# UNH P.O.W.E.R

**(Permanent Outfit for Water Energy Recovery)**

## TIDAL TURBINE TEST FACILITY DESIGN


**Team Members**

Jeffrey Byrne (Project Manager)
Alex Costa
Daniel Johnson
Isagani Kimball

**Advisor**

Dr. M. Robinson Swift

# i. Table of Contents

# ii. List of Figures

# iii. List of Tables

# 1. Acknowledgements

Our team would like to recognize the following people and groups:

We would like to thank our advisor Dr. M. Robinson Swift for his guidance throughout the course of the year.

We would also like to thank Dr. Martin Wosnik and Dr. Ken Baldwin for their help during the project.

We would like to extend thanks to
Jenn Bedsole for her incredible organizational support.

We would like to thank Ryan Despins for working with us during tow testing and showing us the old barge.

We would like to extend thanks to Jud DeCew for his help in acquiring a load cell.

Finally we would like to thank the University of New Hampshire Center for Ocean Engineering as well as the departments of Mechanical and Civil Engineering for their facilities, tools and supplies throughout the course of the year.

This work is the result of research sponsored in part, by the National Sea Grant College Program, NOAA, Department of Commerce, under grant #NA06OAR4170109 through the New Hampshire Sea Grant College Program.

## 2. Abstract

There is an ever growing interest in environmentally friendly energy production these days such as, wind, solar, and tidal energy. Solar and wind energy is used worldwide in generating electricity and both rely on unpredictable natural forces as sources of energy; although reliable, little has been done in terms of tidal energy. Tidal energy is slowly growing in popularity but the lack of proper full scale testing facility is hindering commercial development of tidal energy systems. Tidal energy is an excellent source of power due to its predictability, and low impact on the environment.

The University of New Hampshire's P.O.W.E.R (Permanent Outfit for Water Energy Recovery) Team's goal is to provide a testing platform for a variety of tidal energy turbines. This report discusses the steps taken to design a twin hull deck barge for use as a test facility. These steps include determining design criteria, exploring design alternatives, hydrostatic and tipping analysis, full scale design parameters, scale model testing, and structural analysis.

# 3. Introduction

## 3.1 Background

Tides are a result of the gravitational forces on the earths oceans caused by the moon and the sun. These forces cause the oceans to rise and fall twice a day. The amount of energy required to move the oceans is tremendous and the goal of tidal energy production is to capture a portion of the energy created by the tides and use it in the production of electricity.

Tidal energy has been used throughout history with the use of barrages. Barrages work like a two way dam. As the tide is incoming the water builds behind the barrage and creates a head. The head is the difference in water elevation between the two sides of the barrage. It is the head which makes is possible for the barrage to produce electricity. The most famous Barrage is the La Rance Tidal Barrage (Figure 1) located in France.

Figure 1 : La Rance Tidal Barrage

Barrages can negatively impact the environment inside bays by changing the flow of water in and out of them and all can reduce the number of fish which travel between the bays and the open ocean. Another disadvantage of barrages is extremely large construction costs.

Another means of capturing tidal energy is the deployment of tidal stream generators. Tidal stream generators are an immature technology, but there are several prototypes however it is still unclear which style turbine would be best suited for this technology. These use the same principles employed in wind energy conversion; however instead of using wind to spin a turbine, water is used. The idea of a tidal stream generator is to place a turbine in areas where the velocity of the current created by tides is greater than 2 knots. The advantages to this technology are a relatively low cost of infrastructure, and a low impact on the surrounding environment. The main disadvantages of tidal stream generators are a lack of knowledge and testing facilities.

There are a number of prototype generators around the world currently. One example is the EVOPOD (Figure 2). The EVOPOD is based out of the UK. The system is deployed the tidal stream and can generate power for up to 20 hours per day.

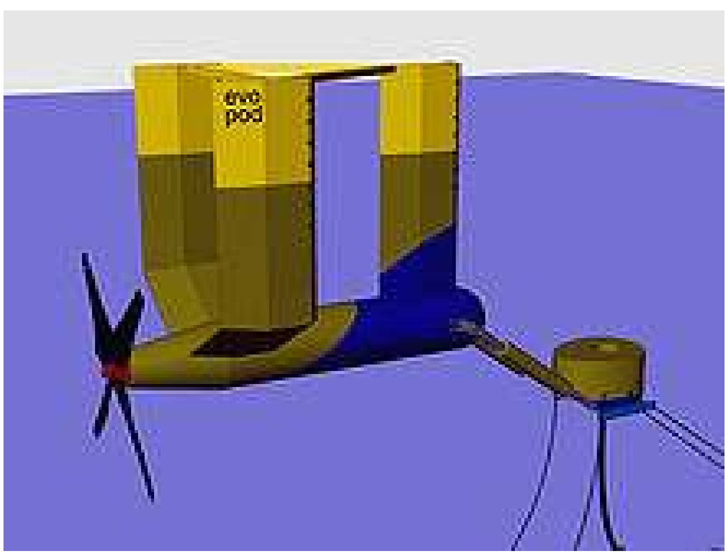



Figure 2: EVOPOD Tidal Stream Generator.

Another Example of a tidal energy generator is the SeaGen in Ireland (Figure 3). The SeaGen was the first commercial generator to be connected to the grid. It is capable of producing 1.2MW for 18-20 hours per day.

Figure 3: SeaGen prototype in Ireland, Predecessor to First Commercial Tidal Stream Generator

The need for a test facility for tidal energy turbines is great. Currently, there exists a large gap between conceptual models and full scale tidal energy applications like the EVOPOD and SeaGen. Turbine models can be analyzed in computer programs and subjected to rigorous lab testing, however a full scale testing facility is in dire need to act as a stepping stone between the laboratory and real world applications. The ability to gain accurate data on full scale turbines subjected to real world scenarios will instill confidence in this emerging renewable energy industry.

### 3.2 Previous Work

This is the third academic year that UNH has been researching tidal energy. Over the last two years the school has done a lot in terms of tidal stream generator research. The 2007-2008 team found an ideal location for testing of turbines, designed and began constructing a test platform for testing of turbines. The 2008-2009 team finished the platform and preformed tests using the platform.

The site for testing the tidal stream generator turbines is located in the Piscataqua River in Newington, NH. This location is known to have some of the highest tidal current velocities in North America and can reach speeds up to 5 knots. The exact location is directly under the old General Sullivan Bridge on Route 16 (Figure 4).


Figure 4: Test Site Location

The NHDOT has approved the section under span 6 of the bridge for use by UNH (Figure 5).

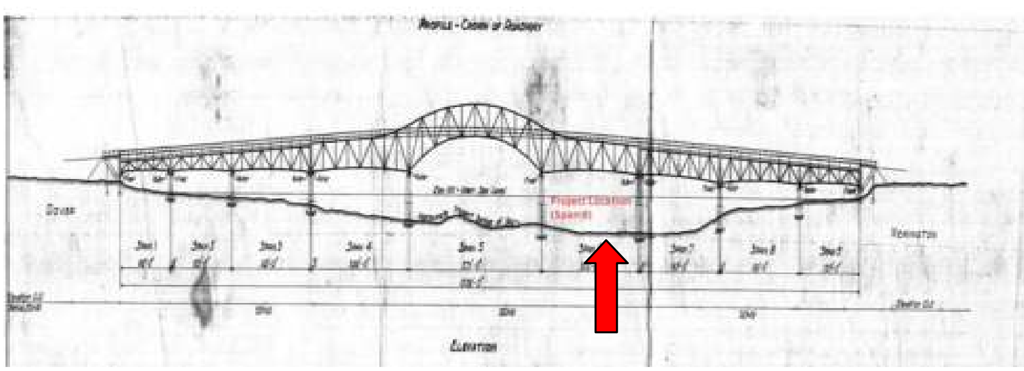


Figure 5: Test Bay Location

The 2007-2008 team created a design for a twin hull deck barge which supported a derrick (Figure 6). The derrick housed a cage which held a Gorlov style turbine. The design involved a platform capable of resisting the tipping moment created by the turbine, the cage design, derrick design, gearing from turbine to generator and mechanism for raising and lowering the cage in and out of the water (Browne et. al).

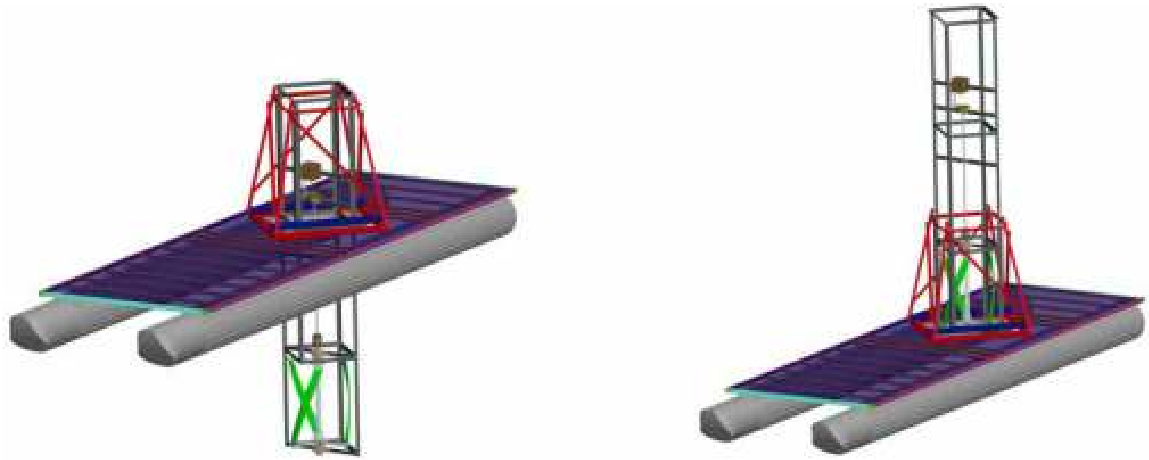


Figure 6: Design of Current Barge

The 2007-2008 team began construction of their design and it was later completed by the 2008-2009 team. After the 2008-2009 team finished the construction they began testing and collecting data from the test barge (Figure 7).

Figure 7: Current Barge Test

The test platform created by the two previous year's teams is an excellent test platform for the small Gorlov style turbine. However it is limited to its testing abilities due to the fact that the barge can only be testing while facing forward. Also there is a need to test larger turbines and different styles of turbines.

### 3.3 Goals

The major goal of UNH P.O.W.E.R is to design a platform for testing various tidal stream generator turbines. The team will provide the design of a twin hull deck barge to act as a platform. It will also include the design and structural analysis of the cage, derrick and deck. Finally scale model testing of the barge will be preformed. The ultimate goal of the project is to provide a test facility for long term testing of different style turbines, so that future development of commercial tidal stream generators can be achieved.

### 3.4 Approach

The UNH P.O.W.E.R team began by researching the work done by the 2001-2008 team and the 2008-2009 team. The major focus of the group was to have the design of the pontoons and cage done so that there would be enough time for model construction and tow testing. The team started by designing the barge, from picking material types and sizes for pontoons, deck beams and decking. Once the barge was designed the cage and derrick designs followed. The cage and derrick design was extremely iterative due to changes in the design criteria part way through the project. After the basic design was established the team built a scale model of the test platform. The model was used in the tow tank in the Chase Ocean Engineering Lab for proof of concept, verify stability and to determine drag forces produced by different style turbines.

# 4. Design Criteria

## 4.1 Turbines

This barge was designed to analyze and support four styles of turbines; the horizontal/transverse axis turbine, horizontal/longitudinal axis (propeller), vertical axis turbine, and a ducted turbine. These turbines will be targeting the fastest moving tidal range. The submerged cage was designed to support all four styles of turbine

The horizontal/transverse axis turbine is to be 2m in diameter at a length of 5m. It will be submerged 3m below the surface of the water to target the maximum velocity flow of the tide. One example of this style of turbine is the 'Gorlov' Helical Turbine (Figure 8). Alexander M. Gorlov of Northeaster University invented the Gorlov turbine in 2001. Its design was similar to that of a Darrieus turbine, but used for waterpower. Compared to the Darrieus turbine; the Gorlov Helical Turbine blade have a helical twist to eliminate the pulsatory torque issue.

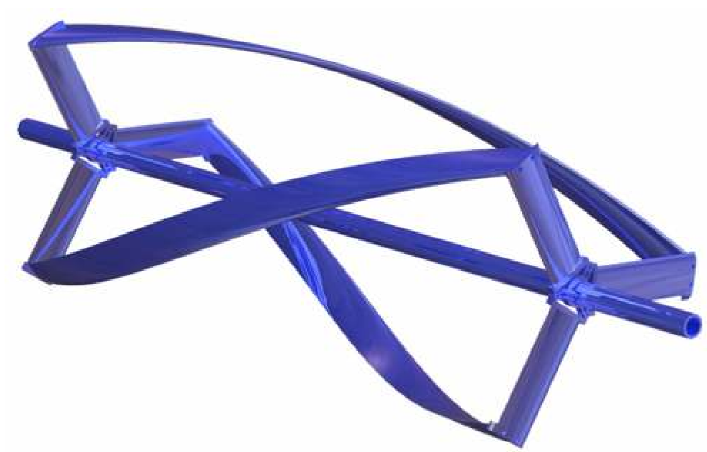


Figure 8: Gorlov Helical Hydrokinetic Turbine.

The vertical axis turbine supported by the barge could also be the same design as the Gorlov Helical Turbine. The vertical axis turbine will be 3m tall with a 2m diameter. It will be oriented 3m below the surface of the water to target maximum tidal flow. Both turbines will most likely be constructed of aluminum.

Propeller turbine styles are also in the interest of testing. The barge will support a horizontal/longitudinal axis propeller turbine (Figure 9). Propeller turbines use the perpendicular flow of water to turn the blades. The turbine being applied to testing will be 4m in diameter, and will be submerged to target 3m below the surface tidal flow.

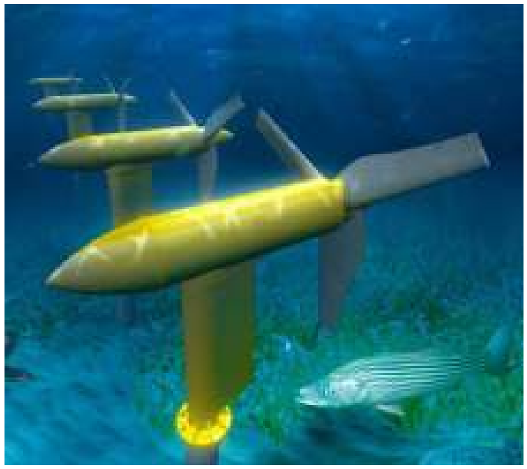


Figure 9: Propeller Style Tidal Turbines.

The final style of turbine that the barge is able to support is the large 'Ducted' turbine (Figure 10). Ducted turbines consist of a rotor blade that is housed in a large duct that flares outwards in the back. Ducted turbines can operate in a larger range of tidal velocities and turbulence, and they can generate a higher power per unit of rotor area. The only disadvantage of ducted turbines is their bulk. The ducted turbine of interest will have a drag force of 7000 lbs and weigh roughly 5000 lbs.  It will have mounted point at 3, 6, 9, and 12 o'clock.

Figure 10: Ducted Style Hydrokinetic Turbine.

### 4.2 Functionality

The design of this barge should handle all these turbines and have less than 1 degree of bow down under maximum drag loading. 1 degree of bow down equates to roughly a 6.5” bow drop from equilibrium. This was determined to be the maximum allowable deflection.

# 5. Design Alternatives

Many iterations of the barge were designed, partially designed, discussed or just thought about before the current design was formulated. Here, many of the different design alternatives will be discussed, what was chosen, what needed to change and what the final decisions were. The barge will be broken into its components with each part discussed individually.

### 5.1 Hull

The main concern with the pontoon hull was the material they were fabricated out of. Because the pontoons are to be in a marine environment it is important that they be corrosion resistant and strong enough to withstand any impacts from objects floating in the water. For these reasons, aluminum and high density polyethylene (HDPE) were the two materials that were investigated.

Aluminum was chosen as the best material for the hulls. This was a factor of its corrosion resistance and ability to withstand long term exposure to the sun and the weight savings over HDPE. In order for the HDPE to have comparable strength as the aluminum it would have to be about two inches thick where as the aluminum was only 3/8 of an inch thick. This would have caused the HDPE pontoons to weigh about 13,000 pounds versus the aluminum weighing only 5000 pounds; this accounted for a weight savings of 8,000 pounds. For these reasons 42 inch aluminum pontoons are recommended for this barge.

### 5.2 Derrick/Cage Material

A derrick system, used to raise and lower the cage into and out of the water was also designed. This system had to be robust in order to withstand the forces and moments caused by the drag force on the cage from the turbine in the water. Again the derrick is going to be in a marine environment with salt water all around it; however it is not going to be submerged into the water directly. The main concern with the saltwater would be splashing on to the derrick. This means that the derrick would have to be corrosion resistant and strong. Both aluminum and steel were investigated for the derrick. The aluminum has greater corrosion resistance to the salt water, but steel has a higher yielding and fracture strength than aluminum. It was decided that steel would be used for the derrick because of its stronger material properties. There would also be a greater cost savings by using steel over aluminum. The steel could be coated, painted or galvanized in order to be more corrosion resistant, and even if it had to be re-coated, in the long run it would still be less costly and stronger than using aluminum.

The cage also had the same options of being constructed out of steel or aluminum. The cage, however, is to be totally submerged in the saltwater and then it will also be raised out for transport, so the cage would be subjected to both saltwater and air. For this reason, aluminum was the first choice of material for the cage. But after structural analysis of the cage made of aluminum it was found that the deflections on the cage due to the drag force were too great and could cause serviceability issues. Galvanized steel was used instead to reduce the deflections to a reasonable amount.

**5.3 Derrick/Cage Configurations**

There are four different style turbines that the barge needs to be able to accommodate easily. These came from the design criteria and the barge should be able to be used for all four without any major modifications to the barge. The original idea for this was to have two different cages, one to accommodate horizontal axis turbines and one for vertical axis turbines. The derricks would then be able to move on the deck to fit the different style cages.

This changed when the addition of the ducted turbine was introduced. After this idea was added, it was decided that it would be possible to use on location for the derrick and a two part cage to make it more modular. This means that the derricks will always be in one location with one part of the cage that will always be inside the derrick, so neither of those parts will change. The bottom part of the cage, where the turbine will attach, will then be removable and there will be a bottom segment for each of the different turbines. This bottom segment will just bolt on and should make the system, both modular, in that any style turbine should be accounted for and strong because the derrick will be attached permanently in one spot.

It is also recommended that the bottom beam on each of the cage configurations have a foil shape in order to decrease drag as much as possible where the beams cross in front of the turbines. It is also recommended that there be some sort of acrylic or plastic attached to both the upper section of the cage and the derrick, to reduce friction and avoid metal on metal rubbing when the cage is lowered and raised inside the derrick.

### 5.4 Structural Beam Materials

The beams that run between the pontoons that the deck rest on are to be 30 feet long as dictated by the design criteria. The main questions regarding the beams were what shape to use and what material. Again, the beams will be exposed to salt water splashing on them so it is important to be corrosion resistant but they also have to be strong enough to span the 30 feet. It was decided that a wide flange (W-section) would be used as the shape. Galvanized steel will be used because of its higher strength and minimal deflections when compared to aluminum.

# 6. Design Description

## 6.1 Barge

There are three main components that make up the test facility.  The first is the barge itself which consists of the pontoons, deck beams and deck.  The next is the cage which will hold the turbines.  The last is the derricks.  These support the cage and help to transfer the load to the barge.  A 3-D model of the full scale barge design was produced in Google Sketchup (Figure 11).

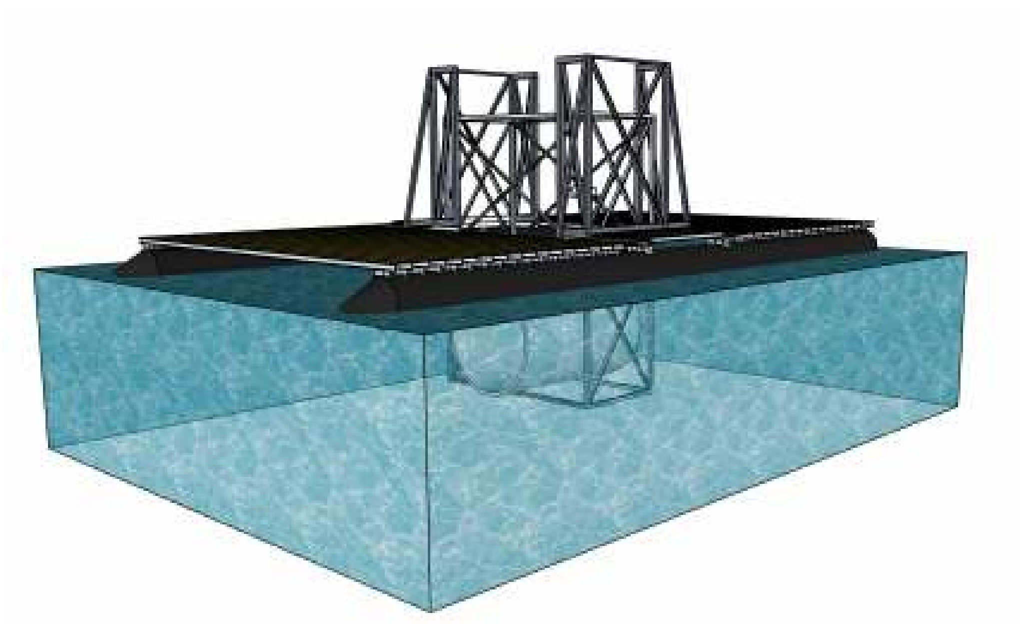


Figure 11: 3-D Computer Generated Model

The barge will be 60' long by 30' wide and will have 42" diameter aluminum pontoons. The large pontoons allow the barge to have a have a capacity of 35,000 lbs when half submerged. The barge is expected to see a maximum load of roughly 30,000 lbs.  On top of the pontoons will sit 30' long steel beams. A more detailed beam layout can be found in Appendix I and II.  The beams will provide be able to support the weight of the cage and turbine sitting on the deck.  There are two options for a deck material.  The first choice is a 2 ply layer of ¾" marine grade plywood. Two layers would be advantageous because the seams could all be offset from one layer to the next adding additional rigidity to the structure. It would be attached using predrilled holes in the beams and bolted down. This is the same technique used on the previous test facility. However in talking with Ryan Despins this was an extremely difficult process. The teams other option is a product called Versadeck™. This product is an aluminum decking which is capable of handling 60 lb per square foot with supports spaced at 48". The product is skid resistant, light weight and comes in 4'x4' square sections. Another upside to this product would be less beams would be required as well as less bolts. Also it has been requested that sections of the deck be removable and the Versadeck™ would allow this to be simpler. The down side of this product is a much higher cost than a plywood deck. However it is our recommendation that the Versadeck™ be used.

### 6.2 Cage

The cage is a steel frame which will support the turbines. This structure will be part submerged when testing and will be capable of being lifted in and out of the water as well as set at different depths (Figure 12). The cage is made of two separate parts, an upper half and a lower half. The upper half of the frame will be a 12' tall, 9' wide and 18' long box. At the bottom there will be a connection plate where the bottom half of the cage will be able to mount. Each turbine will have its own section of cage which will make up the bottom half (Figure 13). This half of the cage will have the same mounting bracketed as the top so that the two halves can easily be attached. Each turbine will have to have the bottom half constructed to fit its individual needs.

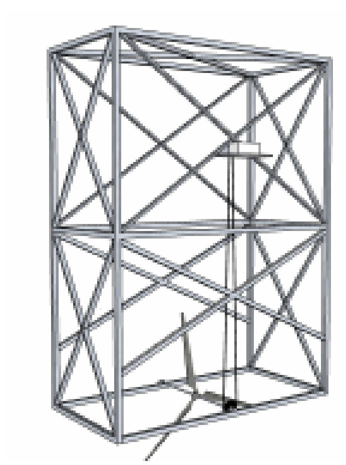


Figure 12: Cage Structure

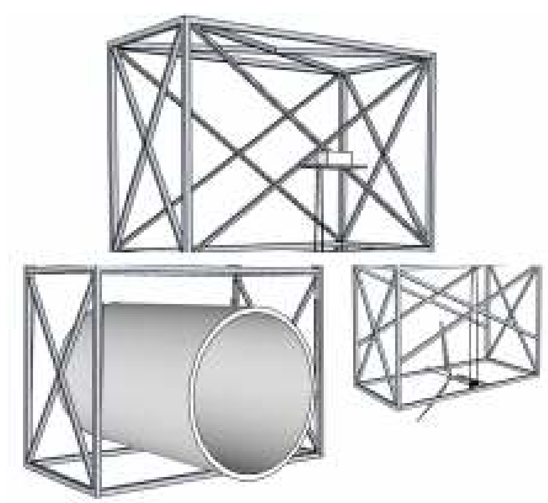


Figure 13: Modular Ability of Cage

### 6.3 Derricks

The derricks structure is a steel frame that will transfer the load from the cage to the barge (Figure 14). It will be 15' tall, 10' wide and 19' long and will be placed around a whole in the center of the barge. The derricks will act as a guide for the cage while it is being lifted in and out of the water.

Figure 14: Derrick Structure

# 7. Cost

The quoted costs of the pontoons were given by Kerry Plunkett at U-Fab Boats (www.u-fabboats.com) and would include two 60' 42" diameter aluminum pontoons with deck mounts. The cost of steel was found from Engineering News Record to be .39 $/lb. These estimates do not include hardware, instrumentation, and shipping since these costs will be highly dependent on factors outside the scope of this project. The construction cost was assumed to be twice the material cost. Two cost estimates were developed (Appendix XVIII), one cost including a plywood deck and the other with the VersaDeck system. Although the second cost is higher, it is our belief that the VersaDeck system would make construction easier and easily allow for sections to be removed.

## 8. Analysis

Hydrostatic and tipping analysis was done to both size the pontoons and determine the overall barge dimensions. It was estimated that this barge would need roughly eight times the area moment of inertia than that of the current test facility which is 30 feet long. The moment of inertia is a function of the length cubed; therefore doubling the length would multiply the moment of inertia by $2^3$ or eight. Archimedes principle was applied to obtain the required volume of water needing to be displaced.

Archimedes principle:
Buoyant Force = Volume of Water Displaced * Unit Weight of Water

Estimating the weight of the barge and knowing the required length, the pontoon diameter could then be determined. The revised area moment of inertia could then be calculated based on these dimension (Figure 16). The tipping moment due to drag is simply the magnitude of the force multiplied by its distance from the center of buoyancy, or h in figure 15. In order to determine the righting moment however, first a metacentric height needed to be obtained. This is done by dividing the area moment of inertia by the submerged volume. The righting moment is equal to $W*m*\sin\Theta$ where W is the barge weight, m is the metacentric height, and $\Theta$ is the degree of bow down. Numerical values for these terms can be found in Appendix XIII.

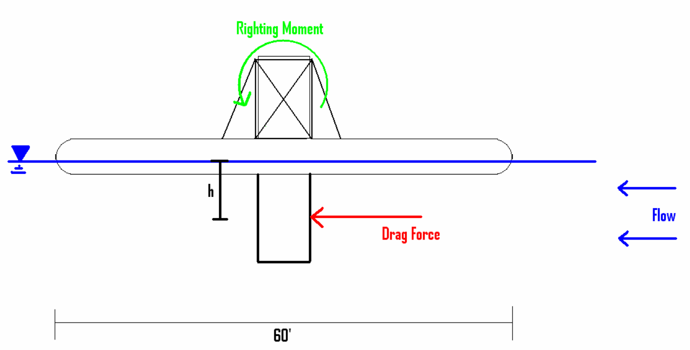


Figure 15: Tipping and Righting Moments

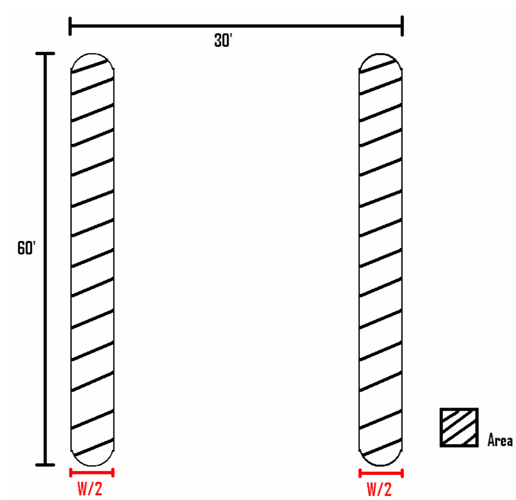


Figure 16: Area Moment of Inertia

# 9. Physical Model Testing and Construction

In any design project, a proof of concept is necessary to both confirm theoretical behaviors and observe possible unexpected ones. During the first half of the spring 2010 semester, the team constructed a scale model based on the dimensions of the completed design. When constructing scale models, an appropriate scale factor needs to be determined. This scale factor is usually based on the sizes of commercially available materials. In this project's case, the scale model dimensions were based on the diameter of the pontoons. From hydrostatic and weight estimate calculations, the full scale pontoon diameter was determined to be 42". In order to obtain a reasonably sized model for ease of constructing and testing, the team decided to use 3" diameter schedule 10 PVC pipes as pontoons. After purchase, an accurate measurement of the outer diameter of each pipe was determined to be 3.25". From this, the scale factor was calculated to be 12.92. This was then used to determine dimensions of the scale model based on the 60' by 30' full scale design. The cage members were also sized using this scale factor.

## 9.1 Scaling

Nominal sizes of members and their corresponding lengths can be sized simply by applying our scale factor of 12.92. However, gravitational forces as well as velocities need to be scaled using a different technique. This is due to the fact that the properties of the medium used for testing, in our case water, will not scale with the model. Both the weight of the scale model and the velocity at which it was tested at needed to be scaled using Froude scaling. The maximum capacity of the full scale barge is about 35,000 pounds, this occurs when the pontoons are exactly halfway submerged. In order to match Froude numbers and accurately mimic the behavior of our scale model in water, the weight is divided by the cube of the scale factor. Under normal operating condition, the full scale weight of the barge is estimated at 30,000 pounds. This yields a model weight of 13.9 pounds. The velocity of the tidal currents under the General Sullivan Bridge is about 5 knots or 2.58 m/s. To get accurate behaviors under model scale conditions, Froude scaling must be utilized again. This is done by dividing the full scale speed by the square root of the scale factor, yielding a testing velocity of 0.72 m/s (Chakrabarti). A full summary of full scale and model scale parameters can be found in Appendix XVII.

## 9.2 Model Construction

Construction of the scale model began with the selection of pontoons to obtain the scale factor. Two lengths of 3” diameter schedule 10 PVC pipes were purchased. Next, the cage was fabricated at RJ’s Furniture Restoration in Manchester, New Hampshire (Figure 17).

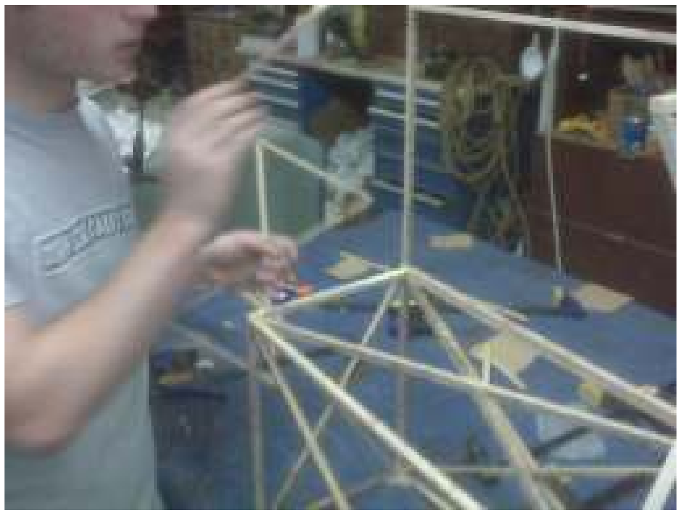


Figure 17: Cage Fabrication

Deck beams and the derricks were both constructed from aluminum sections used for track-lighting and hanging drop ceiling tiles. Beams were laid out and secured to the PVC using an epoxy (Figure 18).

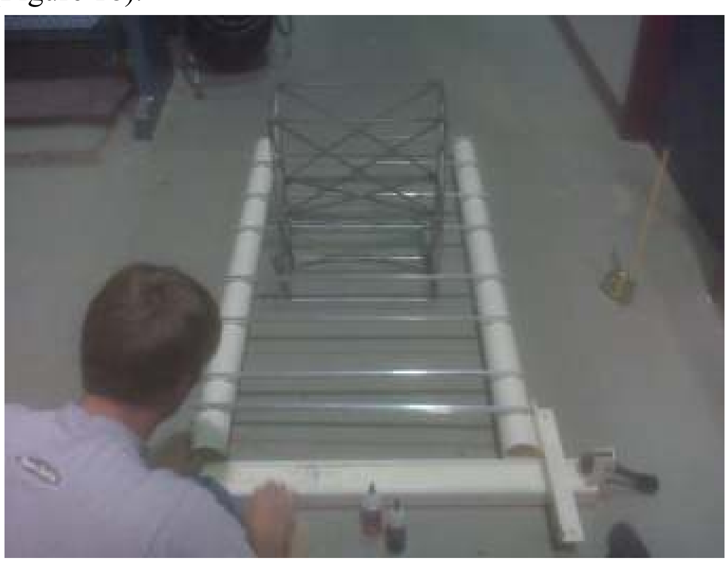


Figure 18: Beam and Pontoon Alignment

There was some concern at first that the bond between the aluminum and PVC would not be sufficient enough to hold under test conditions. Wood blocking was added into the aluminum beams to increase the contact area with the PVC and substantial scoring of the contact areas was done in order to maximize the epoxy's grip. The derricks were then installed using a metal epoxy in combination with small rivets. The deck was cut out of a lightweight corrugated plastic material and glued down to the deck beams. The original plan was to use a clear acrylic deck that would allow us a better view underwater during testing. However, the acrylic proved to be too heavy and was replaced with the plastic. The cage was then placed inside the derrick structure and held with wire at the desired height (Figure 19)

Figure 19: Cage Installed in Derrick

The ends of each pontoon were filled inside with expanding foam to prevent them from filling in the event of an end cap failure. Each end cap was cut and shaped out of a blue foam material. This material was found to easily sand and form to simulate the canoe shape ends of the full scale pontoons. The foam was then covered in Bondo and painted with a white latex exterior paint (Figure 20). Finally, some small eye hooks were added to the ends of the pontoons as tow points.

Figure 20: Pontoon End-Caps

The scale model was then moved into the tow tank for its first successful float test (Figure 21).

Figure 21: First Float Test

**9.3 Testing**

The testing facility used for this project was located in the Jere A. Chase Ocean Engineering Laboratory on the University of New Hampshire campus in Durham, New Hampshire. The tow/wave tank was perfect for this test as drag forces needed to be simulated. This tank measures approximately 120’ long and is 12’ wide. Mounted above the water is a moveable carriage that provides the towing function of the tank. The tow point needed to be significantly lower than the carriage deck to simulate a real world mooring scenario. In order to accomplish this, a tow bar was mounted to the cage and extended down to the height of the eye hooks installed on the model (Figure 22).

Figure 22: Mounting the Tow Bar

Drag forces produced by the pontoons, the cage, and the turbine were all measured by a load cell. The load cell worked by measuring the strain produced by the force, and then converted that strain into an electrical signal that was recorded by the computer. Prior to using however, the load cell needed to be calibrated with known weights in order to understand exactly what voltage equates to what loading. From the calibration test of the load cell (Figure 23) a curve was developed detailing weights and corresponding voltages (Figure 24).

Figure 23: Load Cell Used During Testing

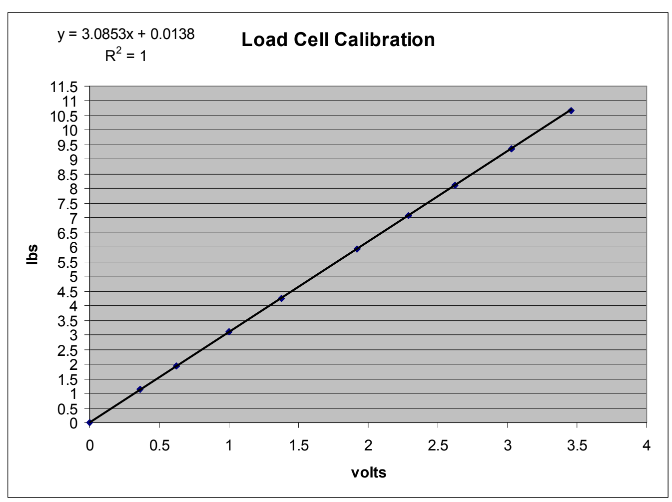



Figure 24: Load Cell Calibration Curve

After calibration of the load cell and modification of the towing carriage, the model was ready to undergo testing. The model was mounted under the tow carriage and towed at the Froude scaled velocity of 0.72 m/s (Figures 25 and 26).

Figure 25: Installing the Tow Bridal

Figure 26: Tow Test

Many different tow configurations were implemented during the test. From the design criteria, the turbine style expected to produce the greatest drag is the ducted turbine. An acrylic plate was mounted inside the cage to simulate the 7000 pound drag force expected from the full scale ducted turbine. This barge is also designed to handle other styles of hydrokinetic turbines so testing was done with a Gorlov style turbine mounted inside the cage as well (Figure 28). The barge was then towed without a turbine, and then without the cage altogether. This way, each component's drag contribution could be quantified. A bow-down test was also performed to confirm hydrostatic calculations. This test was done using a laser mounted on top of the derrick structure (Figure 27).

Figure 27: Bow Down Test

Figure 28: Gorlov Test Turbine

**9.4 Results**

Prior to testing, estimates of the drag force on the cage and turbine as well as the bow-down were made. These numbers (Table 1) were based on surface areas and hydrostatics (Appendix XIII) as well as the design criteria.

| | | |
|---|---|---|
| Drag Force On Cage | (lbs) | 2174 |
| Drag on Ducted Turbine | (lbs) | 7000 |
| Bow-Down (Ducted Turbine) | (deg) | 0.70 |

Table 1: Pre-Test Estimates

Towing the barge at the Froude scaled velocity of 0.72 m/s with the ducted turbine installed yielded the following drag force vs. time graph.

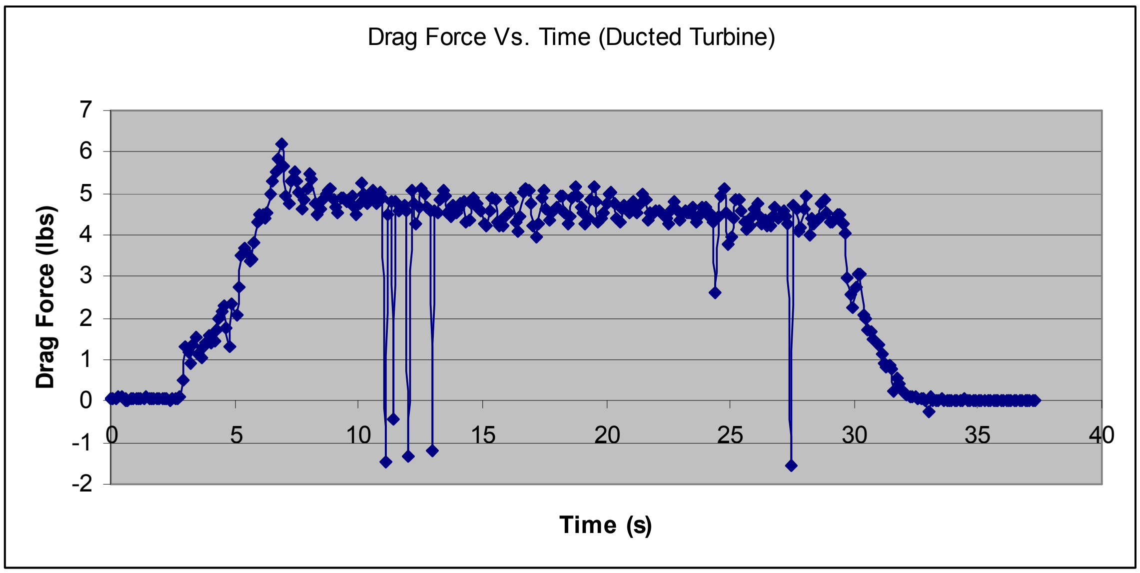



Figure 29: Un-scaled Drag Force vs. Time Graph

Many of these graphs were developed for each barge configuration that was tested (Appendix XIV). Averaging the results from the linear section of each test and comparing with the other configurations yielded the results in Table 2. Also, the barge was towed at varying velocities with the ducted turbine installed (Appendix XVI).

| | | |
|---|---|---|
| Drag Force On Barge | (lbs) | 354 |
| Drag Force On Cage | (lbs) | 1851 |
| Drag on Gorlov Style Turbine | (lbs) | 1327 |
| Drag on Ducted Turbine | (lbs) | 7460 |
| Bow-Down (Ducted Turbine) | (deg) | 0.52 |

Table 2: Results of Scale Model Testing

# 10. Structural Analysis

## 10.1 Deck Beams

The first step in the design of the main deck beams was to determine the worst load case. Conventional live loads were not found to be applicable to this structure since it is unable to be accessed by pedestrians as well as it being highly specific in its purpose. It was then determined that the worst loading scenario would arise if the fully loaded cage was removed from the derricks and placed upon the deck. The cage could be orientated both transversely and horizontally, both of these load cases were analyzed (Appendix IV and V). LRFD (Load Resistance Factored Design) principles were used to size the members, and deflections were limited to L/360 per AISC (American Institute of Steel Design) code. Issues were immediately raised because of the relatively long 30 foot span. Simply handling the moment created by this load case would not be enough to sufficiently design the beam, the effects of lateral-torsional buckling would need to be taken into account. With an un-braced length of 30 feet, the W8x10 A992 steel beams moment capacity drops by 88%. Adding longitudinal bracing, shown in Appendix II, increases the moment capacity without changing the section size.

## 10.2 Cage

Cage design was done mainly in Solidworks, a finite element analysis program (Appendix VII). The cage was modeled using 2.5” x 2.5” x 0.25” A36 steel square tubing. Loadings were based on maximum turbine drag forces as well as the drag forces on the submerged cage members themselves. These loadings were then transferred into RISA-3D, a matrix structural analysis program, so that reactions could be determined (Appendix VII). These reactions, as well as weight estimates, were the basis for the derrick loadings.

### 10.3 Derrick

Derrick analysis was done using RISA (Appendix VIII). At this time, member sizes have yet to be determined. The support reactions from the analysis, as well as weight estimates, were the basis for the derrick support beam loadings.

### 10.4 Longitudinal Derrick Support Beam

Utilizing the reactions from the derrick analysis, a RISA model of the derrick support beam was created. Again, LRFD principles were implemented and deflections were limited to the L/360. Like the deck beams, lateral-torsional buckling limited the moment capacity. The section chosen for these members was a W10x19 A992 beam (Appendix IX). Reactions obtained from the RISA analysis were used as loadings for the transverse derrick support beam.

### 10.5 Transverse Derrick Support Beam

Again, RISA was used to analyze the beam and determine the maximum moments and deflections. This beam, because of its 30 foot span, will be braced laterally like the deck beams. However, the limiting factor for this beam is not lateral-torsional buckling, but rather deflections. A W14x26 A992 steel section was chosen for this beam (Appendix XI).

## 11. Discussion and Conclusion

The need for a full scale tidal turbine testing facility is great. This design would give potential investors in tidal energy the confidence to move forward and take advantage of ocean renewable energy. Looking forward in the development and construction of this facility, there are still challenges that will need to be met. However, the proof of concept herein is a big step in making this facility possible. The team is confident in the results and is excited about the prospect of future developments.

## 12. References


Browne, James, Kevin Buruchian, Dave Dreyer, Thomas Ducharme, Kevin Dutile, and Michele Pelletier. "Tidal Power Generation: Infrastructure." (2009): 1-32. Print.

Chakrabarti, Subrata K. *Offshore Structure Modeling*. Singapore: World Scientific, 1994. Print.

# 13. Appendix

Appendix I

Deck Beam Spacing Layout

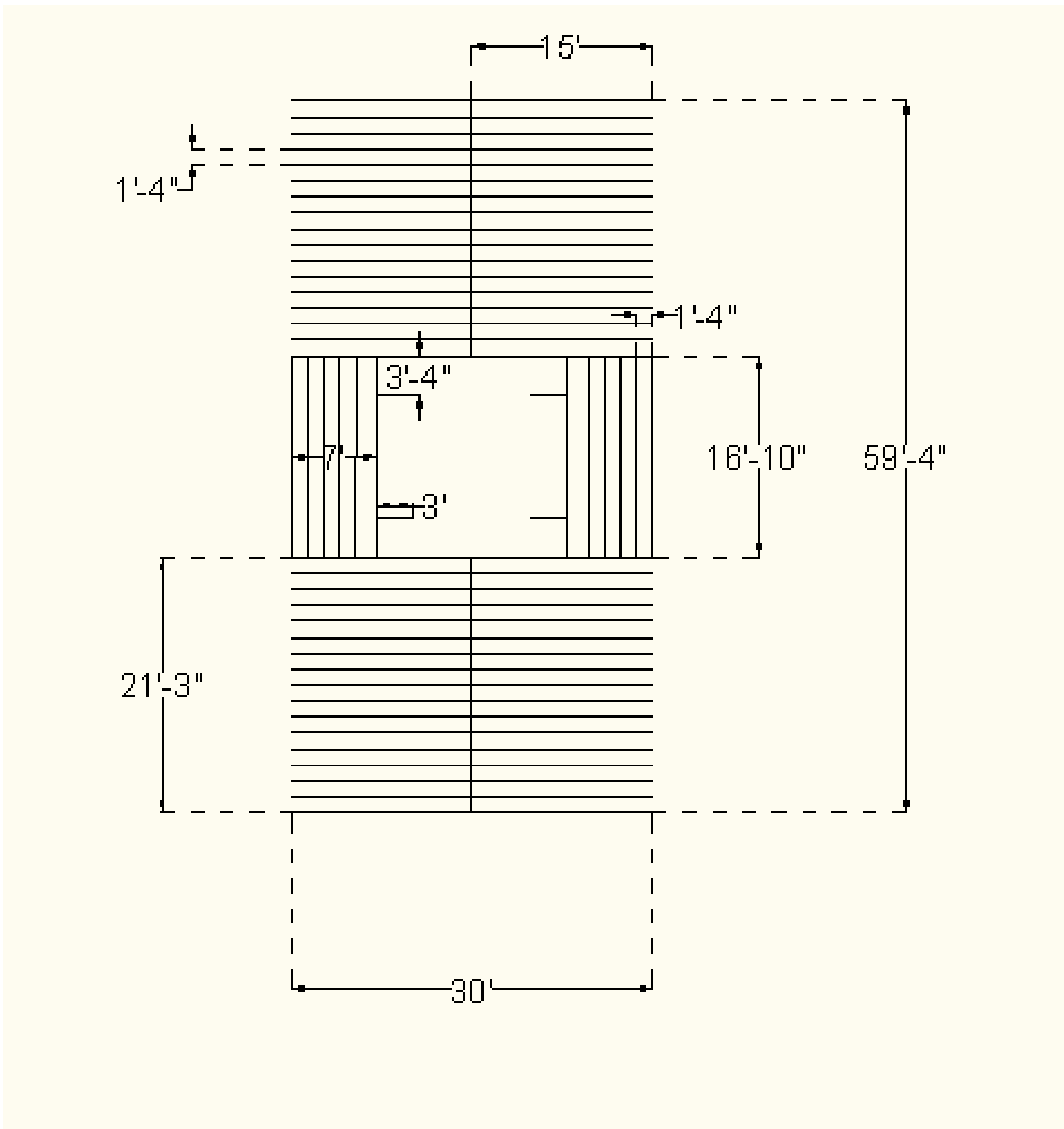



Figure 30: Beam Spacing and Layout

Appendix II

Deck Beam Sizes

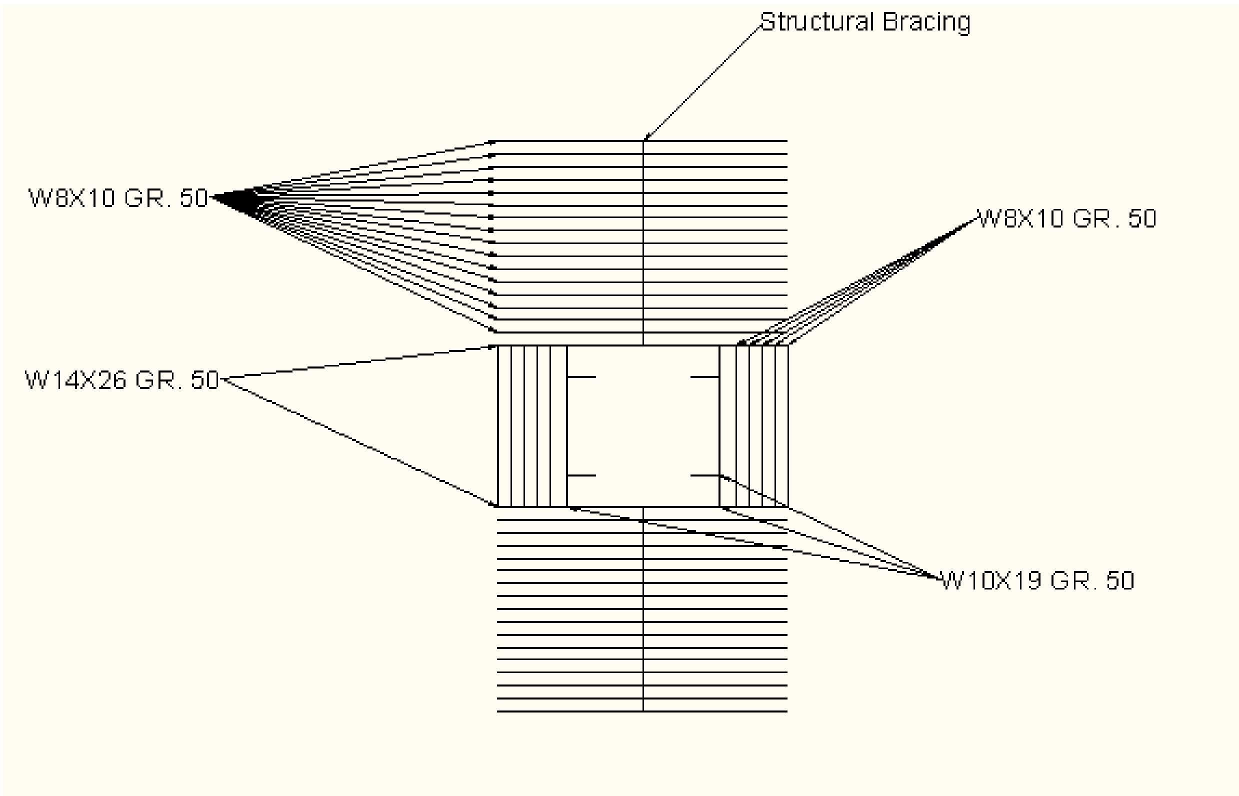


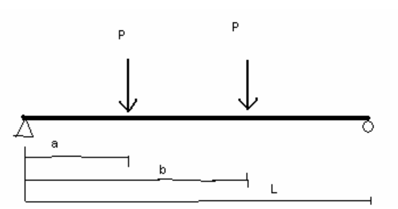

Figure 31: Beam Sizes

Appendix III

Deck Beam Analysis

| **References** | **Inputs** | | | |
|---|---|---|---|---|
| | Name | Units | Variable | Value |
| | Span | ft | L | 30 |
| | Deflection Limit | in | $\Delta_{max}$ | 1 |
| | Deck Beam Spacing | ft | S | 1.5 |
| | Cage Width | ft | $L_{CW}$ | 9 |
| | Cage Length | ft | $L_{CL}$ | 18 |
| | Cage Weight | lbs | $W_{CAGE}$ | 4000 |
| | Turbine Weight | lbs | $W_{TURBINE}$ | 5000 |
| | # Beams (cage long) | | $B_1$ | 12 |
| | # Beams (cage short) | | $B_2$ | 6 |
| | P (cage long) | lbs | $P_{CL}$ | 375 |
| | P (cage short) | lbs | $P_{CS}$ | 750 |
| | a (cage long) | ft | $a_{CL}$ | 10.5 |
| | a (cage short) | ft | $a_{CS}$ | 6 |
| | b (cage long) | ft | $b_{CL}$ | 19.5 |
| | b (cage short) | ft | $b_{CS}$ | 24 |
| Risa Analysis | Max Moment (cage long) | ft-lbs | $M_{MAXCL}$ | 3937.5 |
| Risa Analysis | Max Moment (cage short) | ft-lbs | $M_{MAXCS}$ | 4500 |
| AISC Table 3-23 | Max Deflection (cage long) | in | $\Delta_{CL}$ | 0.717 |
| AISC Table 3-24 | Max Deflection (cage short) | in | $\Delta_{CS}$ | 0.9272 |
| AISC Beam Tables | Moment of Inertia | $in^4$ | I | 30.8 |
| AISC Beam Tables | Flange Width | in | bf | 3.94 |
| AISC Beam Tables | Flange thickness | in | tf | 0.205 |
| AISC Beam Tables | J | $in^4$ | | 0.0426 |
| AISC Beam Tables | $Z_x$ | $in^3$ | | 8.87 |
| AISC Beam Tables | $S_x$ | $in^3$ | | 7.81 |
| AISC Beam Tables | $h_0$ | in | | 7.69 |
| AISC Beam Tables | rts | in | | 1.01 |
| AISC Beam Tables | h | in | | 7.89 |
| AISC Beam Tables | $t_w$ | in | | 0.17 |
| | $M_p$ | in-kips | | 443.5 |

Table 3: Deck Beam Properties



Appendix IV

Deck Beam Analysis Cont.

(Cage Long)

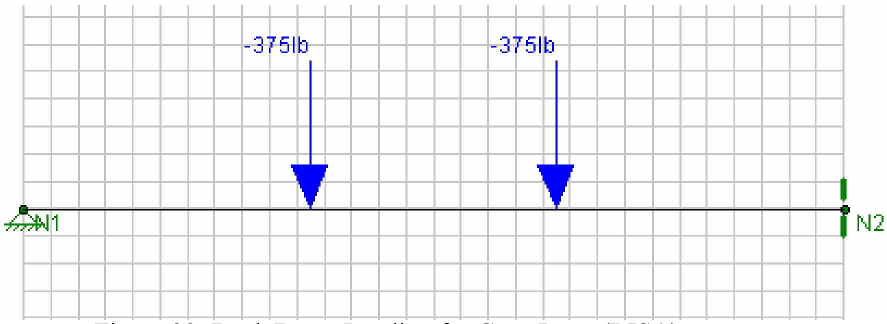



Figure 32: Deck Beam Loading for Cage Long (RISA)

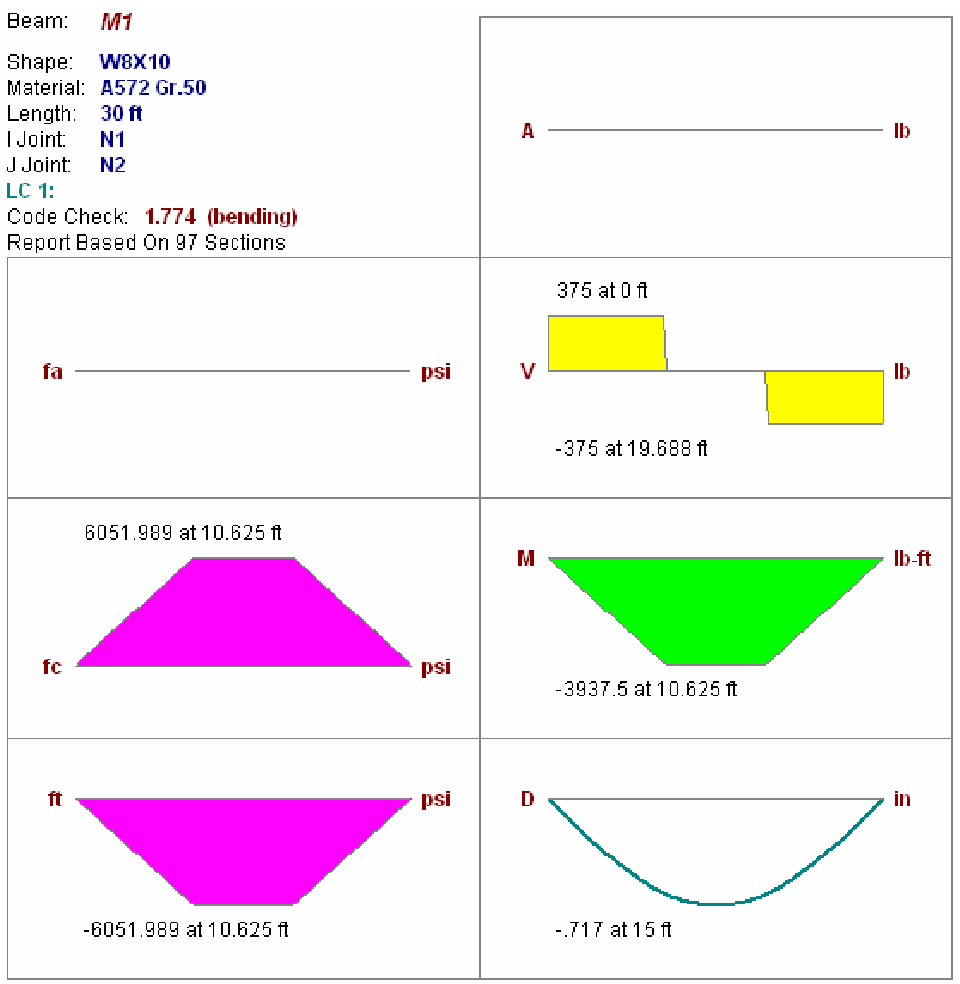



Figure 33: Deck Beam Cage Long RISA Output

Appendix V

Deck Beam Analysis Cont.

(Cage Short)

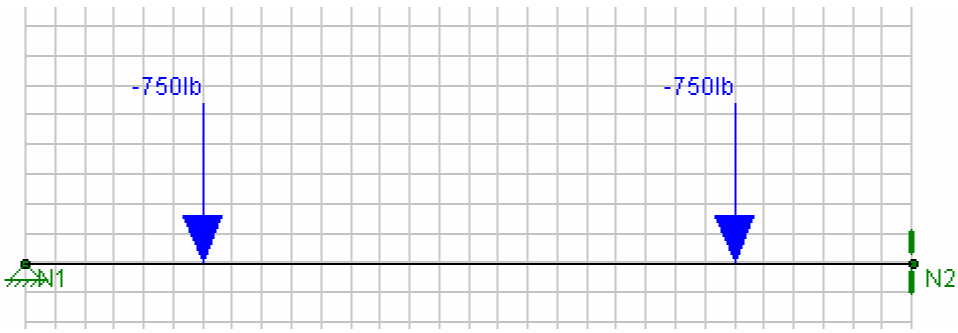



Figure 34: Deck Beam Loading for Cage Short (RISA)

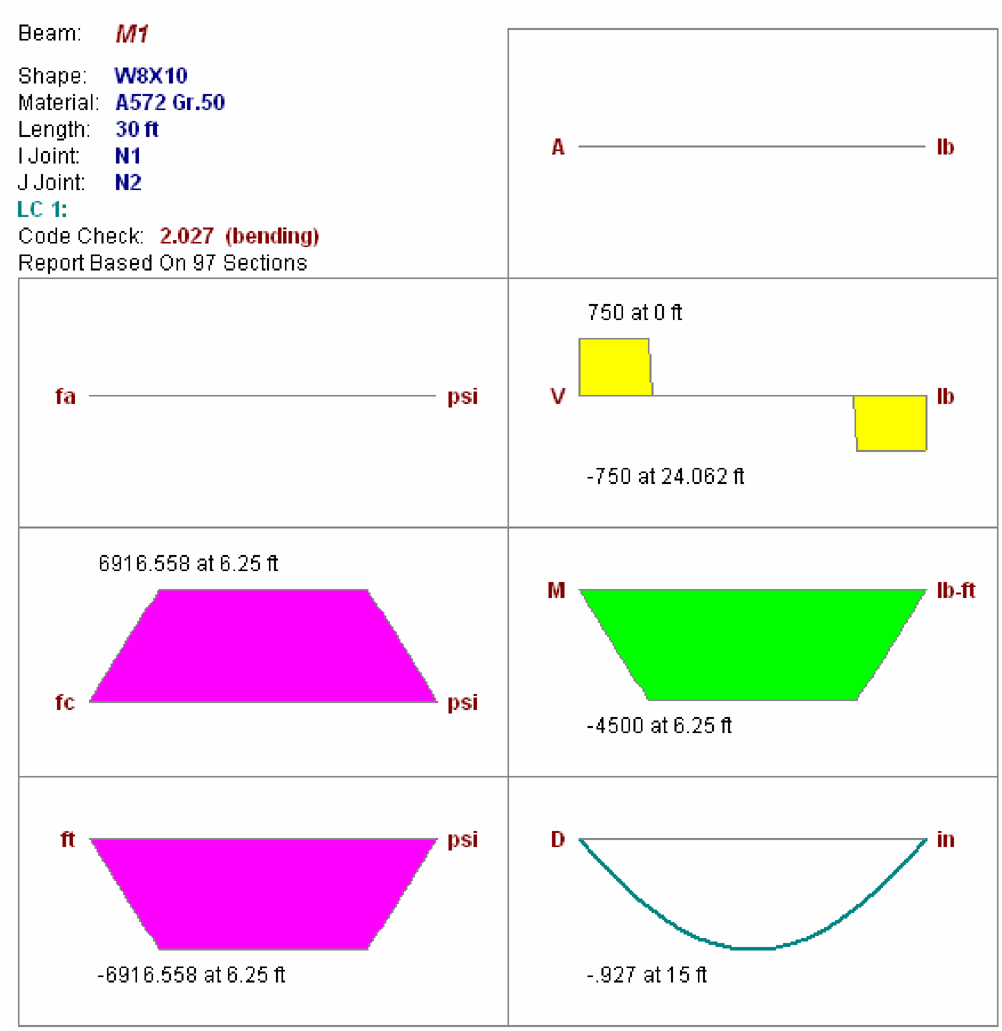



Figure 35: Deck Beam Cage Short RISA Output

Appendix VI

Deck Beam Analysis Cont.

(Cage Short)

| **Lat.Torsional Buckling** | | |
|---|---|---|
| Lb | ft | 15 |
| Lp | ft | 3.14 |
| Lr | ft | 8.56 |
| Cb | - | 1.14 |
| Fcr | ksi | 17.05835 |
| **ΦMn** | ft-kips | **9.991928** |
| **Mu** | ft-kips | **4.5** |

Table 4: Deck Beam Lateral Torsional Buckling Check

Appendix VII

<u>Cage Analysis</u>

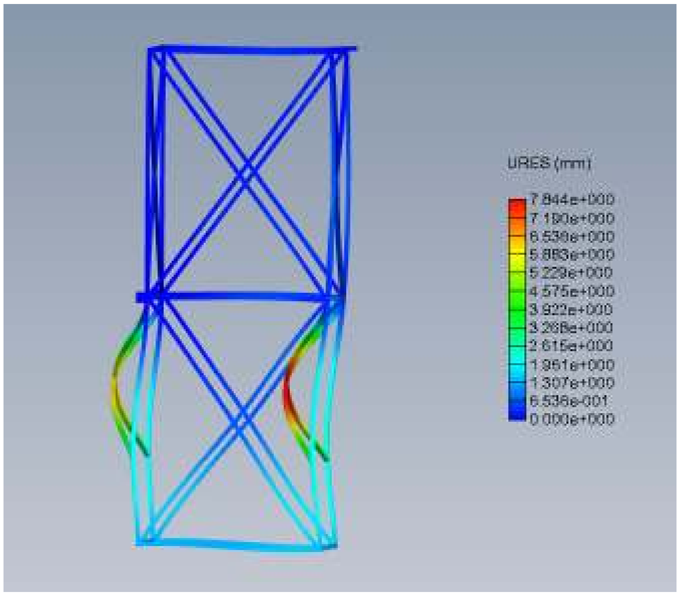



Figure 36: Cage Deformations (SolidWorks)

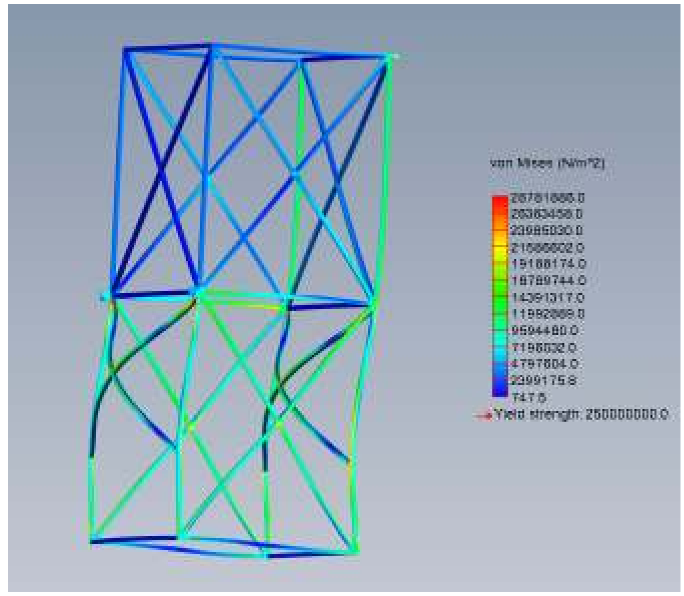



Figure 37: Cage Stresses (SolidWorks)

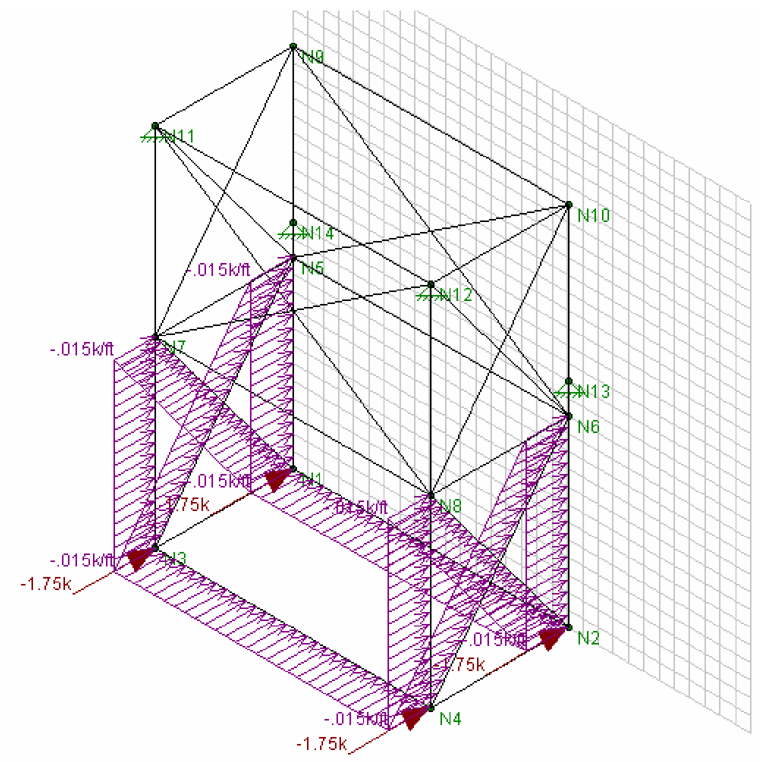



Figure 38: Cage Loadings (RISA)

| Joint Label | X [k] | Y [k] | Z [k] |
|---|---|---|---|
| N11 | -1.233 | 11.53 | 4.451 |
| N12 | 1.233 | 11.53 | 4.451 |
| N13 | .011 | -11.53 | .129 |
| N14 | -.011 | -11.53 | .129 |

Table 5: Cage Support Reactions (RISA)

Appendix VIII

Derrick Analysis

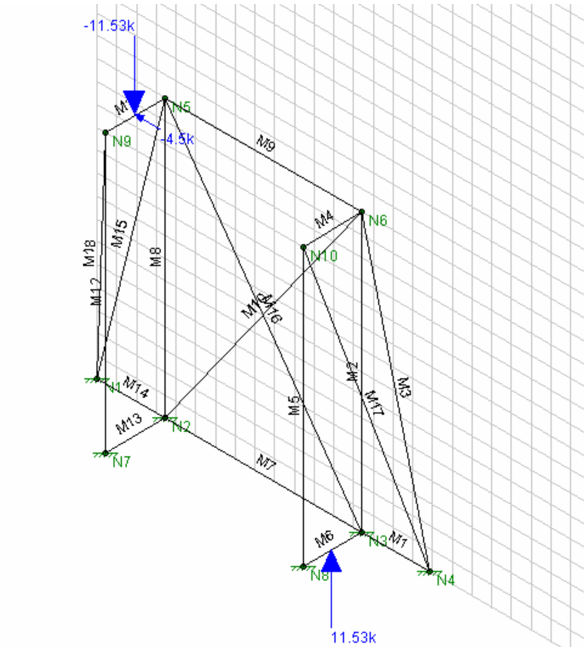



Figure 39: Max Moment Search (RISA)

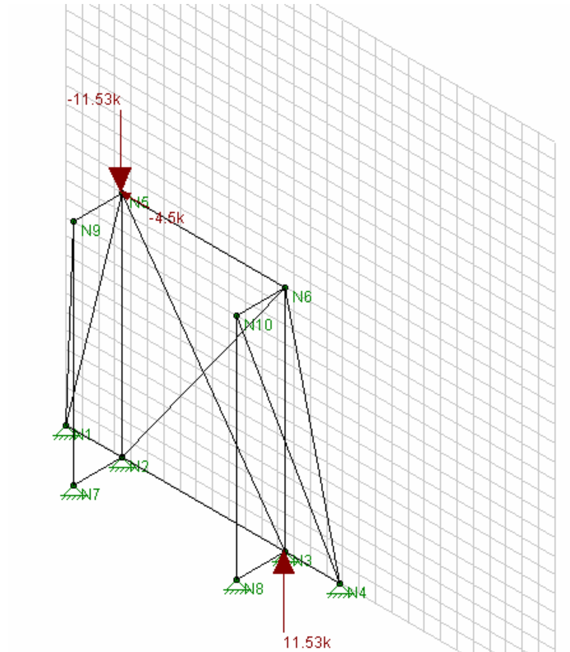



Figure 40: Max Reaction Search (RISA)

| Joint Label | X [k] | Y [k] | Z [k] | MX [k-ft] | MY [k-ft] | MZ [k-ft] |
|---|---|---|---|---|---|---|
| N8 | -.004 | -.007 | .003 | 0 | 0 | 0 |
| N3 | .466 | -12.626 | -.001 | 0 | 0 | 0 |
| N4 | .513 | -2.117 | 0 | 0 | 0 | 0 |
| N2 | 1.846 | 7.802 | -.003 | 0 | 0 | 0 |
| N7 | -.006 | .007 | -.006 | 0 | 0 | 0 |
| N1 | 1.685 | 6.941 | .009 | 0 | 0 | 0 |
| Totals: | 4.5 | 0 | 0 | | | |
| COG (ft): | NC | NC | NC | | | |

Table 6: Derrick Support Reactions

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| M6 | 1 | 0 | -5.765 | 0 | 0 | 0 | -4.324 |
| | 2 | 0 | -5.765 | 0 | 0 | 0 | 0 |
| | 3 | 0 | 5.765 | 0 | 0 | 0 | 4.324 |
| | 4 | 0 | 5.765 | 0 | 0 | 0 | 0 |
| | 5 | 0 | 5.765 | 0 | 0 | 0 | -4.324 |

Table 7: Derrick Maximum Bending Moment

Appendix IX

Longitudinal Derrick Support Beam Analysis

| References | Inputs | Units | Variable | Value |
|---|---|---|---|---|
| | Name | Units | Variable | Value |
| | Span | ft | L | 16.833 |
| | Deflection Limit | in | $\Delta_{max}$ | 0.5611 |
| Risa Analysis | Max Moment | ft-lbs | $M_{MAXCS}$ | 24890 |
| Risa Analysis | Max Deflection | in | $\Delta_{CL}$ | 0.098 |
| AISC Beam Tables | Moment of Inertia | $in^4$ | I | 96.3 |
| AISC Beam Tables | Flange Width | in | bf | 4.02 |
| AISC Beam Tables | Flange thickness | in | tf | 0.395 |
| AISC Beam Tables | J | $in^4$ | | 0.233 |
| AISC Beam Tables | $Z_x$ | $in^3$ | | 21.6 |
| AISC Beam Tables | $S_x$ | $in^3$ | | 18.8 |
| AISC Beam Tables | $h_0$ | in | | 9.85 |
| AISC Beam Tables | rts | in | | 1.06 |
| AISC Beam Tables | h | in | | 10.2 |
| AISC Beam Tables | $t_w$ | in | | 0.25 |
| | $M_p$ | ft-kips | | 90 |

Table 8: Derrick Support Beam Properties

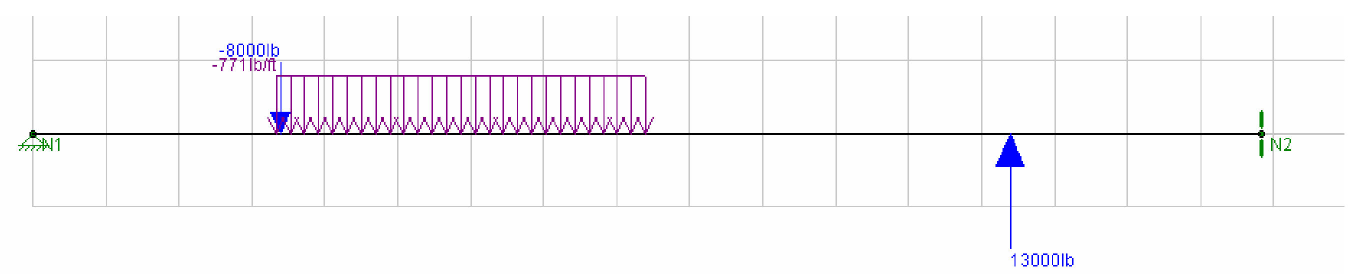



Figure 41: Derrick Beam Worst Case Loading

Appendix X

Longitudinal Derrick Support Beam Analysis Cont.

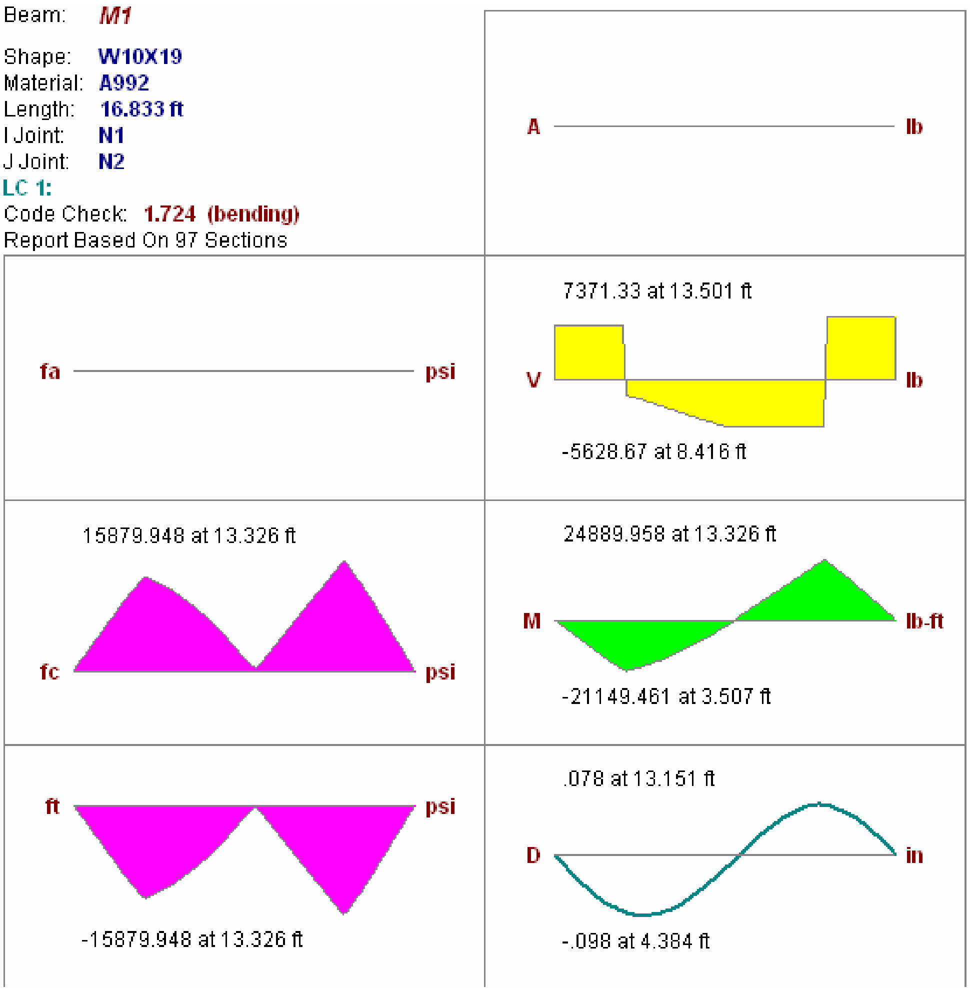



Figure 42: Derrick Support Beam RISA Output

| **Lat. Torsional Buckling** | |
|---|---|
| Lb | 16.73 |
| Lp | 3.09 |
| Lr | 9.72 |
| Cb | 1.14 |
| Fcr | 19.34 |
| **ΦMn** | **27.27** |
| **Mu** | **24.89** |

Table 9: Derrick Support Beam Lateral Torsional Buckling Check

Appendix XI

Transverse Derrick Support Beam Analysis

| **References** | **Inputs** | | | |
|---|---|---|---|---|
| | Name | Units | Variable | Value |
| | Span | ft | L | 30 |
| | Deflection Limit | in | $\Delta_{max}$ | 1 |
| Risa Analysis | Max Moment | ft-lbs | $M_{MAXCS}$ | 46364 |
| AISC Table 3-23 | Max Deflection | in | $\Delta_{CL}$ | 1.179 |
| AISC Beam Tables | Moment of Inertia | $in^4$ | I | 245 |
| AISC Beam Tables | Flange Width | in | bf | 5.03 |
| AISC Beam Tables | Flange thickness | in | tf | 0.42 |
| AISC Beam Tables | J | $in^4$ | | 0.358 |
| AISC Beam Tables | $Z_x$ | $in^3$ | | 40.2 |
| AISC Beam Tables | $S_x$ | $in^3$ | | 35.3 |
| AISC Beam Tables | $h_0$ | in | | 13.5 |
| AISC Beam Tables | rts | in | | 1.31 |
| AISC Beam Tables | h | in | | 13.9 |
| AISC Beam Tables | $t_w$ | in | | 0.255 |
| | $M_p$ | ft-kips | | 167.5 |

Table 10: Transverse Derrick Support Beam Properties

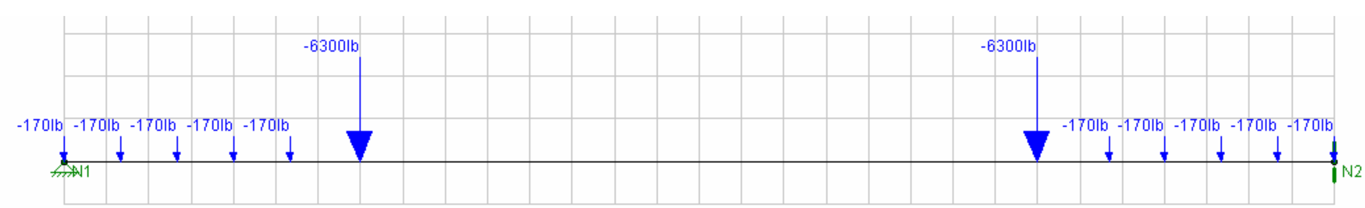



Figure 43: Transverse Derrick Support Beam Worst Case Loading

Appendix XII

Transverse Derrick Support Beam Analysis

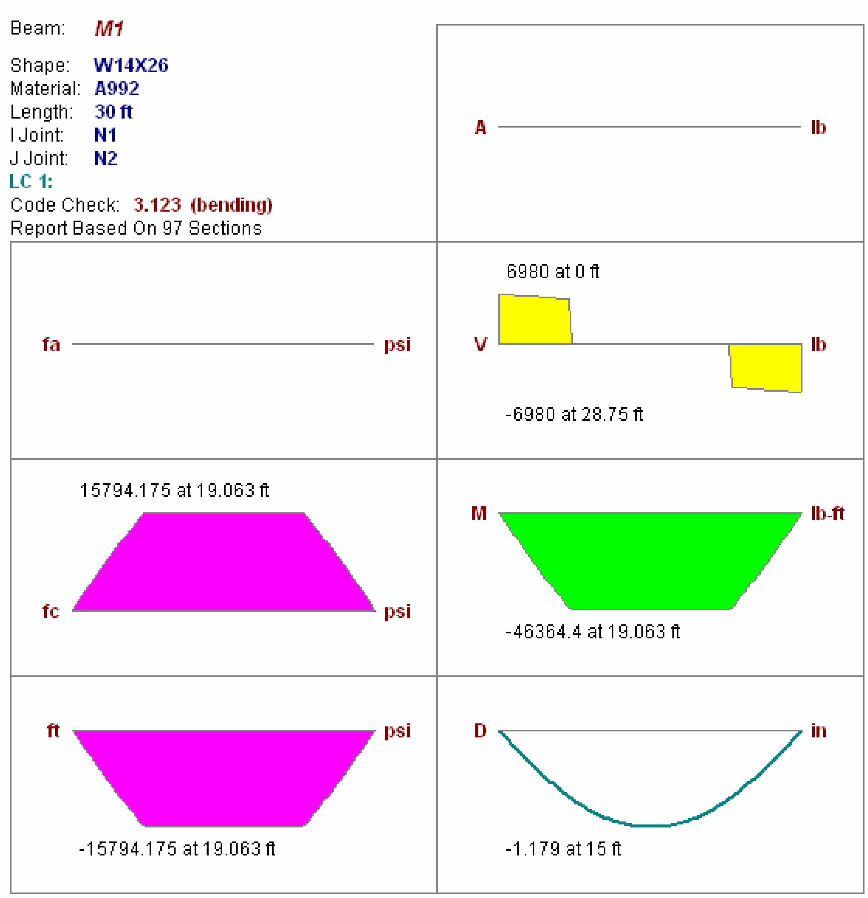



Figure 44: Transverse Derrick Support Beam RISA Output

| **Lat.Torsional Buckling** | |
|---|---|
| Lb | 15.00 |
| Lp | 3.81 |
| Lr | 11.10 |
| Cb | 1.14 |
| Fcr | 25.08 |
| **ΦMn** | **66.40** |
| **Mu** | **46.36** |

Table 11: Transverse Derrick Support Beam Lateral Torsional Buckling Check

Appendix XIII

Hydrostatic, Weight, and Drag Analysis

| INPUTS | |
|---|---|
| Weight of Barge (lbs) | 30000.0 |
| Barge Length (ft) | 60 |
| Barge Width (ft) | 30 |
| Pontoon Width (in) | 42 |
| Total Drag Force (lbs) | 9709.00 |
| Depth to force (ft) | 9.84 |
| Maximum Deflection Angle (deg) | 0.701755727 |
| Center of Buoyancy to Center of Gravity (ft) | 2 |
| Drag Moment (ft-lbs) | 95561.02 |
| Moment of Inertia (ft^4) | 126000 |
| Req Volume Submerged (ft^3) | 480.77 |
| **Metacentric Height** | |
| Center of Buoyancy to Metacenter (ft) | 262.08 |
| Center of Gravity to Metacenter (ft) | 260.08 |
| Righting Moment (ft-lbs) | 95561.00 |

Table 12: Hydrostatics and Tipping

| | lb/ft | linear feet | Weight |
|---|---|---|---|
| Cage | 7.08 | 564 | 3993.12 |
| Deck Beams | 10 | 1130 | 11300 |
| Derrick Support Beam | 19 | 32 | 608 |
| Large 30' beam | 26 | 60 | 1560 |
| Wood Decking | 1545 $ft^2$ | 2.3 $lbs/ft^2$ | 3553.5 |
| Pontoons | N/A | N/A | 4700 |
| Turbine | N/A | N/A | 5000 |
| Derricks | 6.9 | 343 | 2200 |
| Totals | | | 32914.6 |

Table 13: Weight Estimates

| **Cage Drag Estimate** | |
|---|---|
| Velocity (ft/sec) | 8.4 |
| Area of Submerged Cage ($ft^2$) | 31.5 |
| Drag Coeffecient | 1.0 |
| Unit Weight of Water ($lbs/ft^3$) | 62.4 |
| Acceleration Due to Gravity ($ft/s^2$) | 32.2 |
| Drag on Cage (lbs) | 2174.2 |

Table 14: Cage Drag Estimate

Appendix XIV

<u>Tow Test Results</u>

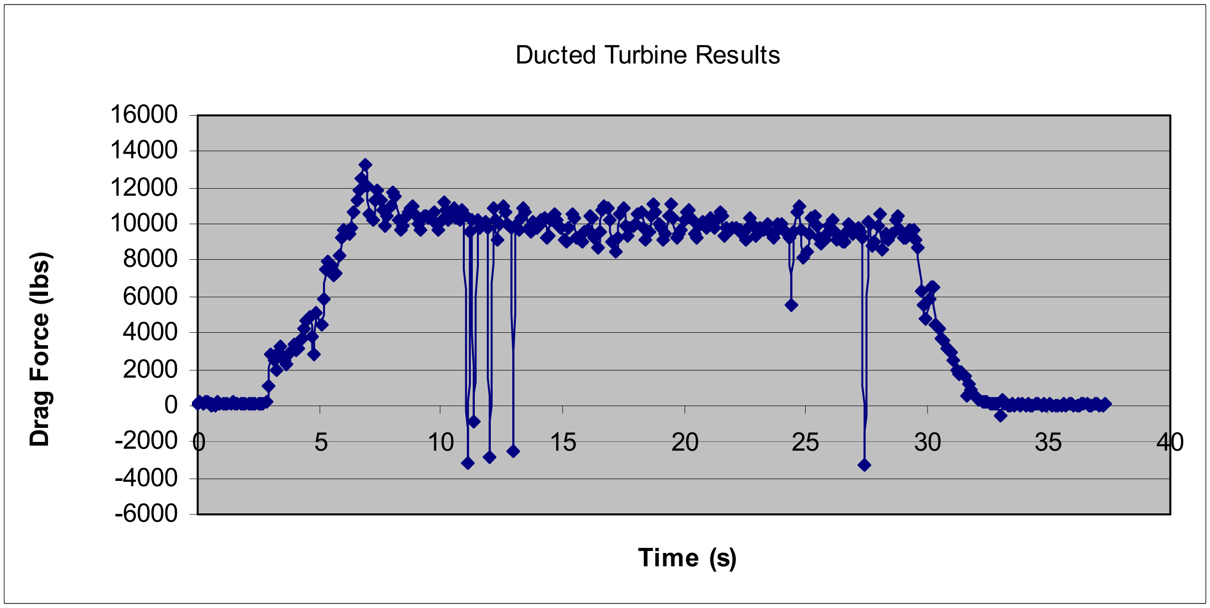



Figure 45: Ducted Turbine vs. Time Graph (Scaled to Actual)

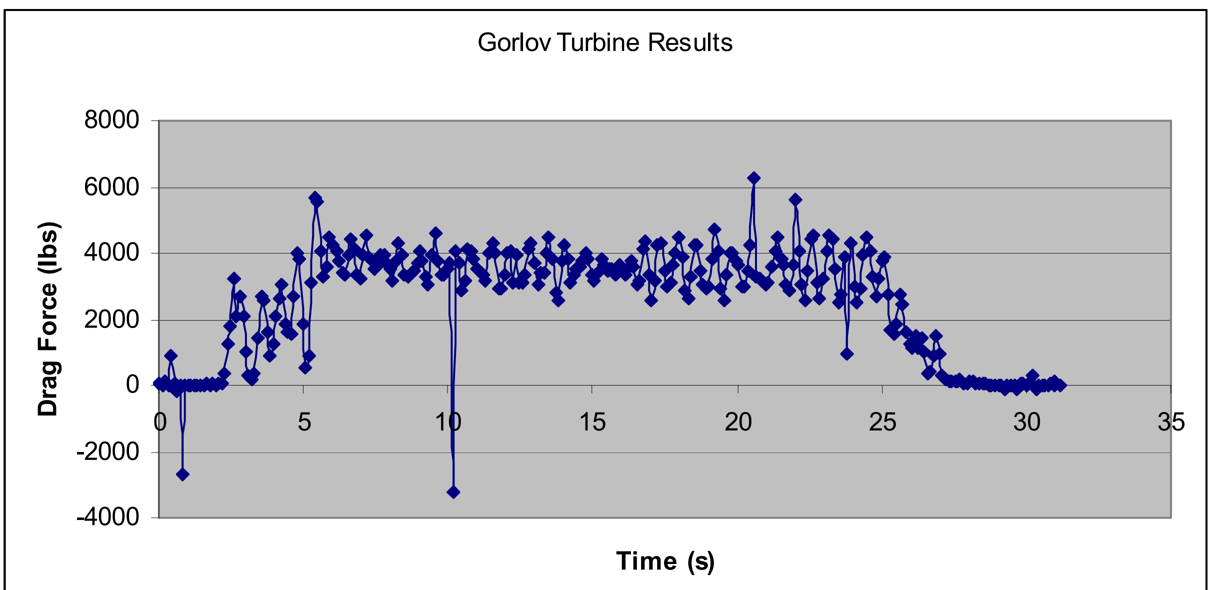



Figure 46: Gorlov Drag vs. Time Graph (Scaled to Actual)

Appendix XV

Tow Test Results Cont.

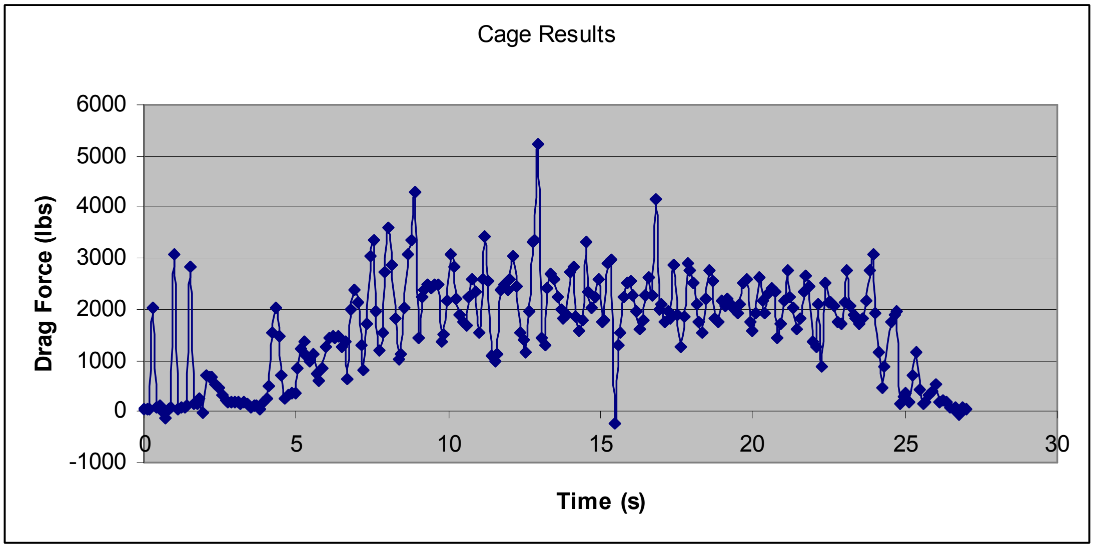



Figure 47: Cage Drag vs. Time Graph (Scaled to Actual)

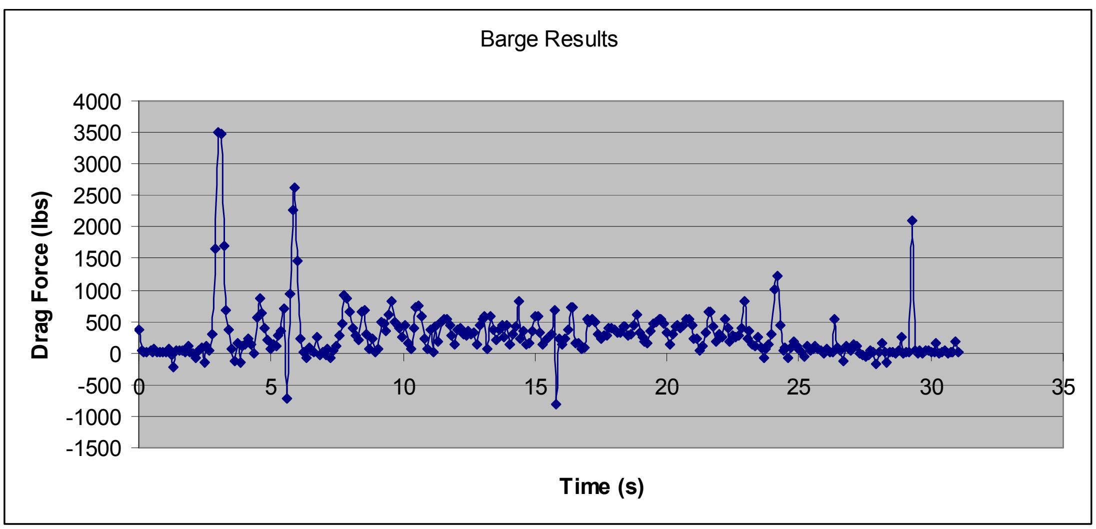



Figure 48: Barge Drag vs. Time Graph (Scaled to Actual)

Appendix XVI

Tow Test Results Cont.

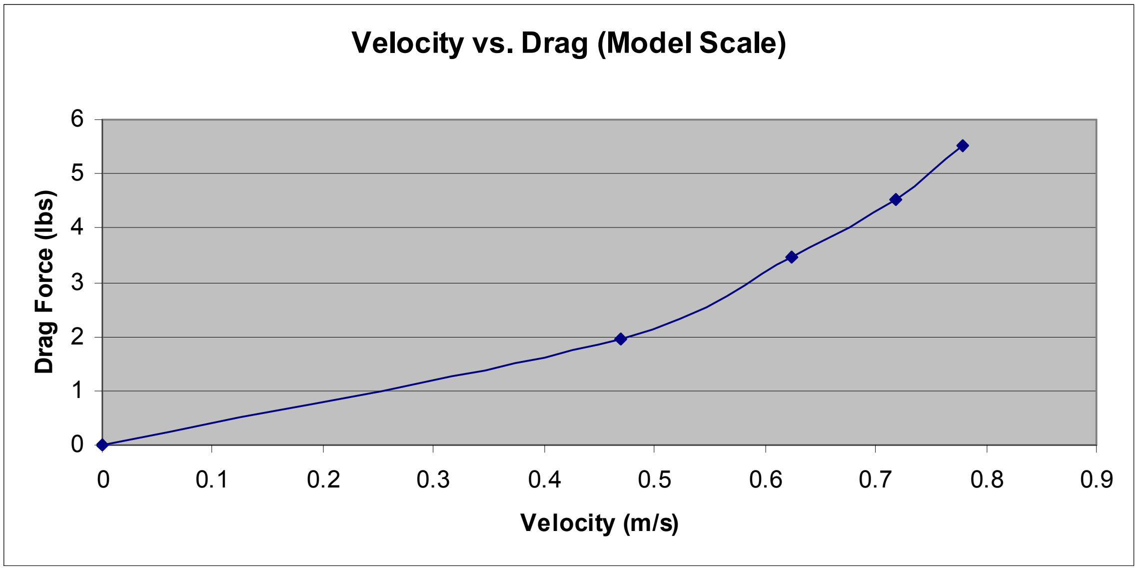



Figure 49: Velocity vs. Drag at Model Scale

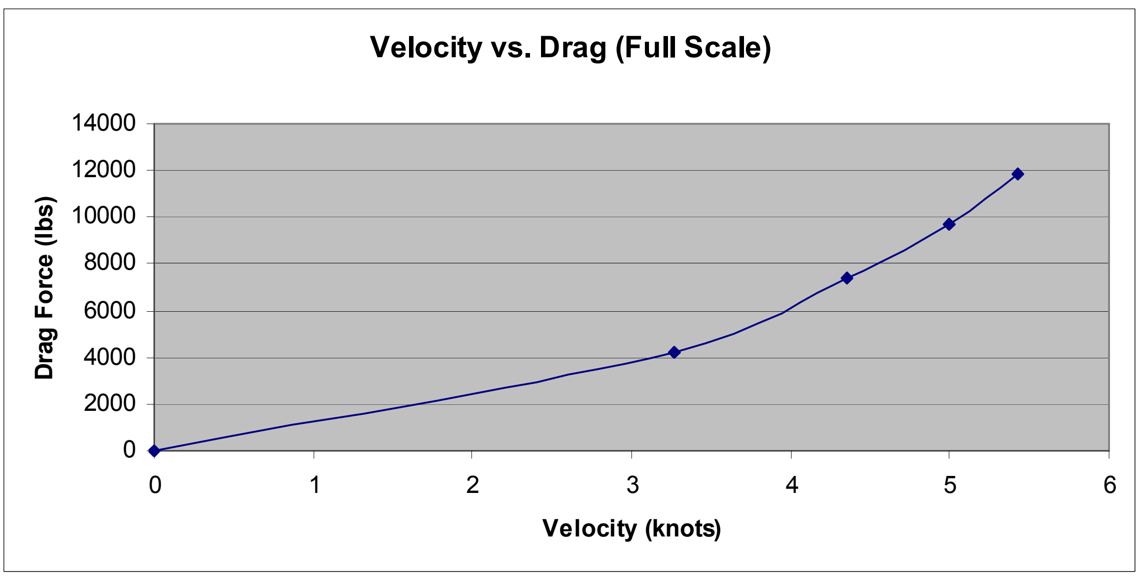



Figure 50: Velocity vs. Drag at Full Scale

Appendix XVII

Model Scaling

**Model Scaling**

| **Scale Factor** | **12.92** |
|---|---|

| **Scale** | **Item** | **Units** | **Value** |
|---|---|---|---|
| Full | Weight | lbs | 30000 |
| Full | Length | ft | 60 |
| Full | Width | ft | 30 |
| Full | Cage Height | ft | 24 |
| Full | Cage Length | ft | 18 |
| Full | Cage Width | ft | 9 |
| Full | Cage Member Thickness | in | 2.5 |
| Full | Water Velocity | ft/s | 2.58 |
| Full | Pontoon Diameter | in | 42 |
| Model | Weight | lbs | 13.91 |
| Model | Length | ft | 4.64 |
| Model | Width | ft | 2.32 |
| Model | Cage Height | ft | 1.86 |
| Model | Cage Length | ft | 1.39 |
| Model | Cage Width | ft | 0.70 |
| Model | Cage Member Thickness | in | 0.19 |
| Model | Water Velocity | ft/s | 0.72 |
| Model | Pontoon Diameter | in | 3.25 |

Table 16: Model Scaling

Appendix XVIII

Costs

| Component | Material | | | | | | | Material Cost $ |
|---|---|---|---|---|---|---|---|---|
| Pontoons | Aluminum | - | | | | | | 41380 |
| | | Square footage | | # of sheets | | $/sheet | | |
| Deck | Marine Plywood | 1575 | | 98.4375 | | 70 | | 6891 |
| | | | | | | | | |
| | | Size | Beam Spacing (ft) | # of beams | lbs/beam | Total weight(lb) | $/lb | |
| Beams | Steel | W8X10 | 1.33 | 45 | 300 | 13500 | 0.39 | 5284 |
| | | | | | | | | |
| | | Size | lb/ft | linear ft | lb | $/lb | | |
| Derricks | Steel | HSS2.5x2.5x.25 | 7.08 | 564 | 3993.12 | 0.39 | | 1563 |
| Cage | Steel | HSS2.5x2.5x.25 | 7.08 | 343 | 2428.44 | 0.39 | | 951 |
| | | | | | | | Total | 56068 |
| | | | | | | | Construction Cost | 112137 |

| Component | Material | | | | | | | Material Cost $ |
|---|---|---|---|---|---|---|---|---|
| Pontoons | Aluminum | - | | | | | | 41380 |
| | | Square footage | | # of sheets | | $/sheet | | |
| Deck | VersaDeck | 1575 | | 98.4375 | | 384 | | 37800 |
| | | | | | | | | |
| | | Size | Beam Spacing (ft) | # of beams | lbs/beam | Total weight(lb) | $/lb | |
| Beams | Steel | W8X10 | 3.00 | 20 | 300 | 6000 | 0.39 | 2349 |
| | | | | | | | | |
| | | Size | lb/ft | linear ft | lb | $/lb | | |
| Derricks | Steel | HSS2.5x2.5x.25 | 7.08 | 564 | 3993.12 | 0.39 | | 1563 |
| Cage | Steel | HSS2.5x2.5x.25 | 7.08 | 343 | 2428.44 | 0.39 | | 951 |
| | | | | | | | Total | 84042 |
| | | | | | | | Construction Cost | 168084 |