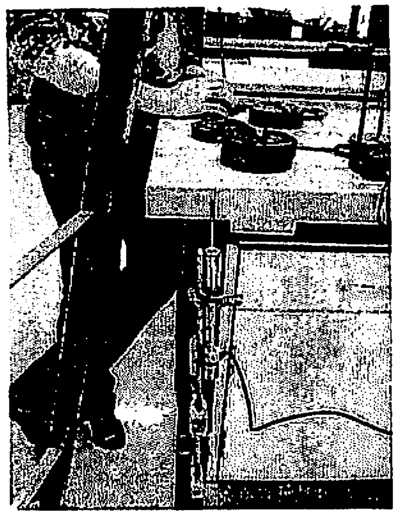


Figure 1: Setup of LVDT

When considering our test setup, it was found that the ropes first need to be spliced. Splicing is a technique that can be used to form a loop on the end of the rope. Both ends are spliced in order to produce a way to attach the ropes to a stable platform and to the weights. The ropes were connected onto a stable platform by wrapping around the beam and then through the loop in the rope. An initial weight of 5 pounds was then hung from the end of the rope above the LVDT. The LVDT was connected to a bar clamp using two hose clamps. The bar clamp was then connected to a magnet that could be moved up and down the leg of the table to make sure that the zero point is exactly at the beginning position of the rope. Weights were then added to the system. After the weight had been added and the system had settled to a steady position, the voltage measurement off the oscilloscope was taken. Two pound increments were added until the total of eleven pounds was reached. It should be noted that this eleven pounds is in addition to the five pound base weight.

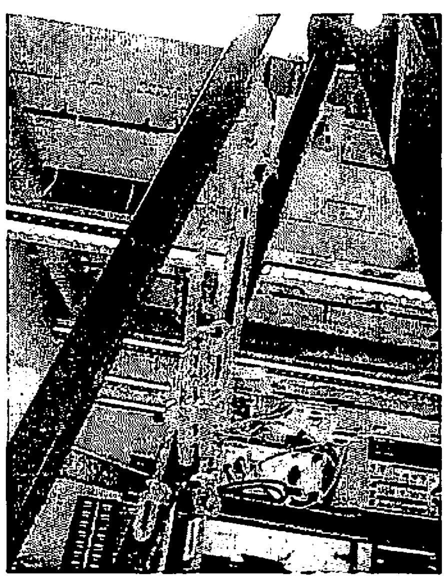


Figure 2: Setup of ropes on ladder before weights were hung

The second measurement was done using the piezo electric accelerometer. The accelerometer was connected into an amplifier. The amplified signal was then connected into the oscilloscope and a dynamic graph of the damping was found. The trigger was used to capture the image of the output voltages.

The setup of the ropes for use with the accelerometer is the same as the when adding weights for use with the LVDT except the initial weight is 9 pounds and then no more weight was added. The accelerometer has a magnet affixed on its bottom which allowed it to be connected directly to the weight plates. The weight plates were then tapped with the head of a screwdriver in a vertical motion. This allowed us to find the oscillation and damping qualities of the rope.

Analysis

To understand how the two types of rope would respond to dynamic and static loading, both a linear variable differential transformer and a piezoelectric accelerometer, were used. The linear variable differential transformer, LVDT, was used to measure the length of rope which had been stretched due to the static loading, while the piezoelectric accelerometer was used to measure the dynamic response of the ropes under load.

A LVDT is a long pin like instrument which contains a metallic core which is displaced. This metallic core creates a magnetic field which, when moved, creates a voltage differential that can be measured. A diagram of the LVDT internals can be seen below.

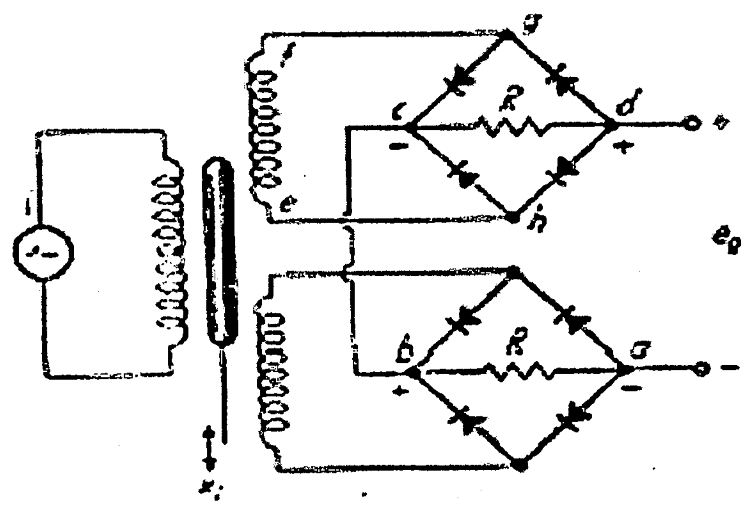


Figure 3: Diagram of the internal wiring of LVDT

As the tip of the LVDT is compressed, the core is displaced, and an output voltage is measured via an oscilloscope. The diagram below shows both a compressed (loaded) and an uncompressed (unloaded) LVDT.

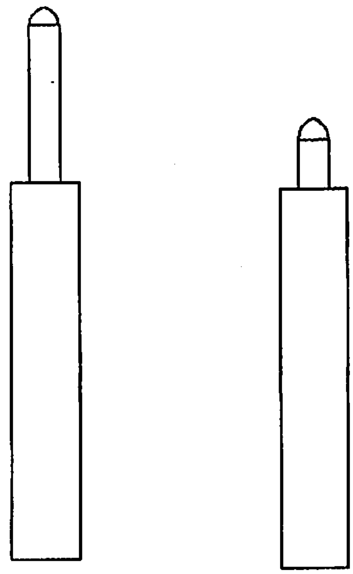


Figure 4: LVDT without load (Left), with load (right)

To analyze the ropes response to a dynamic loading situation, a piezoelectric accelerometer was used. A piezoelectric accelerometer uses a quartz crystal or a ceramic material insert which is deflected proportionally to the vibration of the system. This deflection is output as a voltage on an oscilloscope which can then be analyzed. The piezoelectric accelerometer used to determine the ropes dynamic properties, used an external amplifier to modify the signal such that it could be output via an oscilloscope. Some piezoelectric accelerometers can have an internal signal amplifier to alleviate the need for an extra component.

To determine the dynamic properties such as the natural frequency (1) and damping ratio (2), the log decrement method was used. Below are the two equations used to find these values.

$$\omega_n = \frac{2\pi\zeta}{\zeta T\sqrt{1-\zeta^2}}$$

Equation 1

$$\zeta = \frac{\frac{1}{n-1}\left(\ln\frac{x_1}{x_n}\right)}{\sqrt{4\pi^2 + \left[\frac{1}{n-1}\left(\ln\left(\frac{x_1}{x_n}\right)\right)\right]^2}}$$

Equation 2

To find the static properties of the ropes such as percent elongation and stiffness, the equations below were used. Equation 3 was used to find stiffness.

$$k = \frac{P}{\delta}$$

Equation 3

Data

Before using the LVDT, it first was calibrated to determine its sensitivity. This was done by displacing the LVDT a known distance with a micrometer and recording the output voltage. These values were then plotted and a line of best fit was found. The slope of this line was determined to be the LVDTs sensitivity. Below in figure V is the calibration curve for the LVDT used.

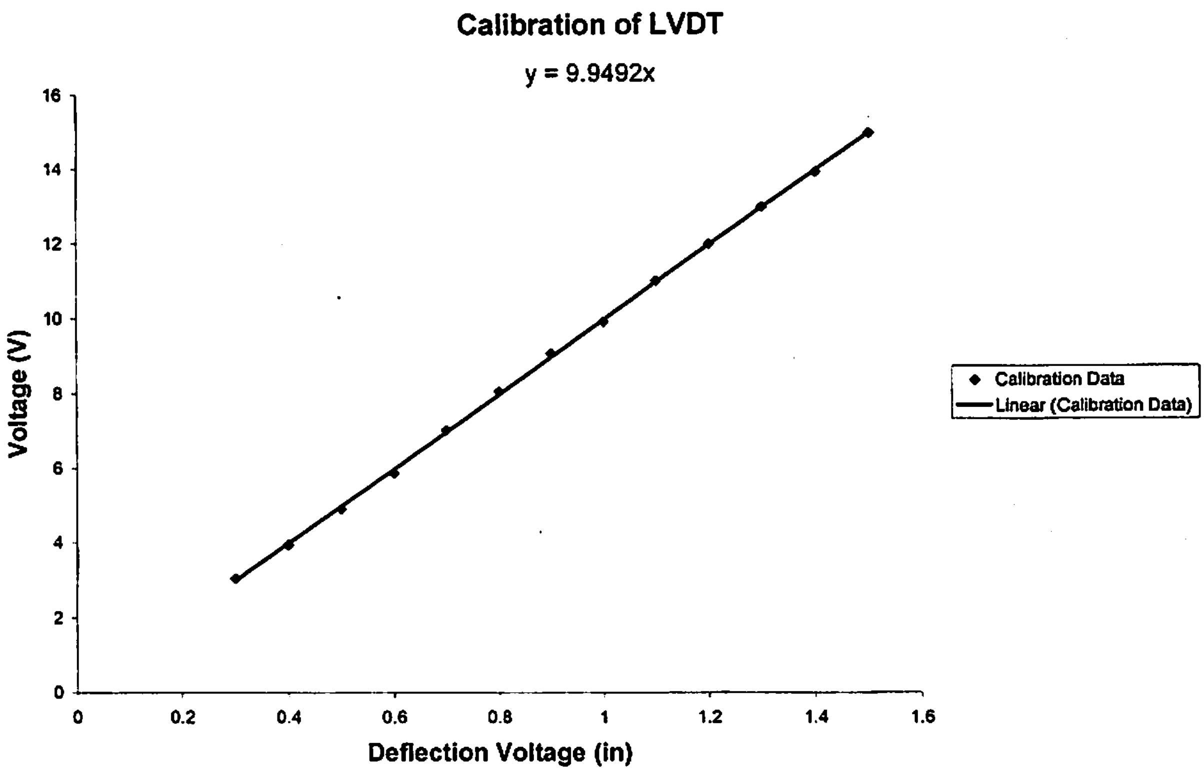


Figure 5: Calibration Curve for LVDT

The found calibration for the used LVDT was 9.9492 volts per inch displaced. The actual sensitivity provided by the manufacturer for the instrument was 9.9 volts per inch. This coincided with a percent error for calibration of only 0.55%. This shows that the experimental methodology used to find the sensitivity was adequate.

Using the LVDT along with its sensitivity, a change in voltage was found which was proportional to the elongation of the rope. Below in Tables 1 and 2 are measurements of output voltage and corresponding displacement for various weights on the nylon and potwarp respectively for each of the diameters tested.

Table 1: Output Voltage and corresponding displacement values for specified forces on Nylon ropes

	3/16" Nylon		1/4" Nylon		5/16" Nylon	
Force	Output Voltage	Elongation	Output Voltage	Elongation	Output Voltage	Elongation
lb	V	(in)	V	(in)	V	(in)
0	19.6	0	19.6	0	19.5	0
2	19.5	0.03811551	19.4	0.0201021	19.5	0
4	19.15	0.17151978	19	0.0603064	19.3	0.02010212
6	18.5	0.41927058	18.4	0.1206127	19.1	0.04020424
8	17.8	0.68607914	17.8	0.1809191	18.9	0.06030636
10	17.2	0.91477218	17.3	0.2311744	18.6	0.09045953
12	16.7	1.10534972	16.7	0.2914807	18	0.15076589
17	15.6	1.52462031	15.4	0.4221445	17.1	0.24122543

Table 2: Output voltage and corresponding displacement values for specified forces on Potwarp

	3/16" Potwarp		1/4" Potwarp		5/16" Potwarp	
Force	Output Voltage	Elongation	Output Voltage	Elongation	Output Voltage	Elongation
lb	V	(in)	V	(in)	V	(in)
0	19.6	0	19.5	0	19.5	0
2	18.8	0.08040848	19.2	0.0301532	19.35	0.01507659
4	18.1	0.15076589	18.8	0.0703574	18.55	0.09548506
6	17.1	0.25127648	17.9	0.160817	17.5	0.20102119
8	15.7	0.39199132	17.1	0.2412254	16.7	0.28142966
10	15	0.46234873	16.2	0.331685	15.8	0.3718892
12	14.2	0.54275721	15.5	0.4020424	15.1	0.44224661
17	12.2	0.74377839	13.9	0.5628593	13.25	0.62819121

For dynamic properties, the piezoelectric accelerometer was used to help determine system responses to step inputs. When the weights were hit, a second order system was captured via Flukeview. These plots were then analyzed and natural frequency and damping ratios were found.

Results

Using the elongation found by the LVDT and the length of rope which was analyzed, percent elongations could be found for each weight. The maximum of these values was then determined to be the final percent elongation factor which could be then used to analyze the entire rope.

Using the force applied to the rope and the length of displacement, the overall rope stiffness could be found. Again the average of all the tests performed was found and used as the overall rope stiffness. Table 3 shows the found percent elongations and stiffness for each rope tested.

Table 3: Percent elongations and stiffness for each rope tested under static conditions

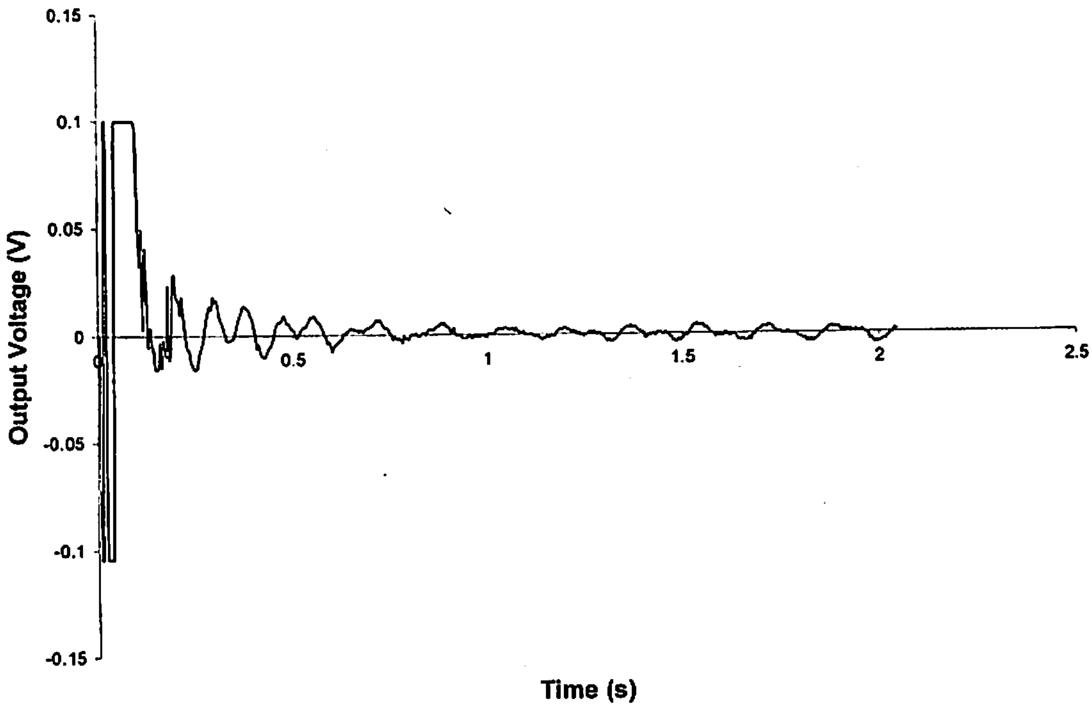
	Percent Elongation	Stiffness (lbf/in)
3/16" Nylon	1.52	44.68
1/4" Nylon	2.14	43.73
5/16" Nylon	1.46	98.32
3/16" Potwarp	2.36	22.18
1/4" Potwarp	2.75	32.13
5/16" Potwarp	3.47	27.87

To assure that the natural frequencies of the different ropes did not equate to the wave frequency, a dynamic step response for each of the different ropes was analyzed. From these step responses, damping ratios and natural frequencies could be found. Table 4 shows these values for each of the ropes.

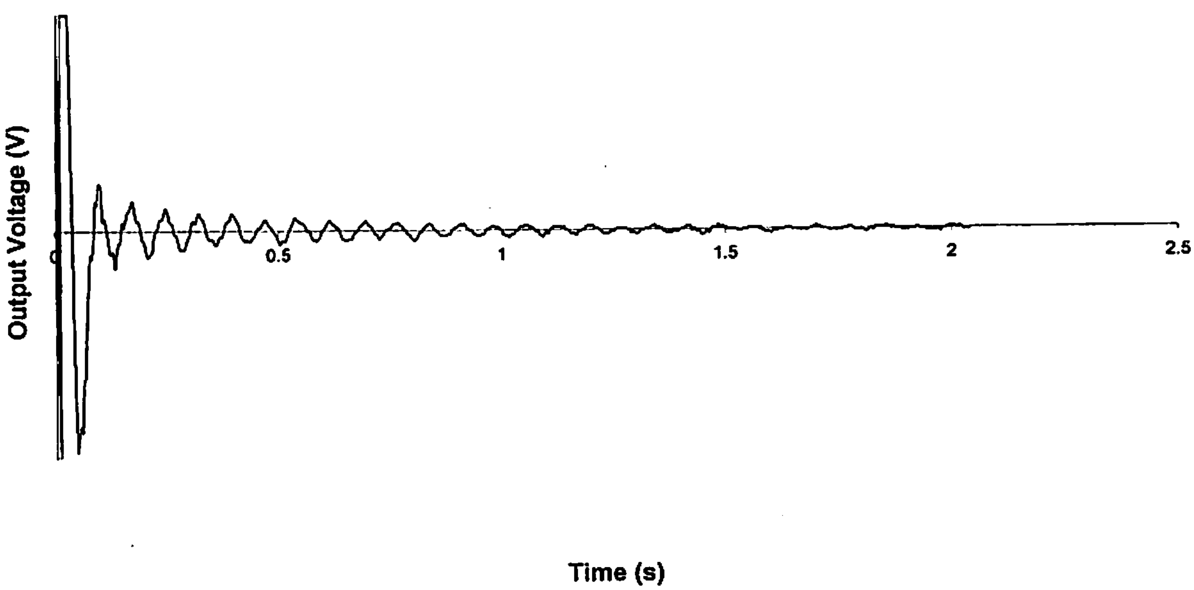
Table 4: Dynamic properties of the ropes tested

	Damping ratio
3/16" Nylon	0.0705
1/4" Nylon	0.0736
5/16" Nylon	0.0817
3/16" Potwarp	0.0361
1/4" Potwarp	0.0632
5/16" Potwarp	0.1271

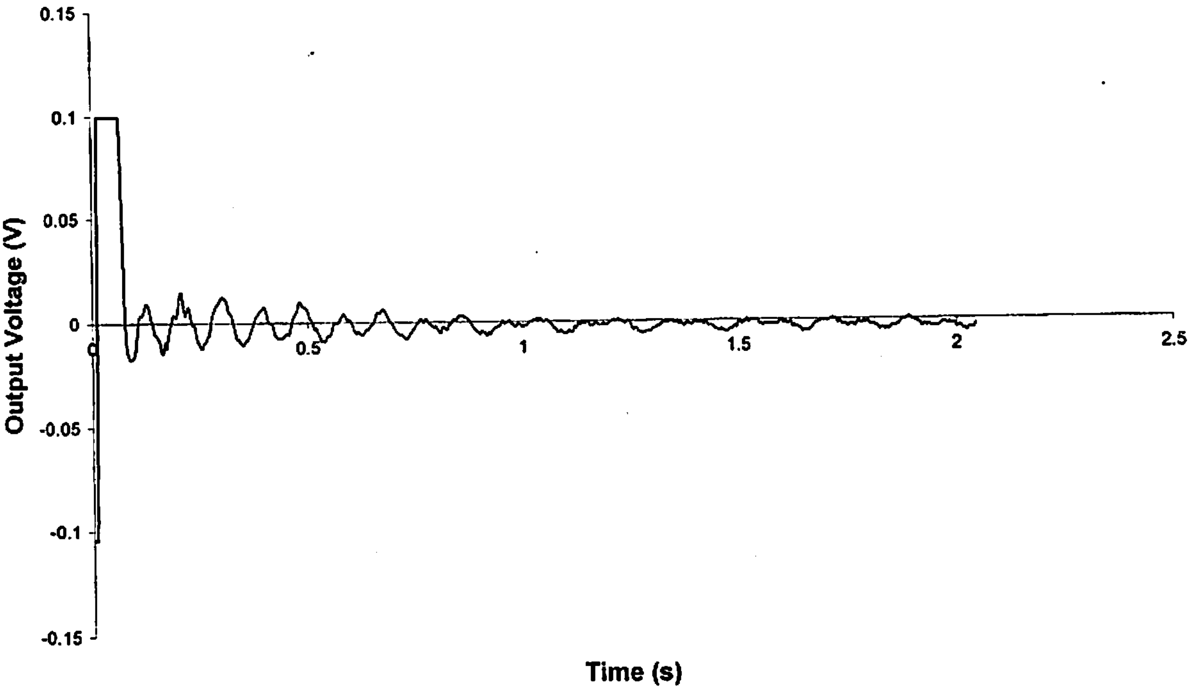
Dynamic Response (3/16") Nylon



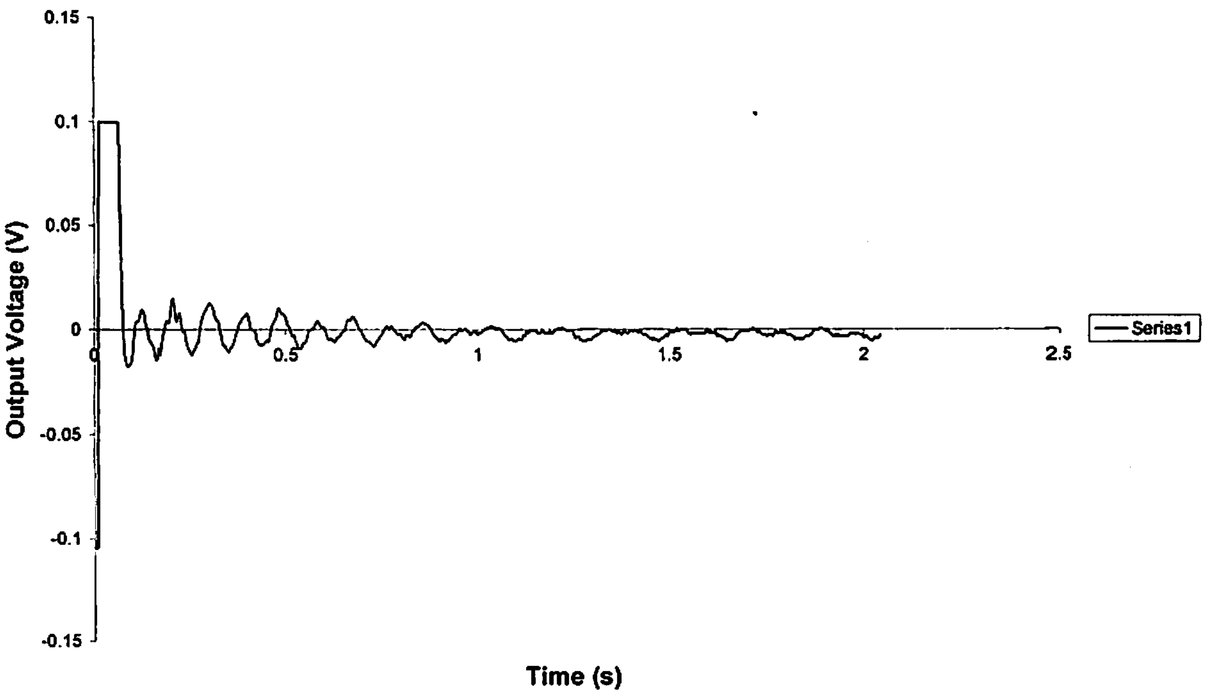
Dynamic Response (1/4") Nylon



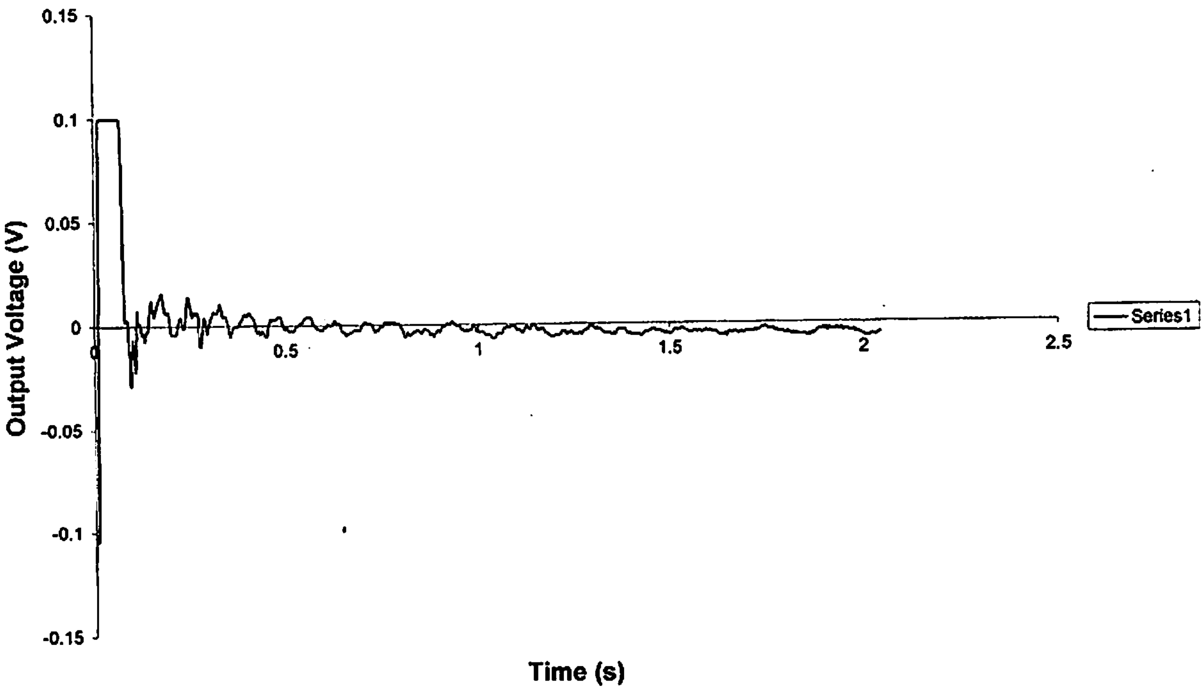
Dynamic Response (5/16") Nylon



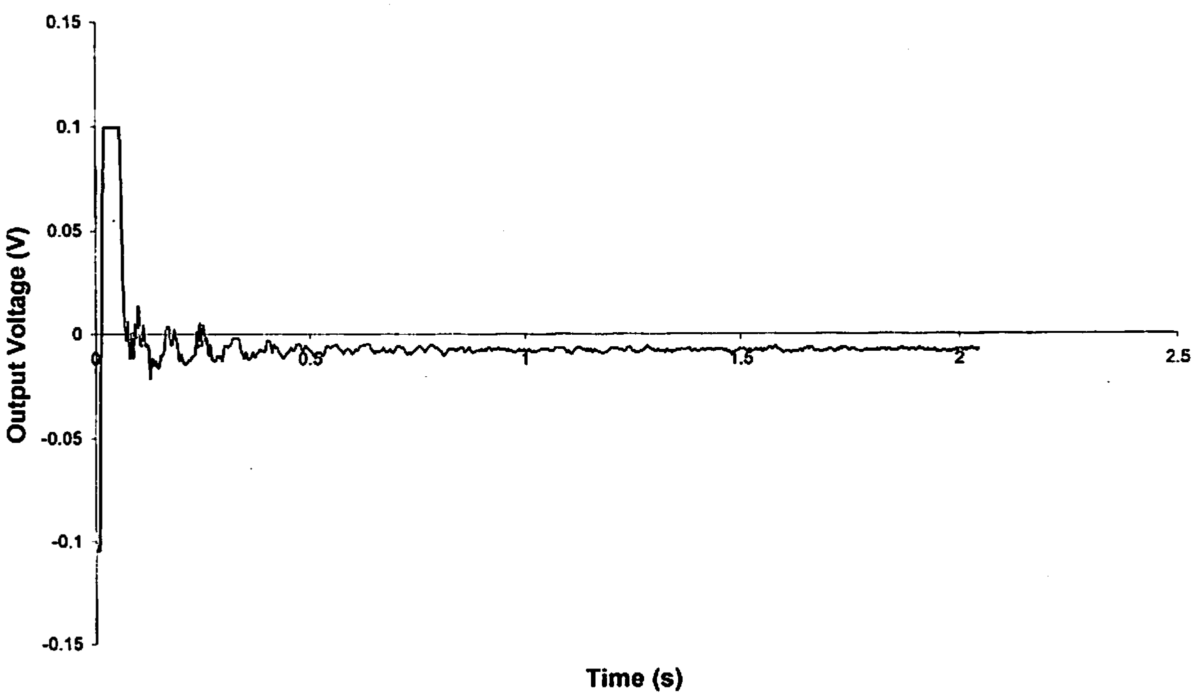
Dynamic Response (3/16") Potwarp

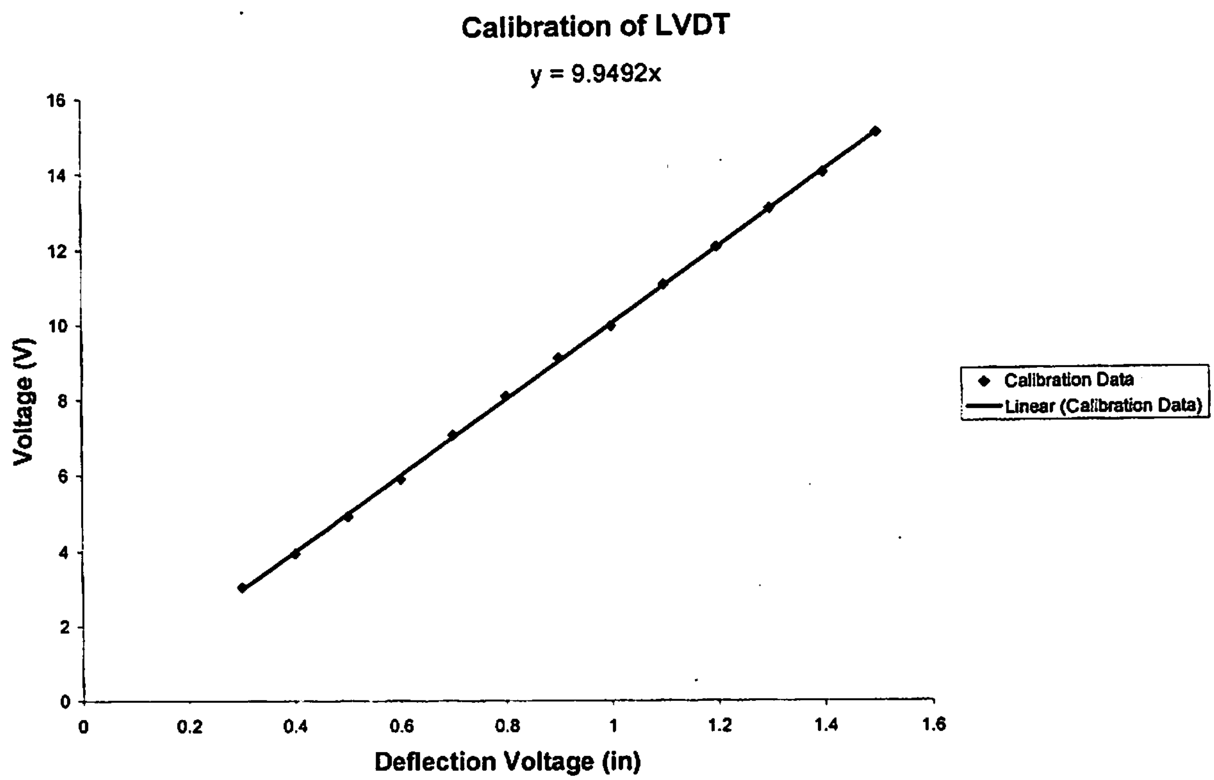


Dynamic Response (1/4") Potwarp

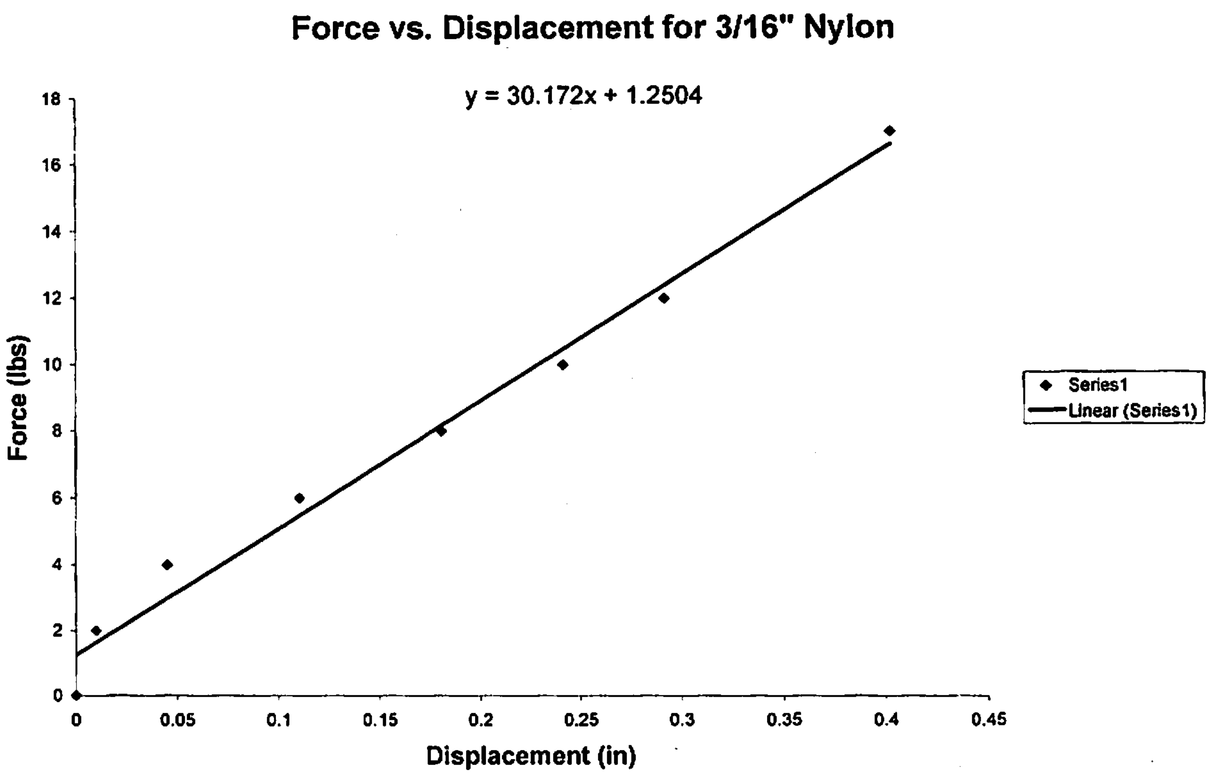


Dynamic Response (5/16") Potwarp

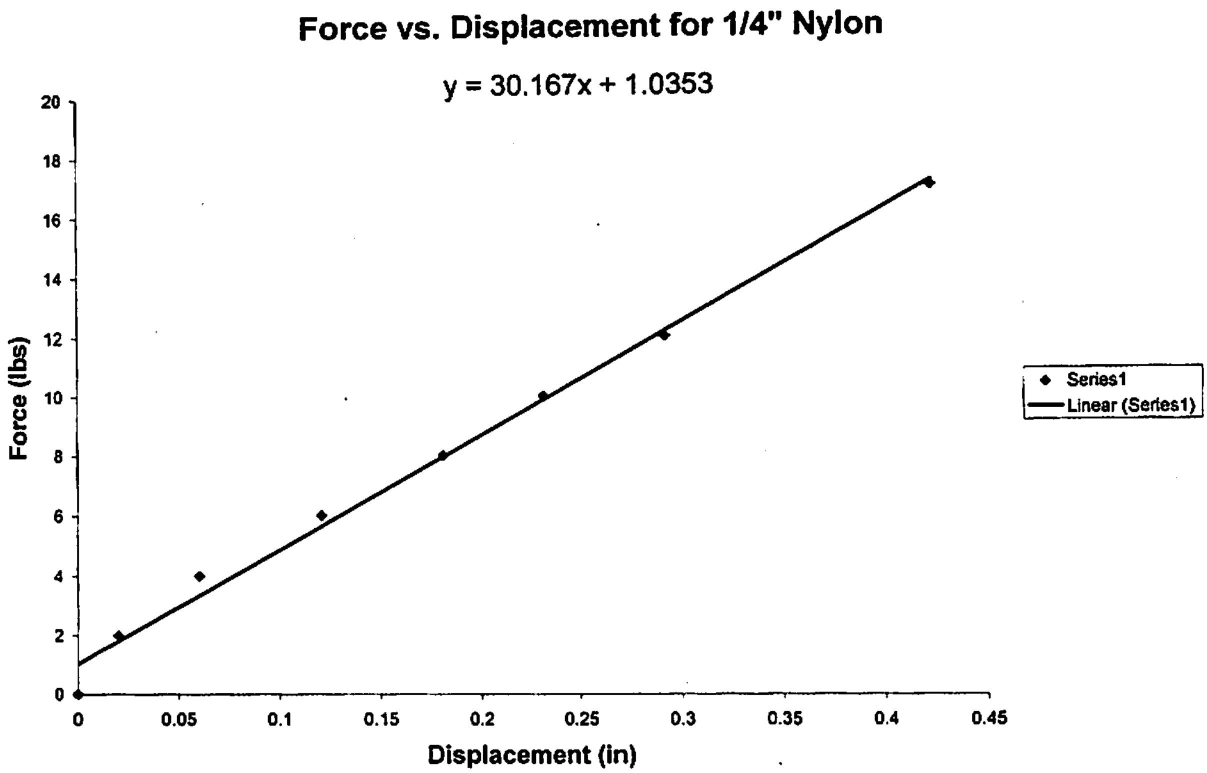


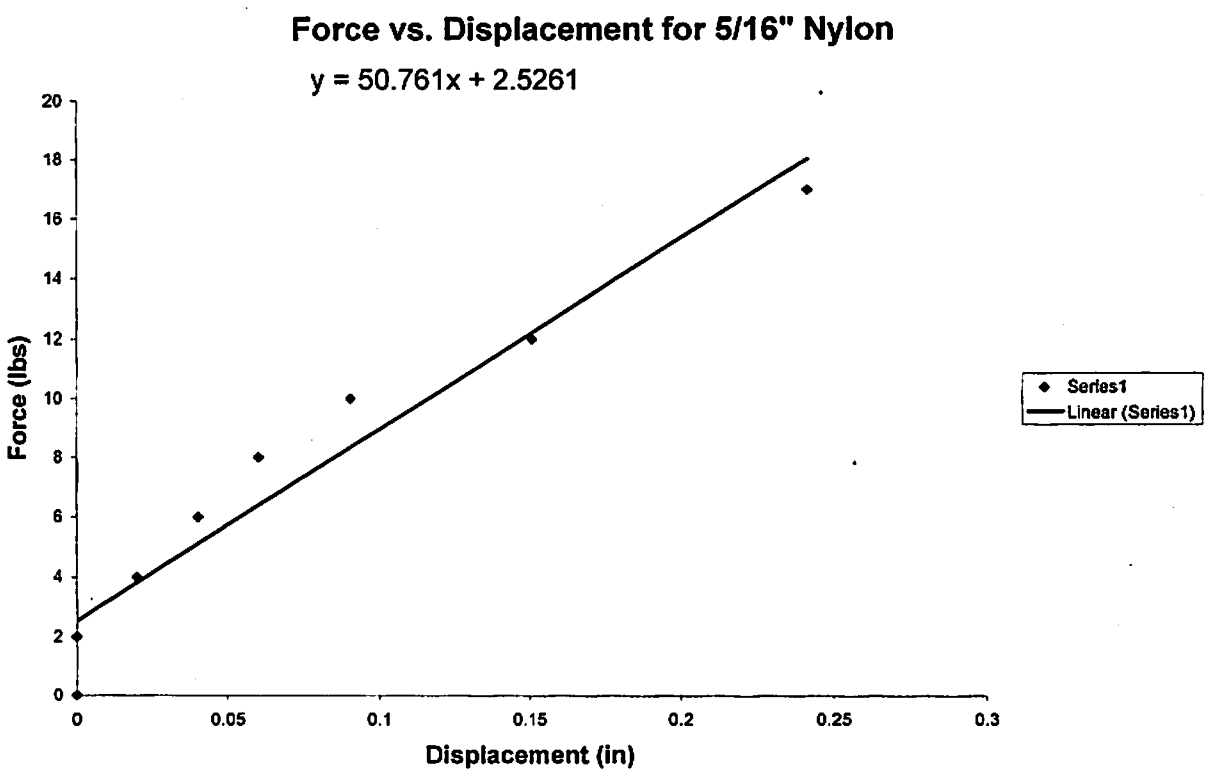


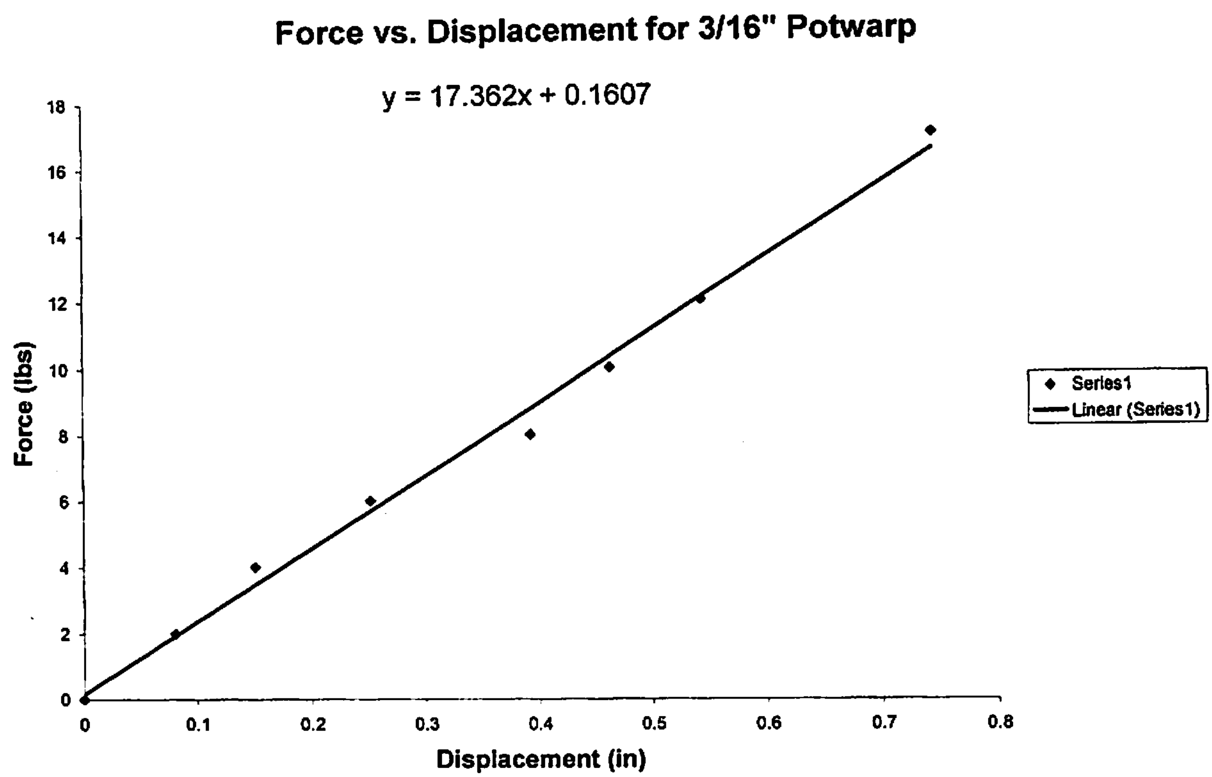
Calibration of LVDT
y = 9.9492x
Voltage (V)
0
2
4
6
8
10
12
14
16
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Deflection Voltage (in)
Calibration Data
Linear (Calibration Data)

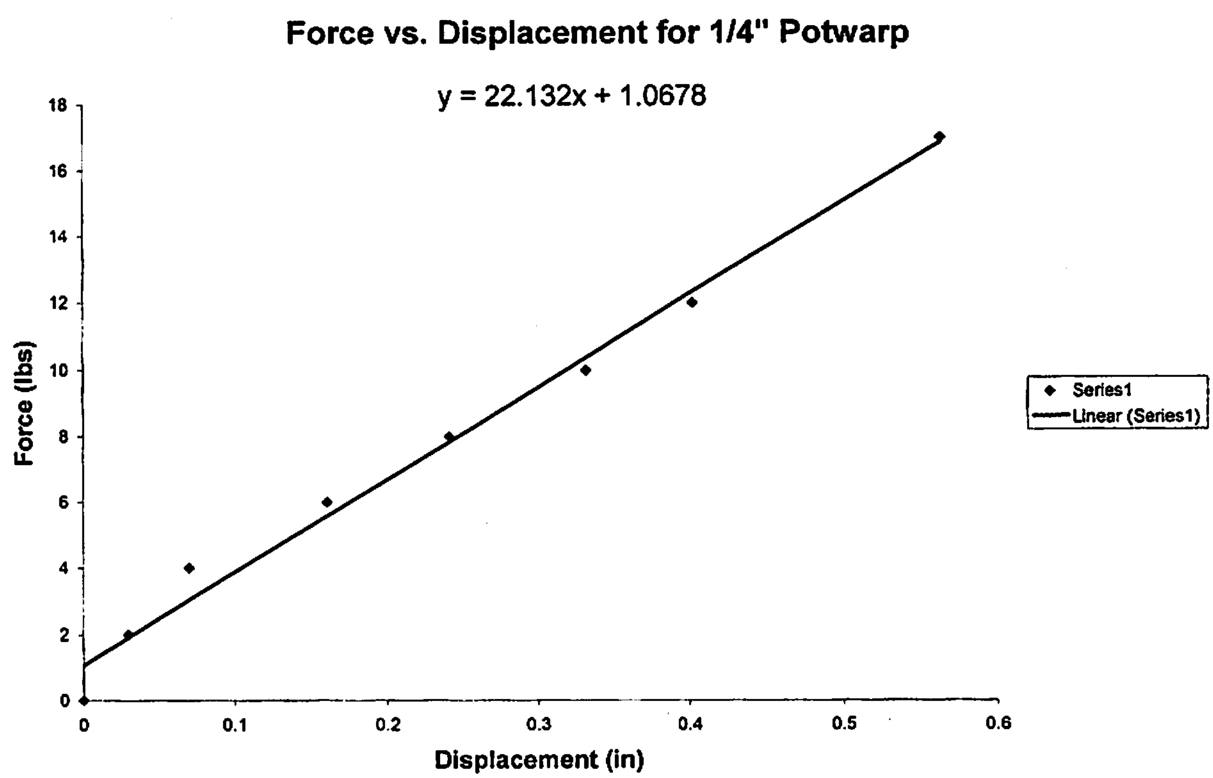


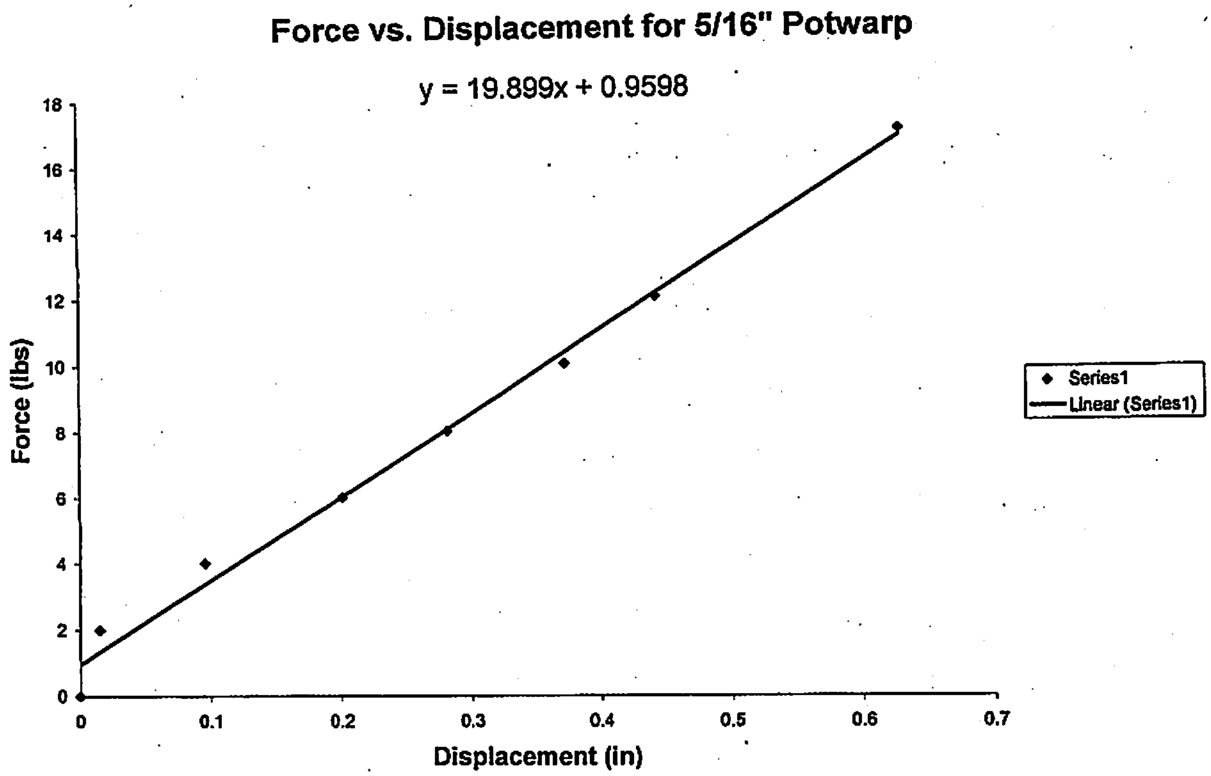
Force vs. Displacement for 3/16" Nylon
y = 30.172x + 1.2504
Force (lbs)
0
2
4
6
8
10
12
14
16
18
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
Displacement (in)
Series1
Linear (Series1)


Force vs. Displacement for 1/4" Nylon
y = 30.167x + 1.0353
Force (lbs)
20
18
16
14
12
10
8
6
4
2
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
Displacement (in)
Series1
Linear (Series1)


Force vs. Displacement for 5/16" Nylon
y = 50.761x + 2.5261
Force (lbs)
20
18
16
14
12
10
8
6
4
2
0
0
0.05
0.1
0.15
0.2
0.25
0.3
Displacement (in)
Series1
Linear (Series1)


Force vs. Displacement for 3/16" Potwarp
y = 17.362x + 0.1607
Force (lbs)
Displacement (in)
Series1
Linear (Series1)
0
2
4
6
8
10
12
14
16
18
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8


Force vs. Displacement for 1/4" Potwarp
y = 22.132x + 1.0678
Force (lbs)
Displacement (in)
Series1
Linear (Series1)
0
2
4
6
8
10
12
14
16
18
0
0.1
0.2
0.3
0.4
0.5
0.6


Force vs. Displacement for 5/16" Potwarp
y = 19.899x + 0.9598
Force (lbs)
18
16
14
12
10
8
6
4
2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Displacement (in)
Series1
Linear (Series1)

Calculation of Kelp Drag Force

Constants

$Kelp_{length} := 10$ m

$Kelp_{width} := 0.1$ m

$Kelp_{thickness} := 0.01$ m

$\rho_{water} := 1030 \quad \frac{kg}{m^3}$

$current := 3 \quad \frac{m}{s}$

$C_{dragrope} := 0.5$

$C_{dragkelp} := 0.001$

$Rope_{Length} := 15.24$ m

$Kelp_{occurance} := 5 \quad \frac{plants}{m}$

$number_{ropes} := 25$

$Rope_{diameter} := .015$ m

Calculations of kelp parameters

$Kelp_{cross} := Kelp_{width} \cdot Kelp_{thickness}$

$Kelp_{cross} = 1 \times 10^{-3} \quad m^2$

$Kelp_{volume} := Kelp_{length} \cdot Kelp_{width} \cdot Kelp_{thicknes}$

$Kelp_{volume} = 0.01 \quad m^3$

Calculations of Drag Forces

$$Drag_{force.plant} := 0.5 \cdot \rho_{water} \cdot current^2 \cdot Kelp_{cross} \cdot C_{dragkelp}$$

$$Drag_{force.plant} = 4.635 \times 10^{-3} \quad \frac{N}{plant}$$

$$Drag_{force.meter} := Drag_{force.plant} \cdot Kelp_{occurance}$$

$$Drag_{force.meter} = 0.023 \quad \frac{N}{m}$$

$$Drag_{forcerope} := 0.5 \cdot \left(\rho_{water} \cdot current^2 \cdot Rope_{Length} \cdot Rope_{diameter} \cdot C_{dragrope} \right)$$

$$Drag_{force.rope} := Drag_{force.meter} \cdot Drag_{forcerope}$$

$$Drag_{force.rope} = 12.278 \quad N$$

$$Drag_{on.rope} := Drag_{force.rope} \cdot number_{ropes}$$

$$Drag_{on.rope} = 306.942 \quad N$$

Calculation of Structure Drag

$$Tube_{length} := 15.24 \quad m$$

$$Tube_{diameter} := .1016 \quad m$$

$$C_{tube.against} := 1.28$$

$$C_{tube.withflow} := .5$$

$$Number_{tubes} := 4$$

$$Tube_{volume} := \left(\frac{Tube_{diameter}}{2} \right)^2 \cdot \pi \cdot Tube_{length}$$

$Tube_{volume} = 0.124 \quad m^3$

$$Tube_{cross.against} := \left(\frac{Tube_{diameter}}{2}\right)^2 \cdot \pi$$

$$Drag_{force.tube.against} := 0.5 \cdot \rho_{water} \cdot current^2 \cdot Tube_{cross.against} \cdot C_{tube.against}$$

$$Drag_{force.tube.against} = 48.099 \quad \frac{N}{tube}$$

$$Tube_{cross.withflow} := Tube_{diameter} \cdot Tube_{length}$$

$$Drag_{force.tube.withflow} := 0.5 \cdot \left(\rho_{water} \cdot current^2 \cdot Tube_{cross.withflow} \cdot C_{tube.withflow}\right)$$

$$Drag_{force.tube.withflow} = 3.588 \times 10^3 \quad \frac{N}{tube}$$

$$Drag_{force.structure} := Drag_{force.tube.withflow} + 2Drag_{force.tube.against}$$

$$Drag_{force.structure} = 3.685 \times 10^3 \quad N$$

Calculation of Drag on Airtank

$Tank_{length} := 3.048$ m

$Tank_{width} := 0.904$ m

$C_{tank} := 0.4$

$Tank_{area} := Tank_{length} \cdot Tank_{width}$

$Drag_{airtank} := 0.5 \cdot \left(\rho_{water} \cdot current^2 \cdot Tank_{area} \cdot C_{tank} \right)$

$Drag_{airtank} = 5.108 \times 10^3$ N

Calculation of Total Drag

$Total_{drag} := Drag_{force.structure} + Drag_{on.rope} + Drag_{airtank}$

$Total_{drag} = 9.1 \times 10^3$ N

$\frac{Total_{drag}}{1000} = 9.1$ KN

Calculation of Buoyancy (assuming kelp is neutral)

$gravity := 9.81 \quad \frac{m}{s^2}$

$\rho_{water} := 1030 \quad \frac{kg}{m^3}$

$Tube_{diameter} := .1016 \quad m$

$Length := 15.25 \quad m$

$Rope_{diameter} := 0.015 \quad m$

$Tube_{number} := 4$

$Rope_{number} := 25$

$Volume_{tank} := 1.893 \quad m^3$

$$Tube_{area} := \pi \cdot \left(\frac{Tube_{diameter}}{2}\right)^2$$

$$Volume_{tube} := Tube_{area} \cdot Length \cdot Tube_{number}$$

$$Volume_{rope} := \pi \cdot \left(\frac{Rope_{diameter}}{2}\right)^2 \cdot Length \cdot Rope_{number}$$

$$Volume_{total} := Volume_{rope} + Volume_{tube}$$

$$Force_{buoyancy} := \rho_{water} \cdot (Volume_{tank} + Volume_{total}) \cdot gravity$$

$Force_{buoyancy} = 2.481 \times 10^4 \quad N$

$\frac{Force_{buoyancy}}{1000} = 24.805 \quad KN$

Calculation of Overall Mass of Structure

$$\rho_{rope} := 55.475 \quad \frac{kg}{m^3}$$

$$\rho_{tube} := 1380 \quad \frac{kg}{m^3}$$ density of polyvinyl chloride

$$Tube_{air} := .0508 \quad m$$

$$Tube_{air} := \pi \cdot \left(\frac{Tube_{air}}{2}\right)^2$$

$$Shell_{volume} := \left(Tube_{area} - Tube_{air}\right) \cdot Length \cdot Tube_{number}$$

$$mass_{tube} := \rho_{tube} \cdot Shell_{volume}$$

$$mass_{rope} := \rho_{rope} \cdot Volume_{rope} \cdot Rope_{number}$$

$$mass_{biofouling} := 500 \quad kg$$

$$mass_{tank} := 544.31 \quad kg$$

$$mass_{total} := mass_{rope} + mass_{tube} + mass_{biofouling} + mass_{tank}$$

$$mass_{total} = 1.65 \times 10^3 \quad kg$$

Calculation of Sinking Force

$$Sinking_{force} := mass_{total} \cdot gravity$$

$$Sinking_{force} = 1.618 \times 10^4 \quad N$$

Calculation of Net Force

$$\frac{Sinking_{force}}{1000} = 16.183 \qquad KN$$

$$Force_{net} := Force_{buoyancy} - Sinking_{force}$$

$$Force_{net} = 8.623\times 10^{3} \qquad N$$

$$\frac{Force_{net}}{1000} = 8.623 \qquad KN$$

Calculation of Counter Weight

$$Mass := \frac{Force_{net}}{gravity}$$

$$Mass = 878.964 \qquad kg$$

$$Mass \cdot .0011 = 0.967 \qquad tons$$

Calculations of Drag of Kelp Farm Modeled as a Solid Rectangle

$C_{drag} := 1.28$

$Side_{Length} := 15.24$ m

$Height := .1016$ m

$Current := 3$ $\frac{m}{s}$

$\rho_{water} := 1030$ $\frac{kg}{m^3}$

$Drag := 0.5 \cdot \rho_{water} \cdot Current^2 \cdot Side_{Length} \cdot Height \cdot C_{drag}$

$Drag = 9.186 \times 10^3$ N

Calculations of Buoyancy of Kelp Farm Modeled as a Solid Rectangle

$gravity := 9.81$ $\frac{m}{s^2}$

$Volume_{tank} := 1.892$ m^3

$Volume_{total} := Side_{Length} \cdot Height$

$Force_{buoyancy} := \rho_{water} \cdot (Volume_{tank} + Volume_{total}) \cdot gravity$

$\frac{Force_{buoyancy}}{1000} = 34.763$ KN

Calculation of Scaled Parameters for Kelp Farm Structure Keeping Froude Numbers Constant

$Fr_{proto} := Fr_{model}$ Parameter to be kept for scaling

$V_{proto} := 3$ $\frac{m}{s}$

$gravity := 9.81$ $\frac{m}{s^2}$

$Length_{proto} := 15.25$ m

$Length_{model} := 0.762$ m

$\rho_{water} := 1030$ $\frac{kg}{m^3}$

$Depth_{proto} := 0.1016$ m

$Force_{model} := \blacksquare$ N Unknown due to no testing in wave tank

$$\lambda_{scale} := \frac{Length_{proto}}{Length_{model}}$$

$$Fr_{proto} := \frac{V_{proto}^{2}}{gravity \cdot Length_{proto}}$$

$$V_{model} := V_{proto} \cdot \left(\frac{Length_{model}}{Length_{proto}} \right)^{\frac{1}{2}}$$

$$Fr_{model} := \frac{V_{model}^{2}}{gravity \cdot Length_{model}}$$

$$Force_{proto} := \lambda_{scale}^{3} \cdot Force_{model}$$

Solutions

$V_{model} = 0.671 \quad \frac{m}{s}$

$Force_{proto} = \blacksquare \quad N$

$Fr_{model} = 0.06$

$Fr_{proto} = 0.06$

$\lambda_{scale} = 20.013$

Part #	Item	Quantity	Length/Dia	Cost	Total
A	**Structure**				
A1	Side Rails	20	10	$32.43	$648.60
A2	Corner Connections	4	4	$11.92	$47.68
A3	Pipe Connectors	12		$8.75	$105.00
A5	Plastic Weld Cement	10		$3.46	$34.60
B	**Growing Lines**				
B1	Lines	25	54	$0.08	$110.25
B2	Line Connections	50	2	$4.64	$232.00
C	**Airlift**				
C1	Pressure Vessel	1	N/A	$2,448.00	$2,448.00
C2	Air Lines	2	200	$1.06	$424.00
C3	Water Lines	2	200	$1.53	$612.00
C4	Fittings, Air	2	N/A	$95.96	$191.92
C5	Fittings, Water	2	N/A	$116.04	$232.08
C5	Connection to Structure	4	400		$2,000.00
C6	Fabrication	1		$500.00	$500.00
D	**Pendent Weight**				
D1	Line		100		$500.00
D2	Chain	1	100	$1,029.99	$1,029.99
E	**Lab Growth**				
E1	NaNO3	250g		$21.10	$84.40
E2	Thiamine hydrochloride	100g		$40.40	$161.60
E3	Biotin	1g		$78.40	$313.60
E4	Cyanobalamin	500g		$60.70	$242.80
E5	Na2EDTA 2H2O	100g		$25.20	$100.80
E6	H3BO3	500g		$26.90	$107.60
E7	MnSO4 7H2O	500g		$80.30	$321.20
E8	ZnSO4 7H2O	100g		$22.00	$88.00
E9	CoSO4	100g		$27.50	$110.00
E10	a2 B-Glyceoposplat	100g		$36.30	$145.20
E11	GeO2	10g		$76.00	$304.00
E12	Betadine	16oz		$31.75	$127.00
E13	PVC Pipe			$27.58	$110.30
E14	Growth Line				$105.00
F	**Other Needs**				
F1	Cold Room	1			$0.00
F2	Boat	1			$0.00
F3	Re-String Device	1			$150.00
F4	Boat Crew	2			$0.00

F5	Lab Crew		2	$0.00
F6	Air Compressor		1	$749.00
F7	Boat Fuel(1)	$150/trip		$150.00

Number of Structures	Initial	1	5	10	15	20	
Total Structure (1 farm)	$9,116.12	$9,116.12	$45,580.60	$91,161.20	$136,741.80	$182,322.40	
Total Others (initial equipment)	$1,049.00	$1,049.00	$1,049.00	$1,049.00	$1,049.00	$1,049.00	
Total Running Cost (per cycle)	$2,471.50	$2,471.50	$12,357.50	$24,715.00	$37,072.50	$49,430.00	
Total Investment	$12,636.62	$12,636.62	$58,987.10	$116,925.20	$174,863.30	$232,801.40	
Price per plant (Assuming 1900 plants/farm)	$6.65	$6.65	$6.21	$6.15	$6.14	$6.13	
Number of years		1	2	5	10	15	20	#Farms

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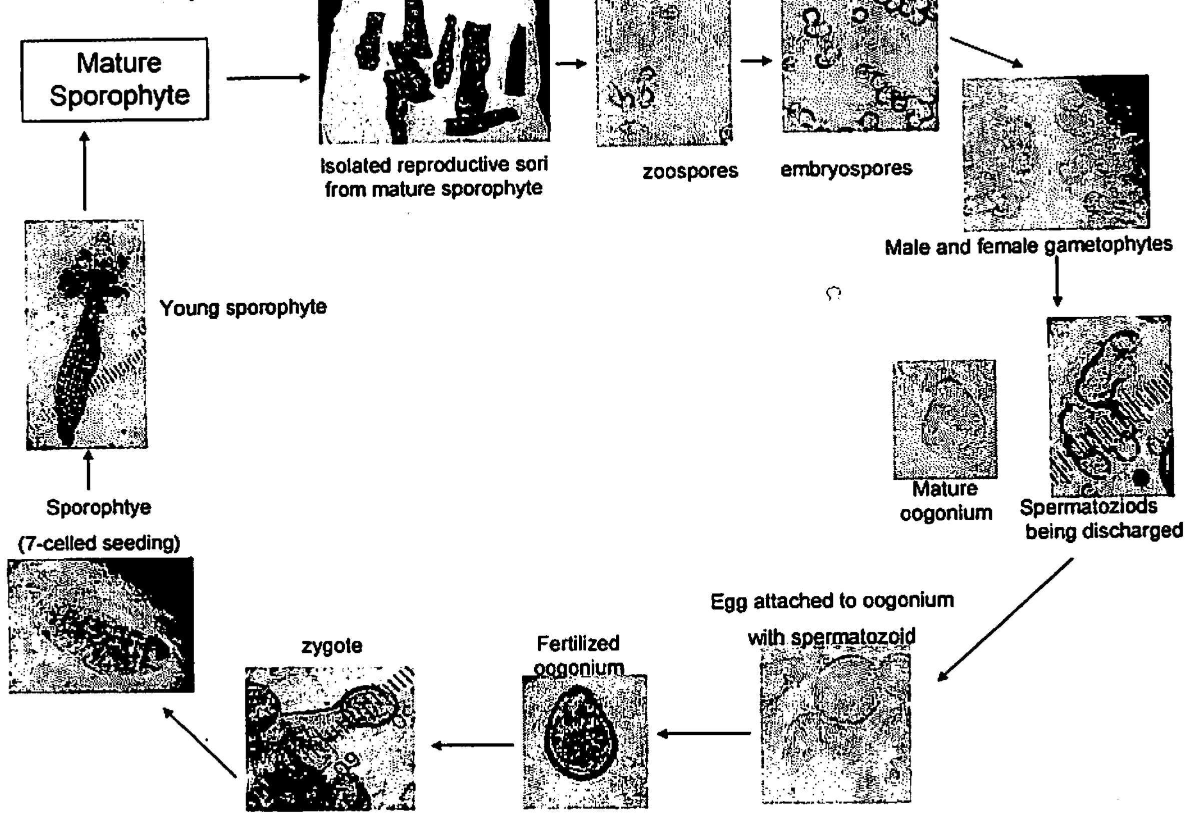
Price Per Plant	$6.65	$3.98	$2.37	$1.84	$1.66	$1.57	1
	$6.21	$3.75	$2.28	$1.79	$1.63	$1.55	5
	$6.15	$3.73	$2.27	$1.79	$1.62	$1.54	10
	$6.14	$3.72	$2.27	$1.78	$1.62	$1.54	15
	$6.13	$3.71	$2.27	$1.78	$1.62	$1.54	20

	1	2	5	10	15	20	
#plants yielded	1900	3800	9500	19000	28500	38000	1
	9500	19000	47500	95000	142500	190000	5
	19000	38000	95000	190000	285000	380000	10
	28500	57000	142500	285000	427500	570000	15
	38000	76000	190000	380000	570000	760000	20

	1	2	5	10	15	20	
profit	-$8,836.62	-$7,508.12	-$3,522.62	$3,119.88	$9,762.38	$16,404.88	1
	-$39,987.10	-$33,344.60	-$13,417.10	$19,795.40	$53,007.90	$86,220.40	5
	-$78,925.20	-$65,640.20	-$25,785.20	$40,639.80	$107,064.80	$173,489.80	10

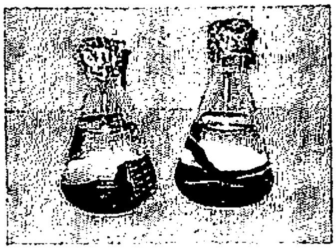
Lifecycle of *Saccharina latissima:*

(all pictures taken at 400X magnification)

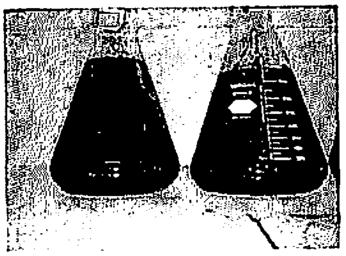


Pictures from *Saccharina* latissima cultivation.

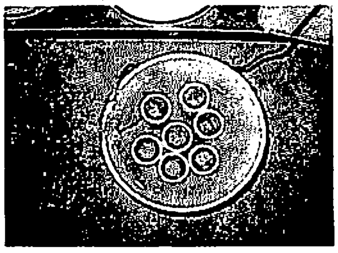
Mature sori after surface disinfection



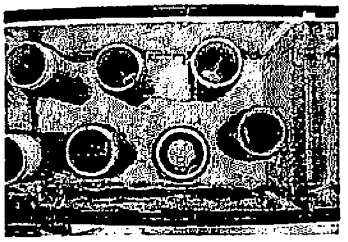
Sori reimmersion in seawater after overnight incubation at 4°C.



Spore release after 4 hours with limited light at 10°C.



PVC pipes with seed line being inoculated with spore suspension.



Inoculated lines placed in growth chamber.

Attempt date and location	Spore Release	Time in growth chambers	Results	Alterations from final protocol
9/27/06 SCUBA, Portsmouth, NH	None	N/A	The samples did not release spores most likely due to rough handling during collection.	Samples were scrubbed too roughly, consistent temperature not maintained, placed at 10°C overnight
10/5/06 Prescott Park and Fort Stark	None	N/A	No spore release most likely because samples were not reproductively mature yet.	Samples were scrubbed too roughly and consistent temperature not maintained.
10/19/06 Prescott Park	Limited spore release but not enough color change to inoculate lines.	N/A	Limited spore release most likely due to usually warm temperatures delaying natural spore release.	These samples were kept at a constant temperature during collection and an iodine bath used in disinfection.
10/26/06 Prescott Park	Good spore release, water was a pale to medium brown color.	Disposed of lines in growth chamber on 1/21/07 after two cold room malfunctions and green algae contamination.	Although good spore release cultivation was hindered because of cold room malfunctions and contamination. Observed young sporophyte in this tank after 1/18/07.	After 2 hours spore release began then reduce light levels and achieved a greater release.
11/2/06 Prescott Park (collected 3 days prior to a full moon which has been suggested to increase percentage of ripe sori, Merrill et al. 1991)	Good spore release, water was a medium brown color.	Disposed of lines in growth chamber on 2/25/07 after two cold room malfunctions and severe diatom contamination.	Although good spore release cultivation was hindered because of cold room malfunctions and contamination. Observed a few gametophytes on slides.	These samples were placed completely in the dark upon reimmersion in seawater.
1/25/07 Prescott Park	Best spore release observed with dark chocolate colored water.	Are currently growing in the laboratory and reached the 7-celled seedling stage.	Samples have shown to be the most promising of the entire experiment and are currently growing with little contamination.	These samples had the greatest spore release most likely due to the cold temperature of the water and almost no bryozoan growth on plants.