Sea Grant
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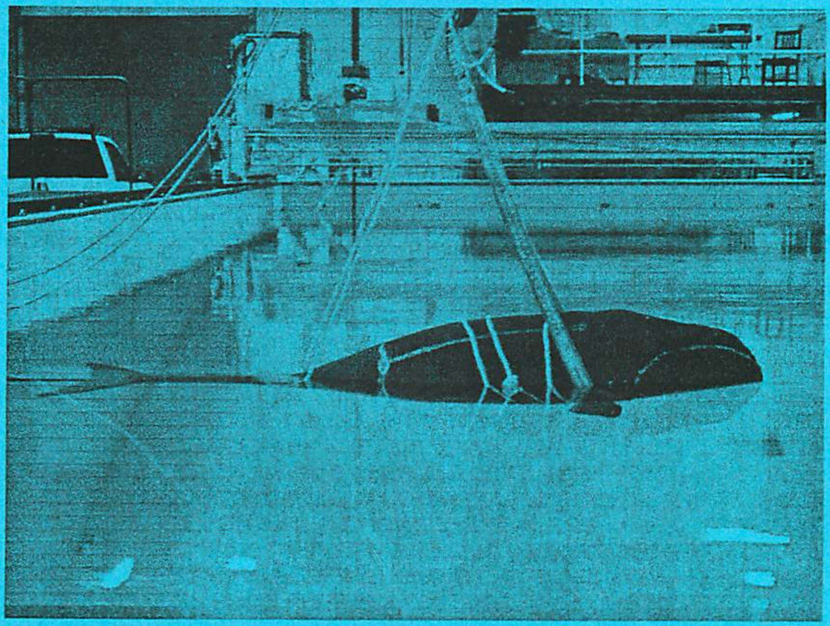
# North Atlantic Right Whale: Designing a 1/8 Scale Model



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## Abstract

This construction of the 1/8th scale model of a North Atlantic Right whale is the first known scale model made to simulate entanglement. This scale model is now a resource and tool for scientists, government, legislation, and education. The construction of the scale model helps to provide information on the building of such scale items. The scale model provides an opportunity to gather qualitative data for enhancing the understanding of the entanglement of marine mammals. It was shown that a scaled model of a North Atlantic right whale can be built and survive submersion in water for over a period of 8 hours. Although some materials should not be used in future model construction, the overall design mimics shape, size, and characteristics. It was estimated that the scale model would require approximately 300 lbs as weight, however it took 296 lbs to make the scale model neutrally buoyant. Initial runs yielded problems areas of the model, namely the pipe and the way in which it is fastened inside the whale. However, initial runs also found that the scaled gear line ripped through the scale model which was traveling at 2 knots (0.25 m/s), which is half the typical traveling speed of a right whale. It was found that this model is a prototype for future models that will aide in the knowledge of entanglement, particularly insight into how they occur.

## List of Figures

## 1. Introduction to *Eubalaena glacialis*

There are approximately 350 individuals in the western North Atlantic right whale population (North Atlantic Right Whale Consortium). As a critically endangered species, there is high concern about the interaction between right whales and fishing gear. This coastal species' habitat ranges from wintering and calving grounds in coastal waters of the southeastern United States to summer feeding and nursery grounds in New England waters and northward to the Bay of Fundy. These habitat areas are significant to commercial fisherman as well as commercial shipping lanes. It is this interaction between human, technology, and cetacean that cause significant human-induced mortality thus declining reproductive rates that affect the population growth (Kraus et al. 2001, Pettis et al 2005).

The population growth of the North Atlantic Right whale (*Eubalaena glacialis*) is threatened by increasing instances of human-induced mortality (Kozuck et al. 2005, Kraus 1990, Kraus and Knowlton 2001, Moore 2005, Pettis 2004). Including ship strikes and entanglements, human-induced mortality accounted for four fatalities between February 2004 and February 2005 off the Atlantic coast (North Atlantic Right Whale Consortium) 3 others – 2 of unknown cause and 1 live stranded neonate during that time frame. Any part of fishing gear has the potential to entangle a whale, and ranks second to ship strikes for known causes of mortality (Kozuck et al, Kraus, 1990).

There is more known on ship strike mortality than entanglements due to the characteristics of mortality type. Whales struck by ships are more likely to wash ashore or be seen, as entanglements often occur far offshore and the whale is likely to sink or drift to the open ocean (Moore et al 2005). *Eubalaena glacialis* is known to be vulnerable to fishing gear entanglement along the Atlantic coast of the United States (Kraus, 1990).

Moore et al. (2005) reviewed necropsy reports of thirty Right whale mortalities from 1970 to 2002 and found that human induced trauma from ship collisions and fishing gear entanglement were the primary causes of death. It is likely that there is a foraging behavior trend between the North Atlantic Right whale and entanglement incidents (Kozuck et al.). Of thirty-one events studied between 1993 and 2002 by Kozuck et al; twenty- four involved the mouth where five were responsible for the death of the whale (Kozuck et al). With approximately 350 individuals in the North Atlantic Right whale population (North Atlantic Right Whale Consortium) each death is critical to the overall population.

Mitigation plans to alleviate ship strikes have already been established, such as moving the shipping lanes in the Bay of Fundy during months when right whales are present as well as the Mandatory Ship Reporting System established in 1999 (Silber et al 2002). By modeling the process of entanglement it is possible to extend that knowledge to the professional communities of cetacean biologists as well as fisherman. This understanding may lead to potential gear modifications and fishery standards. This project aims to quantify the interaction between the North Atlantic Right whale and fishing gear via a scaled model.

It is imperative that the interaction between right whales and fishing gear is modeled in a controlled environment; specifically, using scale models. By designing and building a scale model of a North Atlantic right whale, it may be possible to look at how entanglements occur. By observing the average traveling speed of a right whale (0.5 m/s) and pushing it (via a tow tank) into scaled gear, it may be possible to determine the effect the gear has on skin surfaces, as well as the modes by which lines become entangled. A scale model for the purpose of testing entanglement interactions has never been done. This project will help to lay the groundwork for future model design, construction, and testing. Through testing, valuable information on the way in which line interacts with right whales should be obtained, helping to understand how right whales become entangled.

## 2. Background on *Eubalaena glacialis*

*Eubalaena glacialis* was listed as an endangered species on June 2, 1970 for the entirety of its coastal habitat along the Eastern seaboard of the United States (US Fish and Wildlife Service). The scientific name translated is 'true whale of the ice' which no longer represents this coastal species (Clapham 2004). The common name, the North Atlantic right whale, was given because they were the 'right' whale to hunt. Their characteristic oblong body has no dorsal fin, flat paddle-like flippers, and a head that is one-third of the body; this is often covered in callosities, or roughened skin patches much like human facial hair. Today, these marine mammals have an estimated population of approximately 300 individuals and are considered a critically endangered species (Knowlton et al 1994, US Fish and Wildlife Service).

### *2a. Classification*

Baleen whales (Mysticeti) are one of two Cetacean sub-orders (Appendix 1: Right whale fact sheet). The toothed whales (Odontoceti) rely on the use of teeth, while the Baleen whales feed on rice sized copepods by a process of highly specialized filter-feeding. They have what is called baleen, a series of keratin plates attached to the gum of the upper jaw that are smooth on the outside and fringed on the inner side of the mouth. Skeletal differences occur that define these two species as well as the two blowholes of a baleen whale versus the one of a toothed whale (Encyclopedia of Marine Mammals - pg. 62). Generally, the size of the baleen whale is larger than the toothed whales. Life histories include long migrations for some species, coming close to the coast, but having a primarily open ocean habitat. The right whales are one of four families in the Mysticetes; right whales (Neobalaenidae), pygmy right whales (Neobalinidae), gray whales (Eschrichtiidae), and the rorquals (Balaenopteridae). The right whales are distinguishable due to their narrow and long baleen plates, highly arched upper jaw, large head which is one-third of body length, no dorsal fin, and two to five deep creases rather than the typical ventral grooves of Baleen whales. There are two Families of right whale, the North Atlantic right whale and the Southern right whale.

### 2b. Population Status

#### i. Whaling History

Commercial whaling in the North Atlantic began during the 11th century in the Bay of Biscay by the Basque whalers (Aguilar 1986). The hunt for the right whale spread to Labrador in the 1530's and then to New England by the 1600's. Although not the most desirable of the hunted whales (in regards to the Sperm Whale for oil), the right whale was the easiest to hunt. Right whales were often close to a beach, visible to the land-based hunters and provided an extensive supply of blubber. Right whales move slowly through the water and float once killed, making it easy for a whaler to spot and hunt the whale. The blubber or fat of a right whale comprises approximately 40 percent of the body weight, which can reach upwards of 100 tons (New Bedford Whaling Museum). Both the blubber and baleen (food filtering mechanism in the mouth) provide a plethora of materials for products such as soap, lamp oil, corset stays, and hairbrush bristles (New Bedford Whaling Museum). The 1860's marked the technological advancement to mechanized, steam-powered boats from the old traditional sail and oar powered whaleboats introduced a new era of whaling. This new process was a succession of relentless and efficient technology that not only increased efficiency by volume which enabled the whalers to hunt even blue whales and finbacks–the largest species, which, by reason of their speed in the water, had eluded all previous hunting technologies (New Bedford Whaling Museum). The International Whaling Commission (IWC) was established in 1949 to monitor population abundance utilizing an expert Scientific Committee. However, the IWC did not use enforcement and in 1972 the United Nations asked for a cessation of whaling while Congress passes the Endangered Species Act. A general moratorium was adopted by the IWC in 1982 (which took effect in 1987) to prevent extinction of many cetacean species, including the critically endangered North Atlantic right whale (Twiss and Reeves 1999). Currently, the IWC has assigned "Protected Stock" status to all stocks of the North Atlantic right whale (IWC). The catch quota is therefore set at zero for all signatory nations of the IWC. The North Atlantic right whale experienced the longest hunting history of any large whale species until the moratorium in 1982. Today, the biggest threat the species faces is that of human-induced mortality from ship strikes and entanglement.

## *2c. Distribution and Ecology*

### i. Habitat

Historically, right whales occurred in all of the world's oceans from the temperate to sub-artic regions. The distribution of this species relies heavily on the distribution of their zooplankton prey and their preference for shallow coastal areas (Winn et al 1986). The North Atlantic right whale population ranges from wintering and calving grounds in coastal waters of the southeastern United States to summer feeding and nursery grounds in New England waters and northward to the Bay of Fundy and the Scotian Shelf (Mitchell et al 1986). Knowlton et al (1992) reported several long-distance movements as far north as Newfoundland, the Labrador Basin, and southeast of Greenland. In both the North Atlantic and the Southern Hemisphere not all reproductively active females return each year to the calving grounds (Kraus et al 1986; Payne, 1986). The calving grounds extend from southern Georgia to northern Florida during the months of December through March (Encyclopedia of Marine Mammals – pg. 810). Research suggests the existence of six major habitats or congregation areas for western NARW; these are the coastal waters of the southeastern United States, the Great South Channel, Georges Bank/Gulf of Maine, Cape Cod and Massachusetts Bays, the Bay of Fundy, and the Scotian Shelf (Waring et al 2003). These designated areas were created as critical habitats for the western stock of the right whales due to their importance to the reproductive and feeding activities of the species (Kraus and Kenney 1991).

### ii. Food and feeding

Although Baleen whales include the largest living animals on earth they are primarily carnivorous and feed on zooplankton or small fish. The North Atlantic right whale feeds on tiny plankton called copepods (Clapham 2004). The filter-feeding process by which these whales feed is highly specialized and requires three basic features: a flow of water that brings prey to the mouth, a filter that allows water to pass through but collects food, and a means to remove the food and send it to the stomach (Encyclopedia of Marine Mammals pg. 66). The right whale is considered a skimmer, in that it skims the surface of the water with its mouth open allowing a flow of water through their baleen plates and capturing copepods as its food resource (Appendix 2: Baleen whale head structure and filter feeding). The inner and longer border of each plate includes fringed hairs forming the filter. There are as many as 270 plates on each side of the top jaw (almost 600 total) that reach a length of approximately 2.4 m or 8 feet (Conservation and Management of Marine Mammals). The whales will use their tongue to remove the copepods while forcing water through the plates off the fringe and then they will swallow their prey. Right whales can feed at both the surface waters (skim-feeding) as well as near the ocean floor depending on the season and food resource availability. The whales eat an average of 750 kilograms of copepods each day, consuming 500,000 calories (the equivalent to 1650 hamburgers). Mayo and Marx (1990) suggested that right whales locate and utilize only dense patches of zooplankton for feeding efficiency. Characteristic of the spring, summer, and fall habitats are these dense patches of zooplankton (Kenney et al 1986, 1995). Kenney et al (1995) reported a long-term increase in sighting rates within one feeding area of the western North Atlantic (Great South Channel) of 3.8% per year between 1979 and 1989, but extrapolation of this rate to the entire stock was inappropriate. These dense zooplankton patches may be caused by a process called upwelling which relies on cool nutrient rich water being forced to the surface where depths of 100-200 m adjacent to steeply sloping bottom topography drive the cool water upwards (Winn et al 1986).

## *2d. Life History*

#### i. Behavior

Sound production is thought to be used for communication, display or even establishment of territory and is heavily used by males within the baleen family. Right whales produce low frequency moans and pulses and also utilize a gunshot sound. Most sound is produced at an acoustic energy below 500 Hz. This gunshot sound is thought to be associated with mating or even to stun food. It is a short intense sound mimicking that of a gunshot. Researchers observed both lone and grouped males, where no observations of females making the gunshot sound were made. Right whales are typically solitary, however observations of social groups in the Bay of Fundy have documented 2-20+ whales in surface active groups. Baleen whales, such as the right whale have some of the longest documented migrations where they calve in the warmer tropical waters and mate and feed in the cold nutrient rich waters, such as the Bay of Fundy. Right whales are also known to complete aerial behaviors such as breaching, lobtailing, and slapping the waters surface with their flipper. Each behavior produces a loud sound but the reasoning behind them is still unknown.

#### ii. Growth and Reproduction

The youngest mature female in the western North Atlantic was age 4 and calved at age 5. This data is known from the right whale catalog used in the identification of individuals within the population. However, the typical age of maturity/calving is around 9/10 years of age. The growth of these mammals is rapid and body weight of the young (known as calves) doubles within the first year. After the first year, growth is dependant on food availability and feeding success. It is thought that right whales reach sexual maturity at body lengths of 13-16m (Encyclopedia of Marine Mammals – pg 811). The longevity of whales is unknown, as most deaths (that we know of) occur from anthropogenic influences. The oldest known right whale was approximately 70 years old, but died due to a ship strike. Thus, the longevity is truly unknown. During their life, females average 2-3 years between calving. Gestation lasts approximately one year as does weaning. Milk weaned to young is mostly fat and has been said to have the consistency of cottage cheese.

Relative to other populations (*Eubalaena australis*), the growth and recovery of the North Atlantic right whale is slow, seen in the increase of the calving interval between 1985 and 1997 from 3.33 to 5.36 years (Kraus et al. ?) The number of calves born each year varies and from 1990 to 2004 there were an average of 13 calves per season with an average calving interval of 5.0 years (Right Whale Consortium unpublished data). Currently, there is no prediction to as the number of calves that will be born per season or the calving interval of the species. In contrast, the Southern species (*Eubalaena australis*) has a reproductive rate double that of the northern species (Knowlton et al 1994; Best et al, 2001; Kraus et al, 2001).

### *2e. Population Decline*

The decline in the North Atlantic right whale population is unknown but thought to be due to several reasons. Commercial whaling reduced the North Atlantic stock of the right whales from around 12,000 in the 11th century to nearly 300 individuals in the population by the 21st century (Waldick et al. 2002). Populations with low numbers face the probability of losing genetic variability amongst the population which can be detrimental and reduce the ability of that population to adapt or respond to changes in the environment (Waldick et al. 2002). The North Atlantic population varies greatly from their Southern counterpart (Eubalaena australis) which has greater genetic diversity, a higher birthing rate, but also a larger population. Walkdick et al. (2002) found that the low genetic variability in the North Atlantic right whale predates the most severe population decline in the 18th century. However, with already low numbers the population is more susceptible to human-induced mortality such as ship strikes and entanglement, which is tied to foraging and migration habitats along the eastern seaboard. North Atlantic right whales show a 7% incidence rate of having scars from ship propellers and a 60% incidence rate of entanglement scars (Waring 1999). However, there is a high rate of ship propeller wounds found on stranded whales which indicates that many or most interactions between ships and a whale are fatal (Kraus 1990). Including ship strikes and entanglements, human-induced mortality accounted for six fatalities between February 2004 and February 2005 off the Atlantic coast (North Atlantic Right Whale Consortium). Unlike ship strikes, entanglements are less frequently observed as the whales are more likely to float and move offshore with ocean currents (Moore et al 2005). Anthropogenic induced mortality has a profound effect on the population of the North Atlantic right whale but does not necessarily account for the reason why this population has such low numbers. Other potential factors could include pollution, habitat destruction, and potentially whale watching but none have shown to have profound effects on the population (Marine Fisheries Review). With a reduction of two female deaths per year (in a population of 150 females) a positive population growth can be achieved (Fujiwara and Caswell 2001).

### *2f. Current Status*

The North Atlantic right whale has been protected from commercial whaling for more than 60 years, but their population remains low. The Southern right whales, in contrast, have shown signs of recovery over the past 20 years (Best, 1990; Payne et al. 1990). The populations of E. glacialis are spread across the North Atlantic and the North Pacific while Eubalaena australis roams the waters of the Southern Hemisphere. Considered the rarest of the baleen whale species, the North Atlantic right whale (of the western Atlantic population) has no more than 300 individuals (Knowlton et al. 1994). Using photographic identification data Knowlton et al (1994) estimated the annual population growth rate from 1986 to 1992 was at 2.5 percent. The Southern Atlantic right whales are a thriving population with approximately 7,000 individuals (Marine Fisheries Review).

There is very little data available on natural mortality of this species due to the nature of natural mortality. Kraus (1990) found an average natural mortality rate of 17% per year in first-year offspring. However, those whales entering their second through fourth year had an average natural mortality rate of 3% per year. More information is known on anthropogenic induced mortality such as entanglement and ship strikes.

### *2g. Research methods*

To date there have been no documented attempts at modeling a right whale and simulating the process of entanglement. Early methods included gross anatomical descriptions or published hunting records. The use of logbooks, newspapers, and commercial records began to be investigated during the 1970's. The 1980's discoveries of right whale habitat areas gave way to larger conservation and research programs. These field studies utilize ships and planes for surveys and analysis of behaviors and distribution. Photography of individuals has allowed the identification of individuals and valuable life history data. There is research every day that includes new methods, but researchers are yet to model the most threatened cetacean species. Potentially, the modeling of any animal, especially a marine mammal include many variables, all of which cannot be tested (as of yet) at one time. Recognizing this absence of a lab model and testing, the scale model of the North Atlantic right whale will help lead the way to improved understanding of the entanglement scenario and conservation of this critically endangered marine mammal.

## 3. Steps to Designing a Scale Model

### *3a. Scaling*

A mature right whale is 40-50 feet in length. Based on facility constraint, we must scale the dimensions of the scale model to fit the tow tank we will need for testing. The tow tank is 8 feet deep, 12 feet wide, and approximately 100 feet long. The aluminum carriage is 12 feet wide (to fit tank), 75 inches long, and 12 inches deep. Thus a full size model of a North Atlantic right whale would use half of the two tank. Due to this, the model is scaled to a smaller size to allow testing in the two tank.

When scaling, there are three concepts that need to be considered: geometric similarity, kinematic similarity, and dynamic similarity. Models are designed to mimic as much of the original as allowed. The necessity for geometric similarity is based on size comparison. Kinematic similarity uses the scaling of velocity, or fluid flow. If you add dynamic similarity to a model, the forces will be scaled, however, you cannot scale both kinematic and dynamic at the same time when the model is geometrically scaled. Thus, the two most important should be used, which varies with model use and testing.

Two types of scaling result from this distinction between dynamic and kinematic scaling. Froude scaling is used to scale dynamically: it scales to equate inertial and gravitational forces. Reynolds scaling is used to scale kinematically: it is used for immersed objects, where no surface interaction occurs and the most important factor is viscosity.

The Froude number is a ratio of inertial forces to gravitational forces. Froude scaling is used when gravitational forces predominate, such as waves that are created on the surface of the water. It equates the Froude Number of the scaled system to the original system. The Froude number is

$$Fr = V^2/(gD) \qquad (1)$$

where V is the velocity, g is the gravitational constant, and D is the diameter of the object. To scale using the Froude number, equate the Froude number for the model and the prototype (whale). The gravitational constant will drop out, leaving $V_p^2/ D_p = V_m^2/D_m$. Because the diameter of the model is specified, and there is a need to know how fast the scale model has to be towed at that diameter, the equation becomes

$$V_m = V_p\sqrt{(D_m/D_p)}. \qquad (2)$$

This equation shows that as the diameter of the scale model becomes smaller, the velocity of the whale decreases by its square.

The Reynolds number measures the relative importance of inertial (pressure) and viscous (friction) stresses on a submerged object when determining flow pattern. Fluid particles resist acceleration and deceleration; this effect is the inertial effect. Not only do the particles want to keep moving, they also want to stay together and resist the shear and formation of velocity gradients. This scaling allows us to study flows and forces on a submerged object. The Reynolds number is

$$Re = VD/\upsilon \qquad (3)$$

where V is the velocity, D is the diameter, and $\upsilon$ is the viscosity. To scale using the Reynolds number, equate the two Reynolds numbers of the prototype and scale model to yield $V_pD_p/\upsilon_p=V_mD_m/\upsilon_m$. Because the tests are in the same fluid as the prototype (the actual whale), the viscosities are the same and drop out of the equation, which reduces to $V_pD_p = V_mD_m$. With either scaling regime, the model scale factor influences the model velocity, and vice versa. The velocity needs to be calculated for the chosen scale factor. Therefore, the equation becomes

$$V_m = V_pD_p/D_m \qquad (4)$$

Notice as the scale model diameter decreases, the velocity of the scale model increases. This is opposite of the effect of Froude scaling, when the scale model velocity decreases when the scale model size decreases.

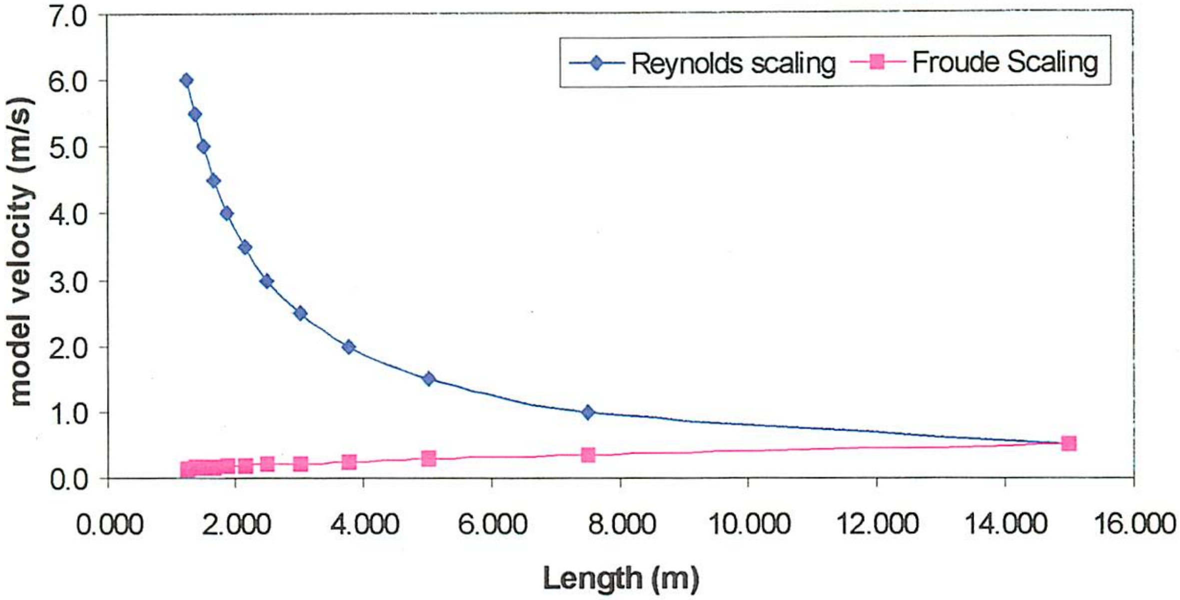



Figure 1: Scale model length vs. Velocity (whale velocity of 0.5m/s). Froude scaling shows that as the length (m) of the scale model increases with the velocity (m/s) of the scale model. However, Reynolds scaling shows that as the length (m) increases, the scale model velocity decreases exponentially.

Reynolds scaling was used to accurately portray the feeding behavior of right whales. There was a limit to the size of the scale model whale based on the relationship between velocity and scale model size (as velocity increases the scale model size decreases). Initially, research and calculations were based on the tow tank sustaining a speed of 12 m/s, a right whale cruising speed of 1 m/s, and the assumption that the tow carriage could sustain maximum speed despite the drag force. These assumptions lead to a 1/10 scale design of the scale model. However, it was determined that the tow tank sustains a speed of 6 m/s (12 knots), the average speed of a feeding right whale is 0.5 m/s, and the tow carriage slows as the drag force increases. The model scale changed to 1/8, to allow a smaller scale model size that would better fit into the confines of the tow tank. Tow tank dimensions allow an object that is smaller than 12 ft wide and 8 ft deep, thus the smaller the scale model the more space in the tank. This change to a 1/8 scale allowed greater maneuverability of the scale model.

The travel speed, mass, weight, and drag force of the 1/8 scale model were calculated. The ~6 ft (1.875 m) long model with a ~1.5 ft (0.5 m) diameter would travel at a speed of 4 m/s. The mass was determined by estimating the volume of approximately half a cylinder of the same length: where m is the mass, ρ the density, L the length, and d the diameter.

$$m = 0.5\rho L\pi d^2/4 \qquad (5)$$

Due to the slightly positive buoyancy of right whales, a little less than the density of seawater (998 kg/m$^3$) was used for the density of the scale model whale. Using the above data, a full size model right whale should weight approximately 78,600 kg. An adult right whale weighs approximately 60,000 to 100,000 kg (Folkens 2002), which means that the estimations are accurate. The 1/8 scale model was calculated to weighs approximately 148 kg (325 lbs).

The drag force is calculated by the formula

$$F_{drag} = \frac{1}{2} C\rho A v^2, \quad (6)$$

where A is the area of the surface perpendicular to the flow and C is a drag coefficient based on geometry. The drag force is equal for all scale sizes of the whale. This occurs because drag force depends on the square of both velocity and diameter of the body while Reynolds scaling makes the velocity and diameter proportional despite the size. The drag was calculated based on a sphere, to mimic that of a whale with its mouth closed. The drag force was calculated at 170 N (Appendix 3: Complete Scaling Calculations).

Material availability was accommodated for in the completed design of the scale model . The design called for foam cross sections. Because the foam used was 3.5 in thick (Section B), the scale was adjusted to 1/7.865. This adjustment did not significantly change the calculated weight or towing speed. The speed desired to best mimic a traveling right whale was changed from 4 m/s to 4.06 m/s. The weight also increased by five pounds (325 lbs to 330 lbs). The final design of the scale model relied on the acquired data of right whale biology and anatomy.

## *3b. Modeling based on scale*

### i. Data acquisition

The majority of the North Atlantic right whale model design derived from photographs. Survey, entanglement, and necropsy photographs provided a strong background to design the shape and structure of the body. Photographs were provided by the North Atlantic Right Whale Consortium (Figure 2: Photographs used in the design of the NARW model). Necropsy reports as well as field measurements of a deceased right whale helped to add quantitative data to the design shape. The North Atlantic Right Whale Consortium provided the necropsy report for Eg #1004 and Dr. Michael Moore provided his 2005 publication; Morphometry, gross morphology and available histopathology in Northwest Atlantic right whale (Eubalaena glacialis) mortalities (1970 to 2002). Dr. Moore also provided specific peduncle measurements from Right whale #2301 found dead on Ship Shoal Island, Virginia March 3, 2005 (Appendix 4: External Morphometrics). These data allow a realistic two-dimensional cross section to be modeled with known width, bottom arc radius, and girth measurements. However, photographs are not always taken as a design drawing would prefer.

Engineers use three views in a design sketch; top, side, and bottom. These three views allow for model generation. Based on the photographs provided, the frontal view of a North Atlantic right whale was extremely hard to come by. Profile views in a photograph are often taken at an angle to encompass the entirety of a whale in a camera lens. Boats also view whales at angles, and not head on, thus most photographs would be angled. Unfortunately, when photographs are taken the angles at which they are taken are not determined nor do they contain a coordinate system for reference. Thus, whales photographed in their natural habitat provide useful information for identification, behavior, and shape. Using photographs of beached whales (deceased) an opposite problem occurs. These views are distorted by gravity on land (versus water), the weight of the whale in sand, and the bloating (gas) associated with deceased animals. Thus, photographs were used as references for shape (qualitative data) while the necropsy reports and field measurements provided the necessary information to determine the distances between anatomical features (quantitative).

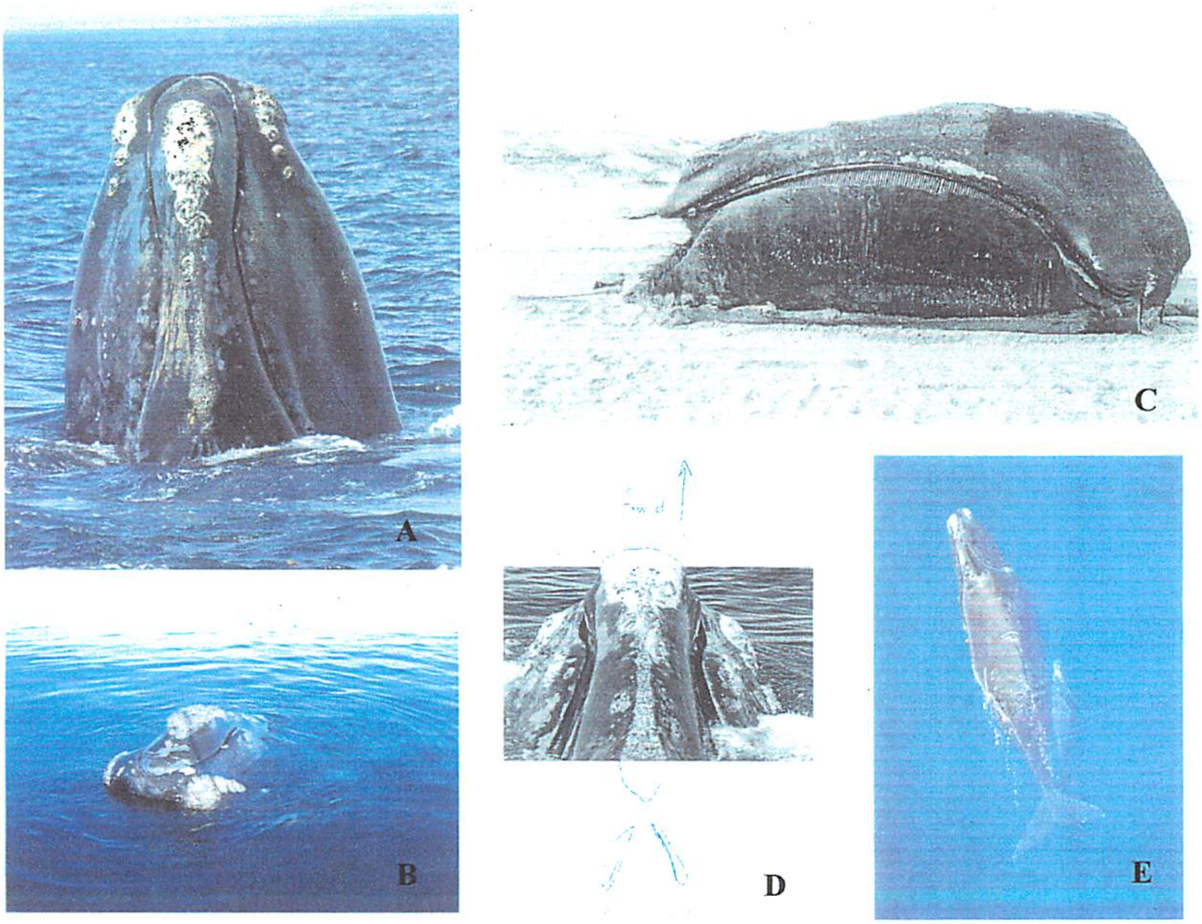



Figure 2: Photographs used from the Right Whale Consortium at the New England Aquarium. Figure A –D represent the modeling of the head and rostrum. A. A NARW spyhopping and demonstrating a strait dorsal view of the head and rostrum. B. A NARW at the surface, notice the flatness at the tip of the head. C. The removed head of Stumpy. Here demonstrating the curvature or the mouth. D. A dorsal view of the rostrum for model design. E. Used for full body design.

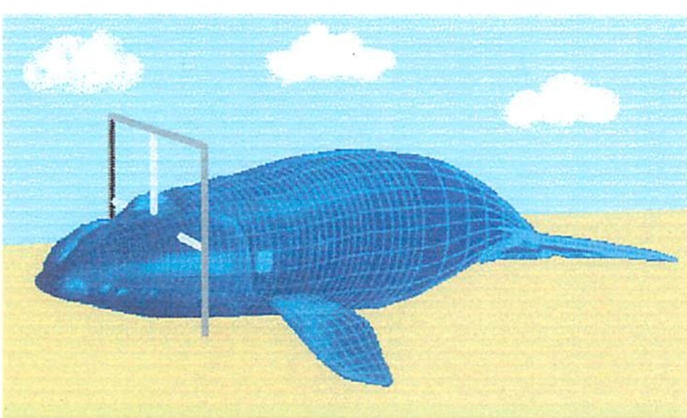


Figure 3: Giant Whale Caliper (GWC). The GWC was designed to achieve accurate measurements along the body length of a beached whale. The obtained data would help to design a more accurate model of a North Atlantic right whale. Although the GWC does not compensate for bloating or deterioration, the data would provide verification of size and shape.

A second alternative for obtaining quantitative measurements was determined. The Giant Whale Caliper (GWC) was designed as a tool to determine the height and width at points along the length of the body (Figure 3: Giant Whale Caliper). The GWC would (and could) only be used on beached whales. Made of adjustable rods, the GWC would also have height and width markings for data collection. It was thought that the measurements would provide data (in combination with photographs and necropsy reports) to better determine the design of a right whale model. The opportunity for such use is limited due to the short time interval prior to a beached whale being removed. Several opportunities arose for the construction and use of the GWC, however, due to timing the GWC was never implemented.

### *3c. Design concepts*

The process of designing the scale model involved a plethora of design concepts, only a few of which were applicable for the time period and budget. Model design concepts included a mechanical model propelled by a human, a model with mechanical flippers, tow structure attachment points for angle variation, static body with two heads that would be alternated, and finally two models.

The first design concept utilized Froude scaling, to simulate a whale feeding at the surface of the water. This design included a mechanical whale propelled by a person. The person inside would act as a swimmer, using their feet to move the fluke up and down in the water column and their arms to maneuver the flippers. This model would allow a simulation with behavioral characteristics. Building a dynamic model would require a longer time period as well as a larger budget. Aside, the scale of the model would not be large enough to fit an adult. Thus, a second idea was contrived.

The second design involved the tow tank and some mechanical anatomical parts. Using the tow tank alleviates the concern of having to mechanically push the whale through the water. However, this design involves the construction of a tow structure to attach to the carriage of the tow tank. The design also called for mechanical flipper to better simulate the movement of these parts during an entanglement. The mechanical flippers would not only be able to move, but they would control the rolling movement of the whale through the water while being pushed. Rather than using static flippers, it would be best to mimic a right whales movements (approximated) during pre-entanglement, entanglement, and post-entanglement. Again, this idea required a larger budget than was available. For the third idea, all moving mechanical parts were removed.

The third design utilized the towing structure as a way to adjust the angle at which the scale model hit the gear. By changing the attachment points at various angles, the scale model would be able to simulate the entanglement via a single angle per gear interaction versus the above ideas which modeled many angles per gear interaction. This design concept would have created a larger drag force (>170 N) and slowed the maximum tow speed of the carriage. This design would also have been difficult to construct based on the amount of attachment points, the way in which they would attach, as well as moving the weight of the whale (~300 lbs) into those points. In the fourth design concept the idea was to make the model as simply as possible.

The simplicity concept helped to create the fourth design where a static body would be used and have two detachable heads. The two detachable heads were meant to simulate an open mouth and closed mouth scenario. It is not known if whales only become entangled when they are feeding, however the two variables would allow observational data on the gear behaviors associated with each variable. With the design of the model evolving the design and process of the detachable heads was questionable. With a removable head the main concern was to not have a seam. Seams on a model of a seamless animal provide more potential areas of entanglement. Also, the question arose on how to attach heads when using foam as many materials do not stick to foam or withstand the prolonged exposure to water. The fifth concept derived from this model.

Desiring both the open and closed mouth models, the fifth design concept included two separate scale models. There would be no seam along the body for potential gear entanglement that may not exist in the natural environment, while also alleviating the pressure of detaching a head on a ~300 lb scale model. The closed mouth model was begun prior to the open mouth for several reasons. First, the closed mouth model was easier to reproduce based on the availability of photographs and data. Second, a closed mouth does not require simulated baleen to be present. Baleen, the filter for the right whales' food would have been another project to create. Given more project time and consideration to the potential ways in which to model baleen, the open mouth model would be invaluable. However, completing a closed mouth design is also invaluable as it provides the first attempt to build a scale model of a right whale for entanglement simulation.

### *3d. Generating the final design*

The final design of the North Atlantic right whale model was constructed via cross-sections derived from calculated intervals along a right whale body length. The data for scaled dimensions was provided in necropsy reports and field measurements of Eg #1004 and Eg #2301. Three sections were determined for the scale model design; head, body, and peduncle.

The head section dimensions were determined by using photographs and cross-referencing quantitative data. The photographs from Clapham (2004) demonstrated several cetacean behaviors, where the head is clearly defined. The body, unlike the head does not have a clearly defined shape.

The shape of the body utilized varying anatomical photographs of Eg # 1004. The length of the design was found using a photograph of a full view belly up carcass (Figure 4:Full body belly-up of Eg #1004). Photographs of body features like the curvature of a whales belly typically derive from floating carcasses (Figure 5: Body curvature of the NARW) or the curvature of the head originate from beached and decapitated carcasses (Figure 5: Body curvature of the NARW). A final sketch of the body shaping includes four sections (Figure 6: Body cross sections). The point at which the body becomes the peduncle was determined by angled profiles of a beached whale (Figure 7: Removal of Eg #1004).

Figure 4: Full body belly-up of Eg #1004. This photo provides the length of body measurement.

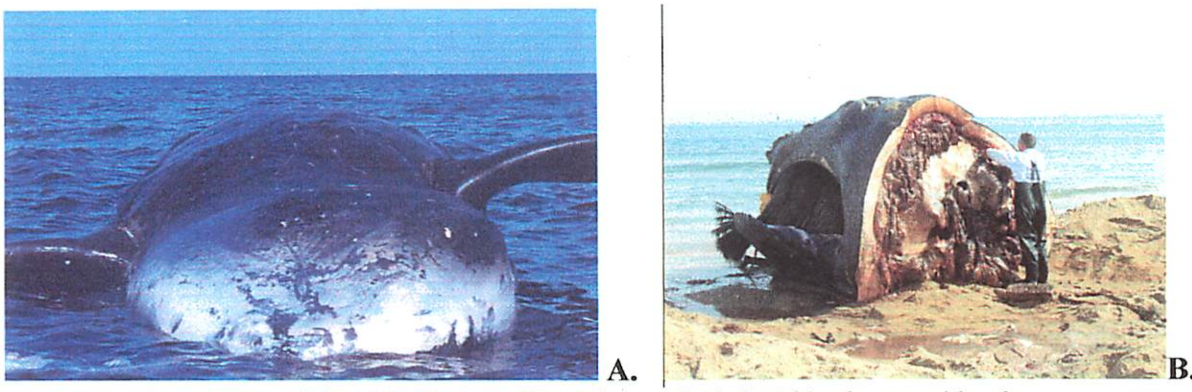



Figure 5: Body curvature of the NARW. A. Belly-up deceased whale. This view provides the curvature to produce the underside of the model. B. Arc of Eg #1004 head. This gives a great view to how the body curves.

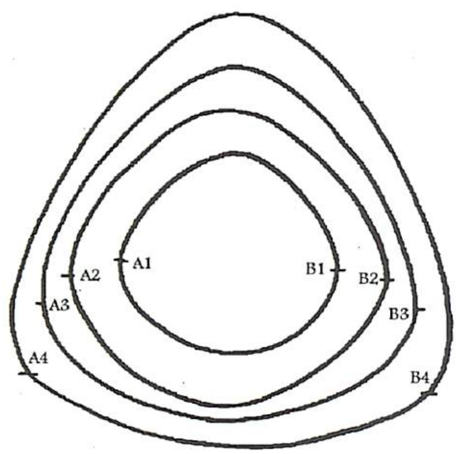
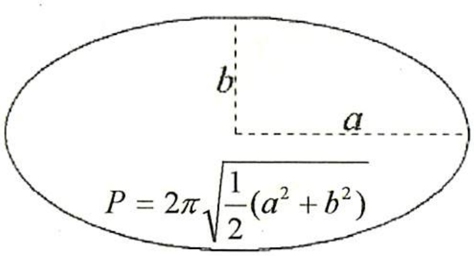



Figure 6: Body cross sections. The final drawing of the body shape based on photographs and morphometry.

Figure 7: Removal of Eg #1004.




$$P = 2\pi\sqrt{\frac{1}{2}(a^2 + b^2)}$$

Figure 8: Peduncle design. This figure demonstrates the process of converting circumferences into the elliptical shape of the peduncle.

Equation 1: Ellipse equation. This was used to determine the shape of the peduncle.

The peduncle measurements from the field ensured an accurate representation of size on the model. The peduncle girths were measured at 20 cm increments from the fluke insertion (Figure 7: Removal of Eg #1004). It was assumed the peduncle was shaped like an ellipse. Using the equations for an ellipse, the girth measurements (P), width dimensions ($b$) gave height ($a$) (Figure 8: Peduncle design). The calculations yielded the elliptical shape of the peduncle (Appendix 5: Calculations for the design of the peduncle). Completion of dimension calculations required scaling the design to the preferred scale of 1/7.865 (Appendix 6: Body cross section measurements).

## 4. Generation of the Model (not including propulsion design)

### *4a. The model step by step*

The scale model of the North Atlantic right whale was generated using foam board (3.5 in thick) cut to the design of the calculated 18 cross-sections. The design drawings were copied onto overhead transparencies where they were projected onto the foam board using the 1/7.865 scale.

**i. sections cut and glued together**

The foam board cross sections were then labeled according to head (H), body (B), or peduncle (P). Each cross section was cut using a hand saw then aligned vertically to produce the basic shape of the scale model. Using a digital photograph of the base model and the graphic of a right whale skeleton the exact placement of the cross-sections was determined. (Figure 9: Step by step process of the model construction). The sections were secured using Liquid Nails.

**ii. ballasting holes**

The body sections had ballasting holes carved into them to create a body cavity that would allow weights to be placed inside to keep the whale neutrally buoyant once it was in the water. A 1 5/8 inch hole was drilled through each cross section to allow for a pole to be inserted along the central line of the whale. This pole was used to attach the whale to the towing structure and to provide axial structural support to the body of the whale.

**iii. smoothing of body**

The edges on the body and peduncle cross sections were designed with positive space so the edges could be cut off and smoothed down. The three head cross sectional pieces were made with negative space and filled with Great Stuff. They were then smoothed and shaped based on the photographs and meetings with Dr. Scott Kraus. The flippers were created from known dimensions and outlines from Eg #1004 and provided by Dr. Ken Baldwin. These were initially made out of foam, but concerns about the forces being applied by the fishing line led to the construction of wooden flippers. The fluke was created by scaling the pictures to Eg #1004 and then scaled once more to fit our model.

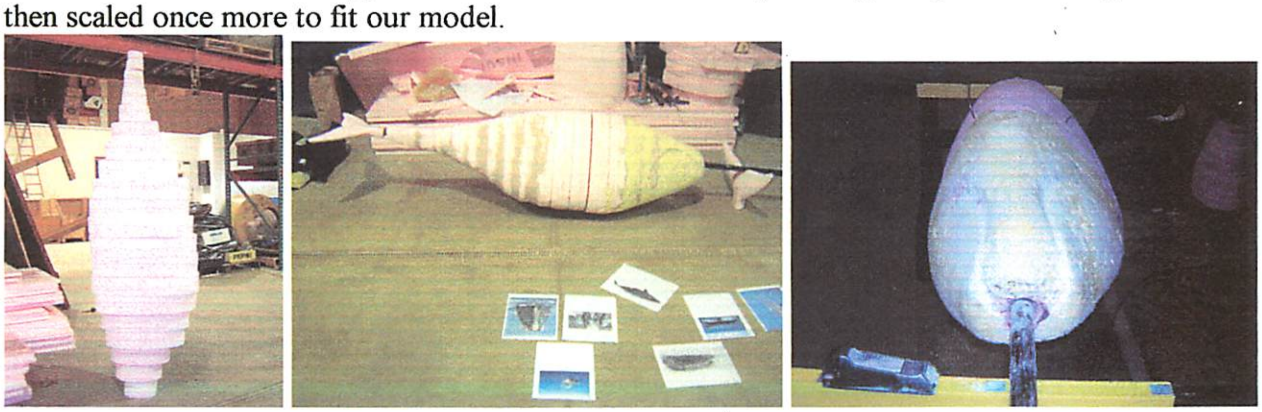


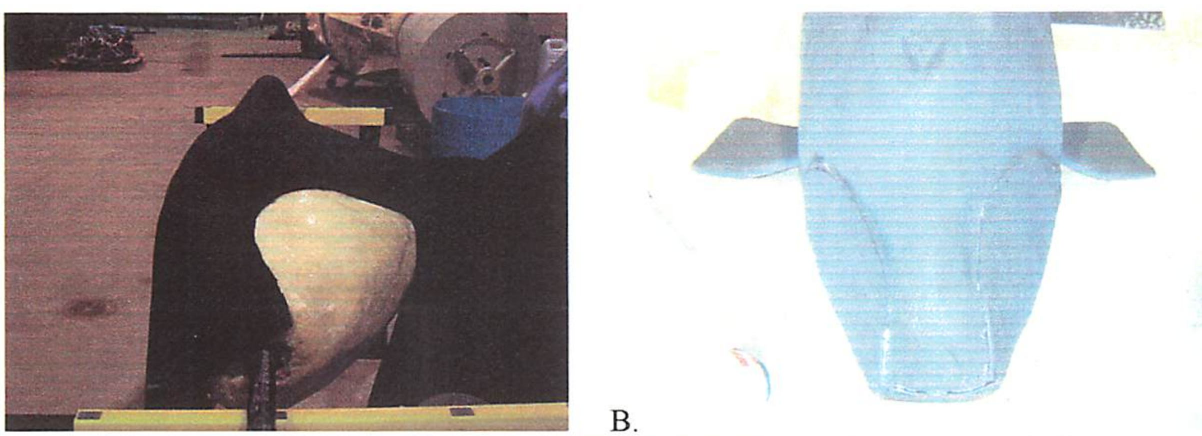
Figure 9: Step by step process of the model construction. A. The cross-sections placed vertically prior to proper placement. B. The shaved body and filled head. Pictures showing are guides to the body shape and head design. C. The shaped head and rostrum out of Great Stuff foam spray.

**iv. epoxy covering**

To create a strong structural integrity a fiberglass coating was applied. Here epoxy resin and hardener were mixed and coated over the fiberglass fabric smoothed onto the scale model body. Once the fiberglass had hardened, visible holes were filled with epoxy and any rough edges were sanded down.

**v. neoprene overlay**

Neoprene was determined to best mimic the skin layer of the North Atlantic right whale. A scale thickness of neoprene was used uniformly around the body (Figure 10: Neoprene application). A 3M multi-purpose extra strength glue was used as an adhesive to the fiberglass. Uniform neoprene was cut out and glued to the fiber glassed model. To make the seams less noticeable, each side was cut at a 45 degree angle to allow for smooth overlapping. They were then filled with Neoprene glue which seals and waterproofs the seams. Although blubber thicknesses do vary, a uniform thickness prevented uneven surfaces. Varying thicknesses with imperfect seams would lead to disruptions in the fluid flow as well as allowing a greater potential for gear entanglement based on snags. To create the upper and lower jaw intersection, neoprene was folded at the tip of the head and gradually unrolled towards the dorsal end.



A. B.

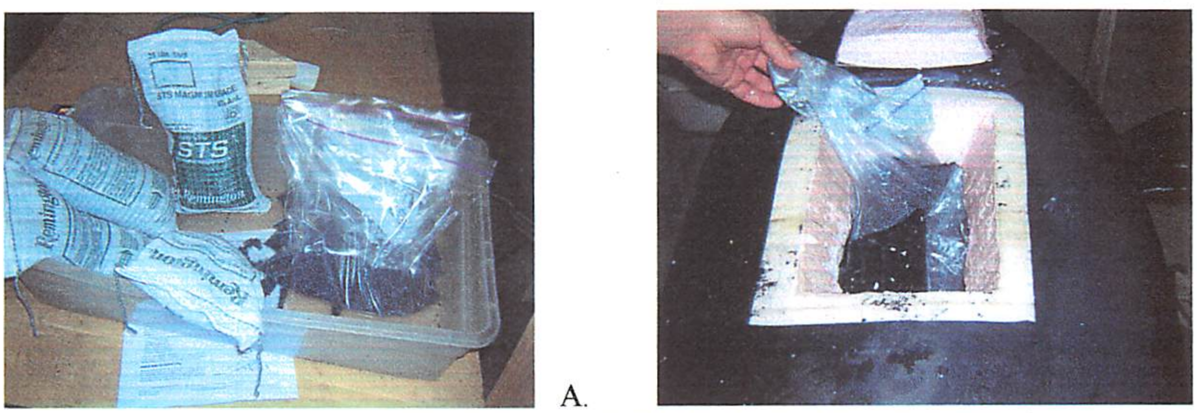
Figure 10: Neoprene application. A. The beginning process of overlaying the neoprene on the body. Seams were cut along the mouth arch to allow for better simulation of gum line and groove. B. Final product of the neoprene layering.

**vi. inserting the Ballast**

Upon completion of covering the scale model North Atlantic right whale with neoprene, the ballast was tested. Ballasting is traditionally referred to as a heavy substance used to improve the stability and control the draft of a ship. Ballasting in a submergible model was used to create desired buoyancy. As North Atlantic right whales are almost neutrally buoyant (meaning they do not sink or float unless an outside force is applied), calculations needed to be made to determine the force needed to sink the foam model to the point where it would be neutrally buoyant. As lead is an inexpensive metal with high density (11340 kg per cubic meter) it was chosen for the ballast.

The ballast was applied along the central cavity of the whale. This went from the 4$^{th}$ cross section to the 11$^{th}$ cross section (from the head). To access this cavity, a trapdoor was cut through the bottom of the whale through the neoprene, fiberglass, and foam layers. This allowed weights to be added and removed until the desired buoyancy was attained.

Initially, seven bricks were placed in the body cavity of the whale (each brick weighs 14.7 lbs.) and the model was placed in the tank to test if it was neutrally buoyant. With these 103 pounds of force and the free space - the body cavity flooded with water and the model did not sink. An additional 3 bricks were crammed into the body cavity, having little effect on the buoyancy. The body cavity was then hollowed out to allow more ballasting room and to remove foam to reduce the buoyancy force of the model. After hollowing out approximately five gallons of foam pieces, fourteen bricks could fit snugly in the body cavity providing a total of 206 pounds of ballasting. This allowed about 2/3 of the model to sink. Unfortunately, there was not enough room for more bricks, and further carving out of the body cavity could severely compromise the integrity of the model structure. One hundred pounds of lead shot was purchased and sealed in Ziploc bags in small, moldable quantities (Figure 11: Lead shot application). These bags were placed in the spaces around the bricks and the model was put into the tank. The model was past neutral buoyancy at 306 lbs. After removing 13.8 pounds of lead shot the model was neutrally buoyant for a total of 293 of ballast.




A. B.

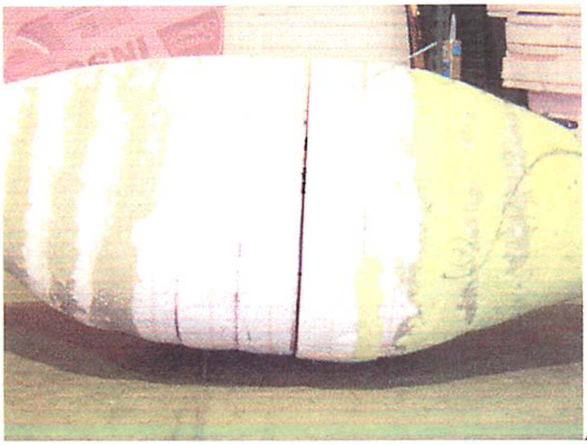
Figure 11: Lead shot application. A. The shot is poured into doubled-up 1 gal. Ziploc bags. B. The bags are placed around the bricks within the cavity.

### *4b. Problems associated with the model*

Problems associated with the model were a pregnant look, too large of curvature of the mouth due to juvenile whale photographs, and spray glue that melted the foam upon application. The biggest problem encountered was the initial designing of the cross sections. The pictures used to model the cross sections were of a dead carcass that had experienced bloating due to gasses (Figure 12: The pregnant whale versus the slimmed whale). This caused the whale to have a rather "pregnant" look that was modified by slimming down the sides on the body sections closest to the peduncle. Other pictures gave what turned out to contain misleading information as well.

The pictures chosen to model the head of the whale were actually of a juvenile whale. This affected the design of the mouth curvature, the width of the head, the shape of the head and the definition of the mouth. Under the guidance of Dr. Scott Kraus, a realistic head replica was attained by altering the shape with Greatstuff and reworking the model with a dremmel tool. Simpler problems to solve were due to incompatible materials.

An initial spray adhesive was to be used to glue the foam pieces. However, preliminary testing on with this substance showed that the spray glue melted straight through the foam.



A.

B.

Figure 12: The pregnant whale versus the slimmed whale. A. The pregnant-like bloated whale. B. The slimmed down un-pregnant whale which mimics a whale more accurately. Picture B shows a whale when it is alive, rather than A, which mimics the shaping of a dead bloated whale.

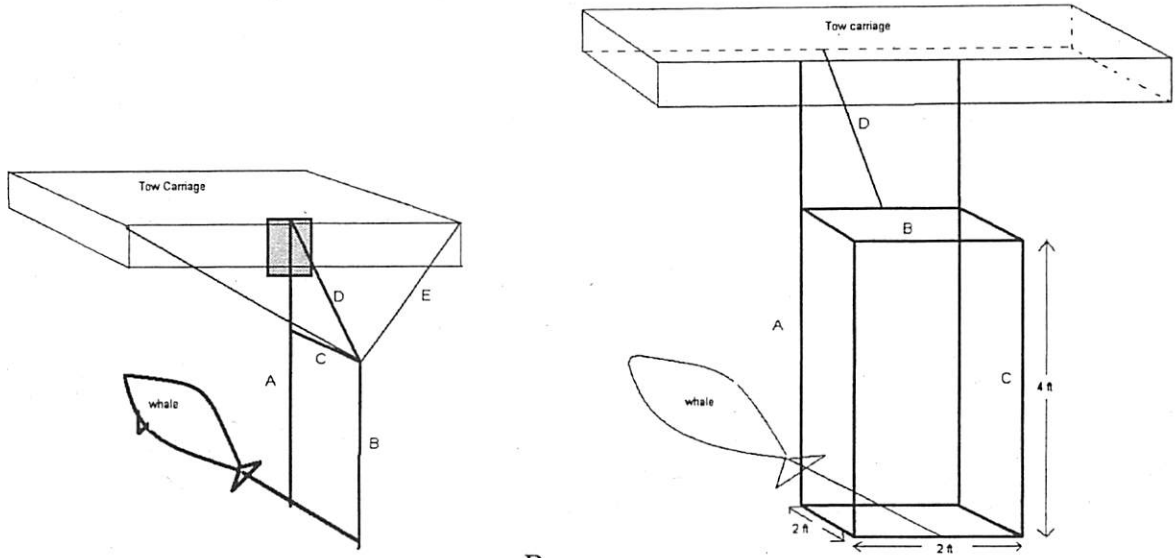
## 5. Pushing/Tow structure of Model

### *5a. Design*

It was decided that our model must be pushed in the tank as opposed to pulled, because the front of the whale must run into the fishing gear without interference from the towing structure. However, pushing something creates a tendency for the object wanting to twist to the side rather than straight. This creates a bending moment that could not be supported by a single pole. Therefore, a more complicated towing structure had to be designed.

Our initial design was to have a tow structure that was two-dimensional (Figure 13: Tow structures). There is a beam (A) that is attached by a steel plate to the tow carriage that extends down to the whale bar. The second beam that extends down to the whale level was put in place to reduce moments on the first beam (B). It was designed to be in line with the front beam to keep the drag force as low as possible. These two bars would attach to a horizontal beam (C) and a beam that was angled from the top of the first bar down to the top of the second bar (D). These would stabilize the structure in the axial direction. Then, two cables were going to be attached from the top of the second bar to the corners of the tow carriage to stabilize the structure in the horizontal direction (E). Although this design is useful for producing a minimum amount of drag force in the water, it had to be modified because the design would probably be too wobbly in the horizontal direction. The modifications to this model yielded our current tow structure.

Our chosen design expanded upon the first idea to have more stability in the horizontal direction (Figure 13:Tow structures). The beams descending down to the whale (A and C) were doubled and horizontal bars (B) added to make a box shape, shown below. Also, a cable (D) was run to the front of the tow carriage to reduce the pull on the back of the carriage. The tow carriage itself is 12 inches thick, and it is located 26 inches above the surface of the water. The tow carriage was made such that the box was 2 feet by 2 feet by 4 feet tall, so the bottom of the tow structure is another 48 inches below the surface of the water. It was designed to keep the whale as close to the center of the tank as possible.




A. B.

Figure 13: Tow structures. A. The original diagram shows the theoretical construction of the original tow structure design, as well as how it would attach to the tow carriage and whale. B. The final tow structure design shows the final tow structure design and how it relates to the tow carriage and whale.

Notice that the angled bar from the back piece to the top of the front piece was removed for this design. The reason is that the material we chose to build the structure out of was Unistrut, shown below. Unistrut is steel U-shaped beams that attach together with nuts that fit inside the U-shape and can be put anywhere, kind of like an oversized erector set (Figure 14 and 15) . The convenience of Unistrut can be cumbersome when an angle greater than 90° is needed, therefore the angled bar was removed.

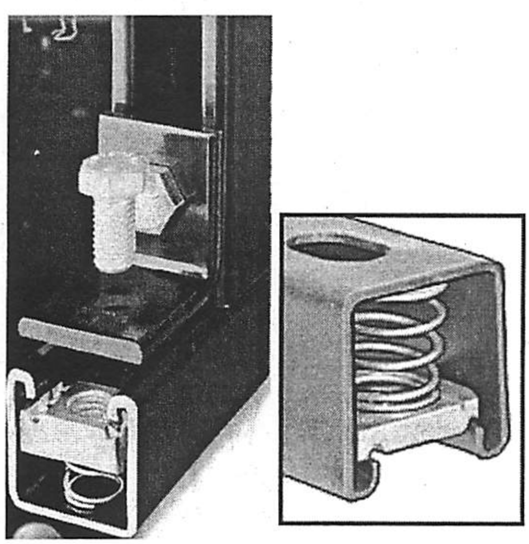


Figure 14: Unistrut, bolt and nut. This image shows the general U-shape of the Unistrut, as well as the nut that fits inside on the grooved edges of the pipe. (www.unistrut.com)

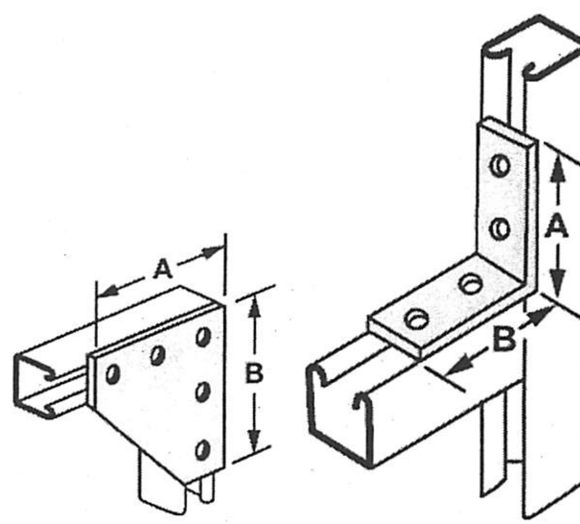



Figure 15:Unistrut corner connectors. These two types of corner brackets were used to create the Unistrut tow structure. (www.unistrut.com)

**i. strength**

Unistrut is a strong material. It is made of steel, and is 1-5/8 (www.unistrut.com) wide by a variable depth. A Unistrut piece that has a depth of 1- 5/8 inches (www.unistrut.com)has an allowable moment of 5080 in-lbs (www.unistrut.com). A Unistrut piece that has a depth of 7/8 has an allowable moment of 1810 in-lbs, and a piece that has a depth of 2-7/16 inches has an allowable moment of 9830 in-lb (www.unistrut.com). The pull-out force for the three nuts inside the channel is 900 lbs (www.unistrut.com). After doing the calculations for the forces on the towing structure (Appendix 7: Towing structure calculations), it was determined that the front members of the structure would undergo a worst-case bending moment of 3060 in-lbs (not including drag force on the structure). With the two front members made out of the 2-7/16 Unistrut, together they have a maximum load of 19,660 in-lbs. There is a safety factor of 6 in incase the bending moment was calculated improperly. The structural supports would experience the greatest bending moment and were considered the critical structural element. While the back pieces do add rigidity to the support, it is an indeterminate problem that requires finite element analysis software to calculate the actual forces unless the structure is assumed to be a truss (pinned at the corners instead of fixed). It was assumed that this part of the structure would never undergo a bending moment higher than 5000 in-lbs, and so the 1 5/8 Unistrut pieces would work. The corners of the Unistrut were braced with angle brackets and plates (Figure 15: Unistrut corner connectors). These provided increased rigidity to the corners of the Unistrut.

**ii. rotation ability**

It was decided to allow the whale to rotate on the structure, and perhaps eventually be able to turn it with a motor attached to the whale's pole. Therefore, the two structure was designed so that the pole was attached in a way to allow rotation. Four 7/16" U-bolts were placed around the pole and attached around the two horizontal bars on the bottom of the tow structure. Additional pieces of Unistrut were used across the bottom of the U-bolts to secure the pole to the tow structure. The curve of the bolts left some extra room if needed to apply bearings or another slippery surface around the pole so that it could rotate. To prevent the pole from sliding through the U-bolts, four collars were tightened onto the pole in front and behind each set of U-bolts. These collars should prevent front-to-back motion, but not prevent any rotational motion.

## 6. Fishing gear

### *6a. Types of gear*

The gear most commonly associated with entanglement is pot gear and gillnet. There is no direct evidence to show what type has a greater affect on the populations. There is also no specific data to show the percentage of entanglement due to right whale death based on the nature of entanglements. Whales may drown from gear or even float to sea where they are never spotted. The threat of these two gear types involves floating lines at the surface and through the water column. Gillnets act like giant tennis nets strung together at the ocean floor while pot gear, such as lobster pots, use floating line between pots that form arches in the water. (Figure 16: Gillnet and pot-gear ).

Gillnets are used globally and target various species of ground fish based on mesh size. Monofilament line is used and traps the gills of the fish (thus the fish) in the line as the fish move through. In the Gulf of Maine region these nets are used to catch monkfish, hake, cod, and haddock. These nets are typically strung together in up to 10 sections that can each reach 10 feet high and 300 feet long (91 m). Buoys mark the end lines between the nets or panels as a weight will hold the floating anchor line as well as the end line. The connecting bridle (below the surface) floats to reduce snag. The bottom line of the net is lead-filled to sink, while the top of the net uses small floats.

Lobster pots include a single line with an attached buoy at the surface and a trap at the ocean floor. Typically the gear is strung together with synthetic line and marked with buoys at the end lines for gear identification. The gangions and lines between the traps float to reduce snag. The gangion lines are typically five feet long and make an arc 15-20 feet high when attached to 80-90 feet of floating line between traps. There is no specific piece of gear that is more likely to entangle with a whale over another type, they all pose a threat.

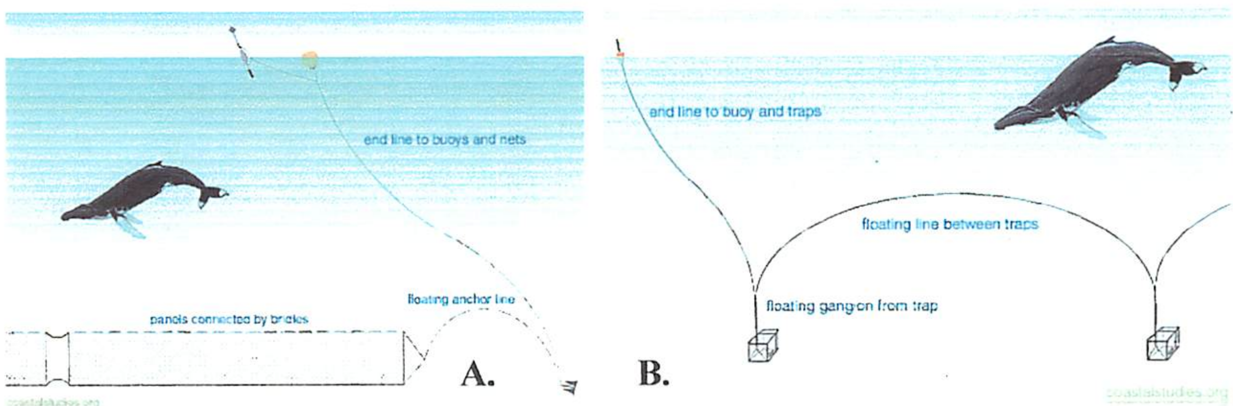



Figure 16: Gillnet and Pot-gear. A. An example of a gillnet. B. An example of pot-gear. Both figures from the Center for Coastal Studies (www.coastalstudies.org).

## *6b. Choosing to model gillnet or lobster pot gear*

The choice to model lobster pot line over gillnet was twofold. First, to scale and build lobster gear is much simpler than a gill net. The model design initially called for an open mouth and closed mouth, but due to time and modeling constraints the project settled on the close mouth design. Therefore the construction of the two gear types was taken into account. A whale feeding at the surface will be more likely to snag a single line (all lines to the surface are single lines) versus a whale feeding near the ocean floor where there are more lines to take into account. Although these are estimates, the modeling of a single lobster pot line proved simpler than a gillnet given the materials, size of tank, and maneuverability of the model in the water.

A publication by Lyman and McKeirnan (2005) looked at the entanglement threat of configured buoy line and ground line profiles using scale modeling of fixed fishing gear. This report helped to understand the process of scaling buoy lines.

### i. Design

1. Scaling

A typical inshore lobster buoy is approximately 1 foot in length and 8-12 inches in diameter, with a 2-foot rod going through it. Offshore lobster buoys are said to be much larger (could not find an actual measurement), so we assumed that they were twice the size of an inshore lobster buoy. This would make the buoy two feet in length, with a four foot rod through it. A 1/8 scale buoy would then be 3 inches in length and approximately 1.5 inches in diameter.

This was made out of the same foam as the model, and four stainless steel bolts were inserted into a hole cut into the bottom of it to make it float correctly. A loop of fishing line was inserted through the buoy to attach the lobster line.

Lobstermen usually deploy the lobster pots with a lead line to the surface that has some slack in it. This slack is called scope, and a lobster line usually has 20-30 % of scope in it at high tide. The median value of 25% was taken to scale the fishing line. For this project, it was assumed that the whale would become entangled when the greatest amount of slack was present in the line. This would represent low tide. High tide is normally eight feet higher than low tide, which in a 1/8 scaling system would add another foot to the tank height. For the calculated scope, 25% of nine feet was used (2.25 ft). The total length of line used in testing was 11.25 ft (11 ft 3 in).

2. Mooring construction

A mooring line with a weight of approximately 5 lbs and large enough to create a drag force if the whale moves it. The lead bricks used in the whale as a ballast may be too heavy (15 lbs) and cause the line to break. A smaller lead weight, such as a diving weight would work. The line used to attach to the mooring should be either crochet thread (red color easy to see, slightly small size), fishing line (right size, hard to see), fly fishing line (right size, yellow to see easily, but floated), or mason twine which is colorful, slightly big but fluorescent pink. The mason line was chosen based on the fluorescent coloring.

# 7. Data Acquisition

### *7a. Data observation design and construction*

There are several components included in the collection and analysis of data for the simulation of entanglement with a 1/8$^{th}$ scale right whale model. For the preliminary testing, data were acquired by observation. Observations were accomplished by humans and a video camera deployed on the pushing/tow structure.

### *7b. Utilizing a camera for observation*

The use of a video camera is an important component to the observation and analysis of this project. It provides real-time video and a record of the process by which entanglements occur. Human observations provide insight into the process, what occurs – pre-entanglement and post-entanglement. It is the camera that provides the center of the entanglement process as well as detailed description of movement by both whale and gear during the simulation. By cross-referencing video and human observations a more accurate depiction of entanglement is gained.

The design of this process is tiered and involves the tow carriage, the view required for maximum data, the function of the water when towing a whale in a tank, and the types of camera's available for such needs. The tow structure is attached on the trailing edge of the tow carriage leaving the ventral end of the whale model free from obstruction (see Section 5 for design). This leaves the leading edge of the carriage available and a good place of attachment for the camera. Unfortunately, an underwater camera is needed to avoid water turbulence (white water) that occurs at the surface from the movement of the tow structure. This white water requires that the camera be placed a few feet below the water's surface for maximum viewing

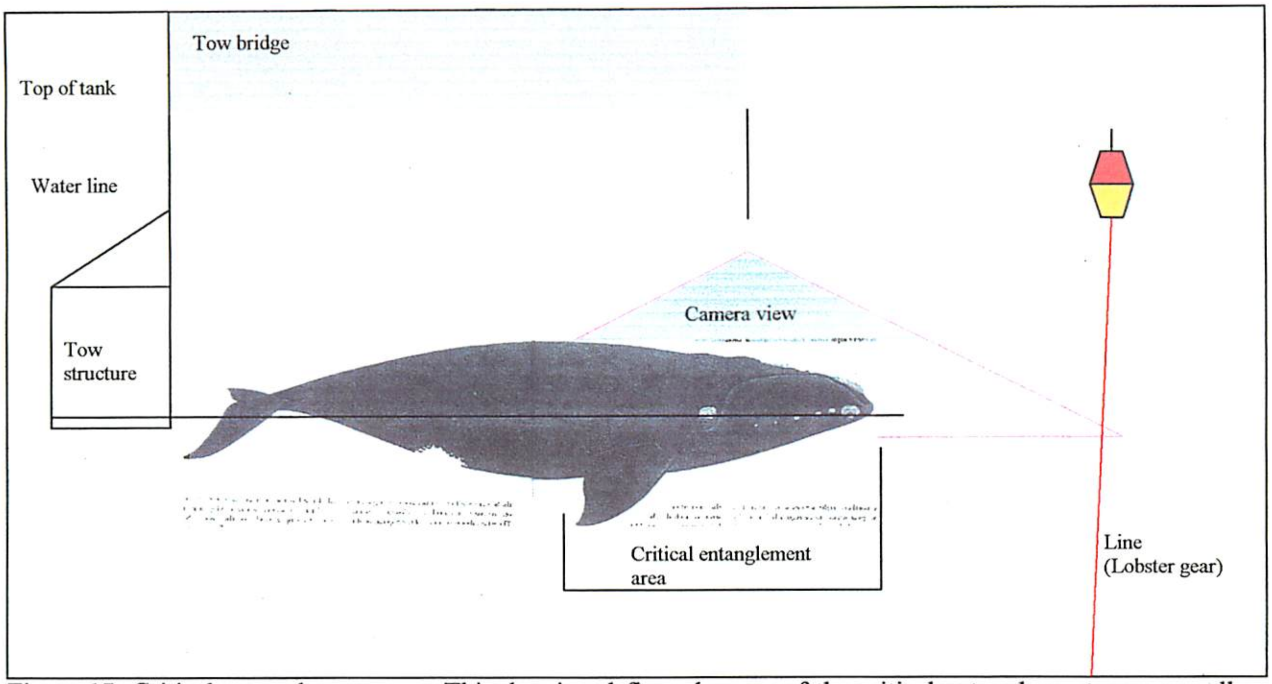


Figure 17: Critical entanglement area. This drawing defines the area of the critical entanglement area as well as depicting the original camera design for the filming of the tow. The camera now sits on the top cross beam of the tow structure. This drawing not to scale.

capabilities. However, this lends to needing a wide angle lens due to the depth of the camera, the distance away of the whale model, and the need to capture not only the line but the critical entanglement area (Figure 17: Critical entanglement area) The line is approximately 8 ft away from the ventral surface of the whale model at rest. As the whale is pushed by the tow structure, at a given point the camera will capture the whale model moving into the line, giving a full view from line to just aft of the flippers. The first place of proposed entanglement of a whale swimming into gear, or the critical entanglement area, is the tip of the head to the dorsal end of the flipper. Camera types investigated included surveillance cameras either weatherproof or with a housing, home use video camera with waterproof housings, and high-end underwater filming equipment through Under Water Photo Tech. in Derry, NH.

The main components of the final design included a Sony miniDV camcorder, Bluefin underwater housing unit, wide angle lens, Bluefin remote monitor and an extension cable for the handheld monitor. This package allows the greatest manipulation of data capture as well as data recording. The remote monitor allows the researchers to stand away from the carriage at all times and manually controlling the camera in regards to all camera functions. These include, start, stop, playback, and lighting. Two estimates were given; one at 12, 032.95 (Appendix 8: Purchase estimates for Camera) and the other at 9,897.30 (Appendix 8: Purchase estimates for Camera).The former quote included a Sony VX-2100 professional camera, carrying case for the camera, and a $600.00 discount. The later estimate included a Sony HC-1000 camera system (more of a consumer camera), no carrying case, and a 10% discount totaling $1,099.70. Both estimates included L&M Bluefin HC1000 Housing, Wide angle lens, Bluefin Remote Monitor, Remote Monitor extension cord (50'), and a Video Out whip. The later was chosen as the viable option due to the financial capabilities of the groups pooling money. However, due to time constraints, the allocation of funds for an Ocean Engineering camera unit will be purchased at a later date. Underwater Photo Tech agreed to rent a camera for $210 a week. This camera utilizes a Top Dawg III sport housing and a Sony DCR-TRV-19 Mini-DV camcorder.

The final design of the filming apparatus involves several criteria. First, the design must include the maximum camera angle. Second, the design must not interfere with the model or the towing of the model. The final design utilizes the existing tow structure (on the trailing edge of the tow carriage) as the basis for the camera structure. This was done to ensure that the camera did not interfere with the tow of the whale and includes the best camera angle possible for its position. Having a camera just above the head would allow the maximum viewing range for the entanglement simulation, however, upon further examination; the structure would potentially interfere with the fishing line, thus affecting the results of the test. In place, the viewing angle has been slightly compensated to a more rear orientation view of the head and flippers as opposed to a strictly dorsal view. The head and flippers compose the critical entanglement area and require the greatest viewing scope for data analysis. The rear-orientated angle will show where the line moves to, but will not provide an up close analysis of flipper or rostrum entanglement. The camera is attached to the tow structure via two 2 ft Unistrut sections (Figure 18: Camera housing attachment). These pieces hang vertically from the leading top cross-beam of the tow structure. Using L-shape hangers and 5/8$^{th}$ hex bolts the 2 ft Unistrut sections are secured to the cross beam. The handles of the camera housing were removed to allow camera attachment between the Unistrut sections. Again, L-shape hangers were used for attachment to the two Unistrut sections (Figure 18: camera housing attachment). This configuration, however, does not make filming simple.

The rental camera must be turned on before entering the housing and while the one connector cable is attached. The camera then stays on until the housing is either opened or the control on the side of the housing is used to turn it off. Once the camera is turned off from the housing, it cannot be turned back on. This is not so much a problem as not having access to the controls. With a separate structure on the leading edge of the tow carriage, moving the camera in and out of the water would be simple and only require lifting the body from the water. However, with the camera attached to the large tow structure, there is a greater level of difficulty to operate the camera. The cross-beam that holds to the two Unistrut sections lies below the water line, which is 26 in from the tow carriage. The camera is then another 1 ft 3 in below the surface. The camera needs to be turned on before the tow structure is attached to the carriage and must remain on through the duration of the set up, testing, and break down. To ensure maximum use of the camera the battery was charged the night before the tow structure entered the water and a new tape was placed in the camera.

A.

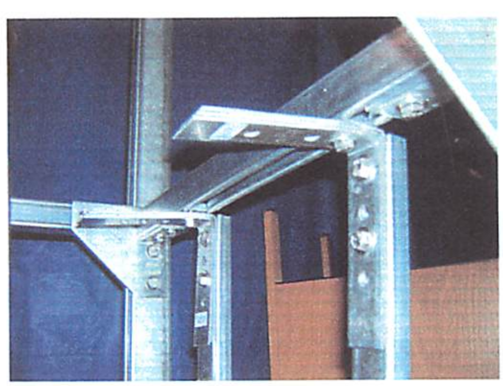

B.

Figure 18: Camera housing attachment. A. is the entire attachment and assembly from the aft portion of the camera. Note the L-shape hangers. B. Close-up view of the L-shape hangers holding the two 2 ft Unistrut sections.

### *7c. Data sheets*

The data sheets were used as a way to cross-reference and organize the video data. There are six sections to the data sheet; general information, tow characteristics, changes to procedure, general observations, problems associated with the tow, and a diagram (Appendix 9: Data sheet). The general information section includes date, time, and trial and observers while the tow characteristics section include tow speed, rotation, rotation speed, and water depth of the model. The last section includes a top-view diagram of a general right whale. This outline drawing allows the observer to draw the process as well as the outcome of the simulated entanglement. This will help to cross-reference will the video to look at the process to the final outcome of each trial. These data sheets will also help to organize and reference each video clip when analyzing data and reporting any observations and findings.

## 8. Results

The construction of the North Atlantic right whale proved to be a difficult and time consuming task. Materials used could be modified or changed based on extended water submergence time. Foam insulation, the basis of the model makes for a sturdy structure, however, may not be strong enough for the 296 pounds held in the belly. This could lead to modifications of an epoxy lined gut cavity. Even with a fiberglass coating, the whale is extremely susceptible to damage due to the foam base and approximately 300 lb belly which acts as a ballast. The fiberglass/epoxy worked very well to smooth down the foam sections and to create a base for the neoprene. Smaller pieces of fiberglass cloth would be ideal due to the shape of the body, however, with small pieces there are more seams which tend to create bumps near the surface of the neoprene. The 3M glue used to attach the neoprene to the epoxy made for a great tack glue, but once exposed to the water for short periods of the time the resin lost its ability to stick creating air pockets throughout the body. The neoprene wet suit of the whale has many seams, and was sealed with wet suit glue much like rubber cement. This glue should have been used as the underside tack to prevent boils and make for a tighter seam construction. Also, the fluke insertions create bumps with the neoprene creating potential entanglement snags. This too was a problem with covering a rounded shape with neoprene. It was necessary to make sure the leading edge of the flipper was free of nicks and seams due to the critical entanglement area. The 3M glue initially bought to attach the foam sections to one another; melted the foam. The liquid nails glue used to attach the foam boards together often took too long to dry and on many occasions broke the bond due to extensive movement. Materials are needed that are durable, long lasting, water resistant, fairly inexpensive, and easily maneuverable.

Based on calculations the desired weight for the model was estimated at 325-330 lbs. The final weight of ballast, including the lead bricks and lead pellets was 296 lbs. The difference in the weight estimate includes the water that flooded the cavity, the weight of the foam, and the extra weight of the pipe that was attached to the body. While this could not be accurately measured, it is estimated that all three combine to approximately 40 lbs.

The lone day of testing yielded promising results (Appendix 10: Tow on April 22, 2005). The tow structure remained sturdy throughout the day. The scale model North Atlantic right whale appeared to be ballast correctly as seen when it dislodged from the tow structure and glided slowly to just below the surface. The flippers of the whale did not dislodge when towed. However, when the scale model dislodged the pole did break through the neoprene. Another material should be taken into consideration to close the hole at the nose top to ensure that does not occur. The one tow at 2 m/s ran the right flipper into the fishing line which ripped through the neoprene layer down to the wood flipper. With only one test run into gear, a conclusion cannot be made to as the severity of the speed and line interaction. However, it can be inferred that if a whale traveling at a speed of 0.25 m/s (model at 2 m/s) then given this interaction the line would have gone through the blubber. Although minimal tow tests were run, the results yielded from the design and construction of the model prove that creating a realistic 1/8 scale model on a 5,000 dollar budget is obtainable.

## 9. Discussion

The 1/8$^{th}$ scale model is the first known scale model made specifically for entanglement simulation. There are known scale models of North Atlantic right whales made for educational purposes and museums, however, no model construction has been published or shared with the public. The importance of designing such a model involves two main factors. First, the critically endangered population of the North Atlantic right whale includes approximately 350 individuals and is affected by anthropogenic influences. Second, by providing the first step to designing a model this project will aide in future research of the subject. The relationship between the right whale and fishing gear will rely on simulation in the near future.

The use of photography for the study of marine mammals is typically used for identification purposes. Long term studies provide information that helps to understand the population and life history traits of marine mammals. However, because most photographs are used for identification purposes only, there are no means by which to scale the photographs. A realistic goal for the future would be to have certain criteria on given surveys to provide engineers with a better base from which to model a whale. These criteria would include taking a photograph from dead on the front, side, back, bottom, or top, a coordinate system to reference, as well as any external information or past history of the known individual. Photographs from dead on angles, although difficult to obtain due to the nature of boats at sea and right whale regulations, would however provide the necessary basis to build a more accurate scale model or to verify the current model. By utilizing a coordinate system or scale reference the whale in the photograph would provide a much stronger quantitative measurement than combining necropsy reports of bloated whales and their live counterparts. However, it should not be overlooked that necropsy reports provide a plethora of data, as might the Giant Whale Caliper (GWC) if they are able to be implemented.

The Giant Whale Calipers (GWC) provides a basis from which to acquire morphometry data on a larger scale than a typical necropsy. The information needed is the circumference and diameters of the whale body. Although smoothing a whale down out of foam based on cross-sections appears to have worked well, having another way in which to measure the body is another resource of numbers. The GWC could potentially aide in more detailed measurements of the head to better model jaw, arch, and baleen height. This would allow a more strongly detailed and orientated open and closed mouth models.

The importance behind having the open and closed mouth scale models of the North Atlantic right whale pertains to the statistics of found gear in/on the whales. Although it is estimated that many of the whales that become entangled in gear humans never see, those that are found contain line wrapped in their baleen most of the time. This indicates that there is a potential correlation between feeding right whales and fishing gear versus non-feeding right whales and gear. The simulation of both scale models would provide a basis on which to compare these two interaction scenarios. It is important that a second model is made, learning from experiences of the present scale model. If the fishing line cut through the flipper of the scale model traveling at a speed of 2 m/s (0.25 m/s scaled for a large whale), than it could cut more into the flesh at the whales true traveling speed of 0.5 m/s. This information is important and can lead to valuable discussion on the gear used in the ocean and the effect it has on marine life, such as the critically endangered right whale. The challenge to the second model will be the simulation of baleen as it is not an easy shape or texture to emulate. More testing would avail many more answers as to the interaction between fishing gear and the North Atlantic right whale.

Entanglements are fascinating to study based on their complexity. They are broken into three steps, pre-entanglement, entanglement, and post-entanglement. There is always a basic knowledge of the species prior to an entanglement. This is when the whale is free of any gear and in a normal state. Entanglement is the process of line becoming lodged on the body or in the mouth. Post-entanglement involves the process of disentanglement until the whale is free of gear. In most cases, scientists have seen the pre-entanglement and post-entanglement, but the actual process of entanglement is yet to be seen or studied. This model will aide in the simulation of such entanglement events to better understand the interaction between the whale and the line.

There are extensive files on the disentanglement of individuals housed at the Center for Coastal Studies (CCS) in Provincetown, MA. The CCS (www.coastalstudies.org) is the only east coast organization in the United States federally authorized by National Marine Fisheries Service to disentangle large, free swimming whales. They have built an entire network to aide in the rapid response of entanglements along the eastern seaboard. However, by the time the whales are identified it is past the moment of entanglement and into the post-entanglement stage. By utilizing drawings of gear locations it may be possible to look backwards and emulate a particular entanglement with the model to help the disentanglement team better understand where to cut lines or scientists understand the movements involved when the entanglement occurs.

This ability to utilize past data with model maneuverability and interaction may help to better explain the reasons to as how entanglements occur. Ideas include; scenarios of entanglement with various cetacean behaviors (feeding versus traveling), determining ratios and percentages of gear type interactions (such that one gear type gets trapped on a flipper while another type in the mouth), this could help to overlay particular feeding behaviors with habitat and gear types. There is a great potential for the use of this model or the construction of future models.

More specialized design models may help to enhance the testing scenario. Although the current model provides a basis for all future testing, it is a model to learn from. Various materials and construction patterns could be modified for material longevity and a more efficient building process. Potential ideas are to team-up with another school to build a robotic version of the whale for a fully operational aquatic right whale robot. This would allow the greatest flexibility for real simulation as obtainable with model material, simulation, and tanks. Upgraded materials such as a waterproof glue to stick the neoprene onto the foam, or even the use of a material other than foam would help to better the model construction, durability, and longevity. Length of time allotted for the project also takes a toll onto what can be done, and what cannot. It is the intent, that with a basic model built, future models will branch into new avenues of exploration with materials and methods to further the reality of simulation.

The importance of a scale North Atlantic right whale model is to provide insight into the processes of entanglement, not just the result. This project aimed to create a model that could be used for and as a basis of further entanglement simulation.

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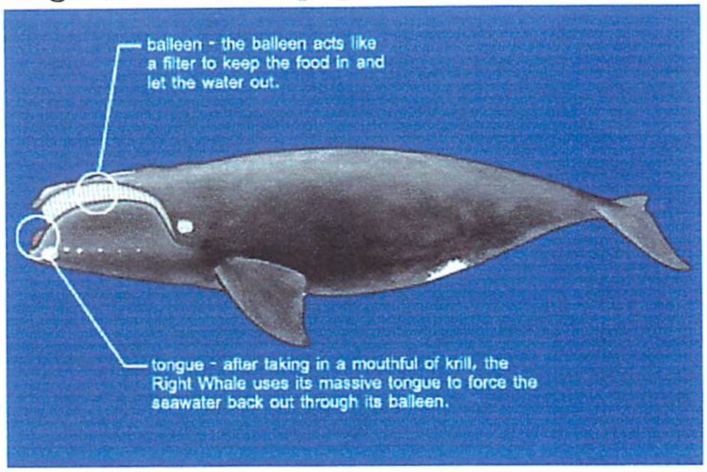
## Appendix

## *Appendix 1: Whale fact sheet.*

### Everything you wanted to know about right whale in one page

Scientific name: *Eubalaena glacialis*




Classification:

| | |
|---|---|
| Kingdom | Animalia |
| Phyla | Chordata |
| Sub-phyla | Vertebra |
| Class | Mammalia |
| Order | Cetacea |
| Sub-order | Mysticeti |
| Family | Balaenidae |

Common name: North Atlantic Right Whale. Named because it was the 'right' whale to hunt.

Status: Critically endangered

Population: Approximately 300-350 individuals in the western North Atlantic.

How big are the right whales?

Adult : 45-55 ft (14-17 m) and about 139,700 lb (63,500 kg).

Calf : 15-20 ft (4.5-6 m) and weigh approximately 1 ton at birth.

What is that funny stuff hanging in a whale's mouth? Baleen, which is made of keratin (the stuff your fingernails are made of). Baleen can reach a maximum length of 5 m with an average of 300 plates on either side.

What does the whale use the baleen for? Baleen acts like a giant strainer. Because whales eat such tiny food, the baleen traps the food and the water runs out of the mouth.

How big is a right whales head? The head is enormous, close to one-third the body length.

How many blow holes does a whale have? Baleen whales, like a right whale have two distinct nares. However, toothed whales like a dolphin have one nare.

Are males bigger than females? No. Adult females are typically larger than adult males

What do right whales eat? Tiny crustaceans called Copepods.

How much do whales eat a day? Whales eat an average of 750,000 kg per day

What is the body temperature of a whale? 36 degrees Celsius (96.8 Fahrenheit)

How often do the females have young? Every 3-5 years is the typical calving interval.

Where do the North Atlantic right whales live? Right whales move from sub polar regions with the onset of winter to lower latitudes. Some good areas to see them are from Cape Cod north to the Bay of Fundy. Depending on the time of year,, right whales will spend much of their time near bays and peninsulas and in shallow, coastal waters.

Fun Facts:

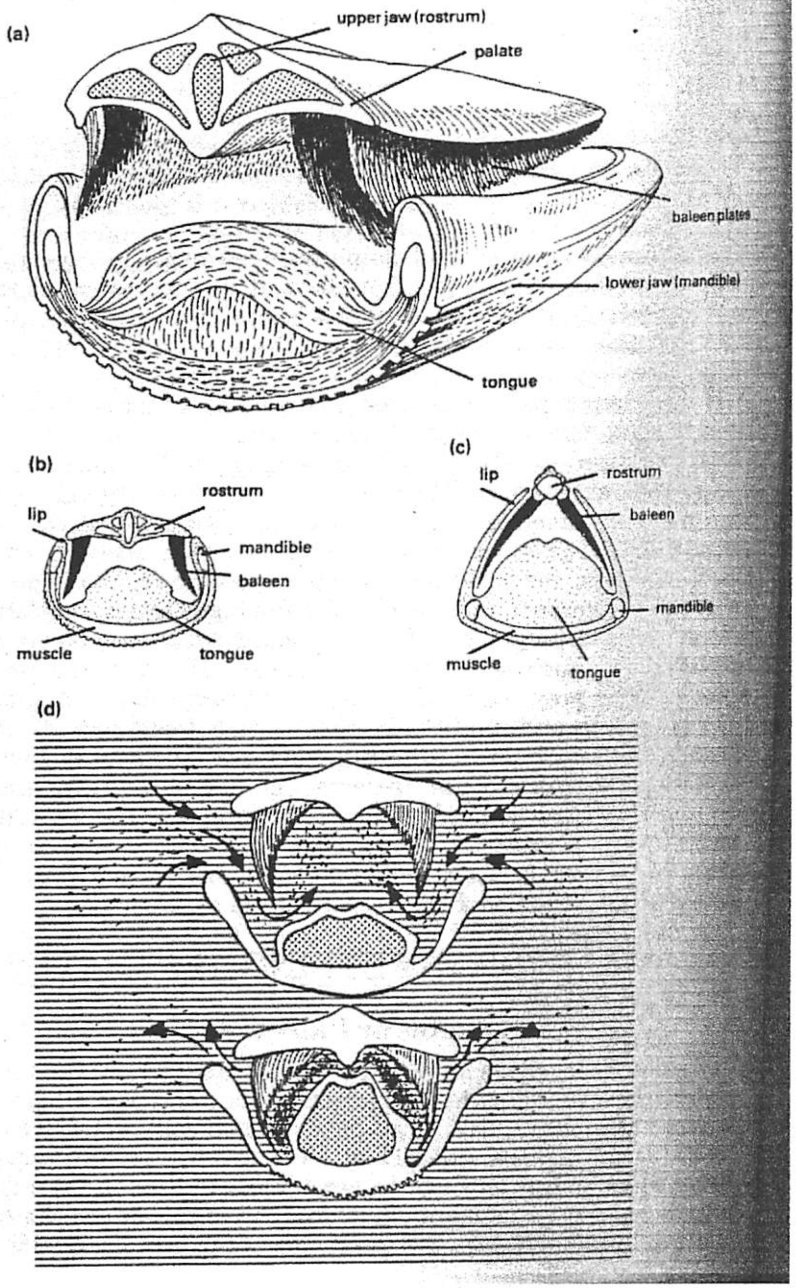
- Right whales have the greatest amount of blubber compared to all the whales. It comprises 36-45% of the total body weight.
- Right whales are identified by using their callosity pattern which contains roughened skin patches, barnacles, and whale lice (cyamids).
- The right whale has no dorsal fin unlike other cetaceans.
- Over 50% of Northern right whales and New England humpback whales have scars from prior fishing gear entanglements.

**Reference: The North Atlantic Right Whale Consortium. http://www.rightwhaleweb.org.**

## *Appendix 2: Baleen whale head structure and filter feeding*

Evans, Peter. 1987. The Natural History of Whales and Dolphins. Helm, London.

*Figure 6.1 How baleen works. (a) Cross section of head of baleen whale. (b) In rorquals such as the sei whale, the broad, gently curved rostrum and expandable throat grooves allow the mouth to open widely to engulf food organisms in a large quantity of water. The water is then sieved through the spaces between the baleen plates as the mouth closes, the throat grooves tighten up and the tongue is raised. Food material such as plankton is retained on the bristles lining the inner edges of the baleen plates before being swallowed. (c) The right whales represent the opposite extreme, with a long narrow rostrum and much longer baleen plates. They feed by skimming the surface, collecting food organisms on their baleen, and then dislodging the food with the tongue. Nevertheless, the principles of filter-feeding through baleen are similar (see (d))*



## *Appendix 3: Reynolds Scaling Calculations*

$Uw := 0.5\frac{m}{s}$ $\quad Lw := 15m$ $\quad \nu := .000001002\frac{m^2}{s}$

$Reynolds := \frac{Uw \cdot Lw}{\nu}$ $\quad Reynolds = 7.485 \times 10^6$

For Reynolds' scaling, the Reynolds numbers must be equal. Because we will be using water, the viscosity will be the same. Therefore, the equation to obtain the model velocity based on a length scale and the original parameters of the whale will be as follows.

$Lm := 1.5m$

$Um := \frac{Uw \cdot Lw}{Lm}$ $\quad Um = 5\frac{m}{s}$

The right whale's width is approximately 3.66 m; this was also scaled down and used along with the length in determining the volume and mass of the model. The model volume was approximated by using the volume of half a cylinder of the same length and diameter.

$Wm := 0.366m$

$Volm := \frac{\left(\frac{Wm}{2}\right)^2 \cdot \pi \cdot Lm}{2}$ $\quad Volm = 0.079\,m^3$

$Mm := Volm \cdot \left(998\frac{kg}{m^3}\right)$ $\quad Mm = 78.749\,kg$

Because of Reynold's scaling, the drag force on the model will be the same no matter the scale. However, it will changed based on the geometry of the head. The closed mouth was modeled as a sphere for these calculations, while the open mouth was modeled as a parachute.

$\rho := 1000\frac{kg}{m^3}$

$Fclosed := 0.5 \cdot 0.42 \cdot \rho \cdot Um^2 \cdot \frac{Wm^2}{4}$ $\quad Fclosed = 175.817N$

$Fopen := 0.5 \cdot 1.4 \cdot \rho \cdot Um^2 \cdot \frac{Wm^2}{4}$ $\quad Fopen = 586.058N$

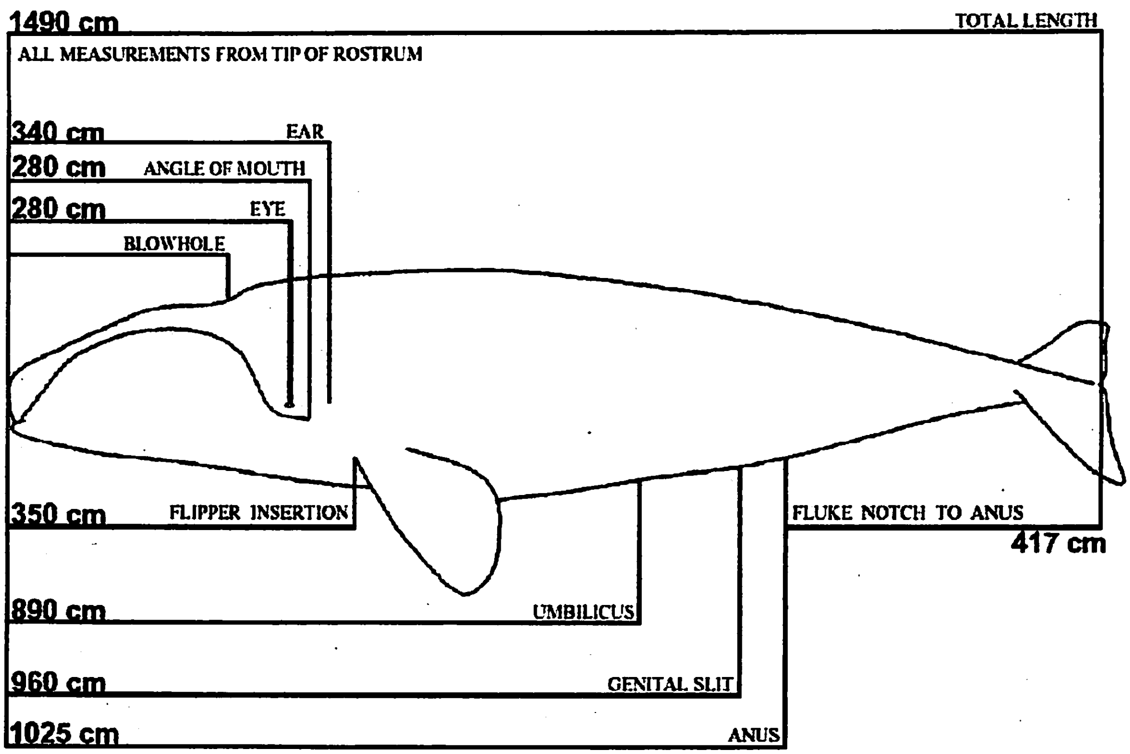
| velocity (m/s) | Length (m) | scale | model L | model wid | vol | mass (kg) | model v m/s |
|---|---|---|---|---|---|---|---|
| 0.5 | 15 | 1.0000 | 15.000 | 3.657 | 78.777 | 78619.741 | 0.5 |
| | | 0.5000 | 7.500 | 1.829 | 9.847 | 9827.468 | 1.0 |
| | | 0.3333 | 5.000 | 1.219 | 2.918 | 2911.842 | 1.5 |
| | | 0.2500 | 3.750 | 0.914 | 1.231 | 1228.433 | 2.0 |
| | | 0.2000 | 3.000 | 0.731 | 0.630 | 628.958 | 2.5 |
| | | 0.1667 | 2.500 | 0.610 | 0.365 | 363.980 | 3.0 |
| | | 0.1429 | 2.143 | 0.522 | 0.230 | 229.212 | 3.5 |
| Chosen Scale | | 0.1250 | 1.875 | 0.457 | 0.154 | 153.554 | 4.0 |
| | | 0.1111 | 1.667 | 0.406 | 0.108 | 107.846 | 4.5 |
| | | 0.1000 | 1.500 | 0.366 | 0.079 | 78.620 | 5.0 |
| | | 0.0909 | 1.364 | 0.332 | 0.059 | 59.068 | 5.5 |
| | | 0.0833 | 1.250 | 0.305 | 0.046 | 45.498 | 6.0 |

| L*v/viscosity | Fdrag = .5*Cd*v^2*d^2/4 | | 0.5mv^2 |
|---|---|---|---|
| | Cd = 1.4 | Cd = 0.42 | |
| Re | Fdrag open | Fd closed | KE model |
| 7485030 | 585.097 | 175.529 | 9827.468 |
| 7485030 | 585.097 | 175.529 | 4913.734 |
| 7485030 | 585.097 | 175.529 | 3275.823 |
| 7485030 | 585.097 | 175.529 | 2456.867 |
| 7485030 | 585.097 | 175.529 | 1965.494 |
| 7485030 | 585.097 | 175.529 | 1637.911 |
| 7485030 | 585.097 | 175.529 | 1403.924 |
| 7485030 | 585.097 | 175.529 | 1228.433 |
| 7485030 | 585.097 | 175.529 | 1091.941 |
| 7485030 | 585.097 | 175.529 | 982.747 |
| 7485030 | 585.097 | 175.529 | 893.406 |
| 7485030 | 585.097 | 175.529 | 818.956 |

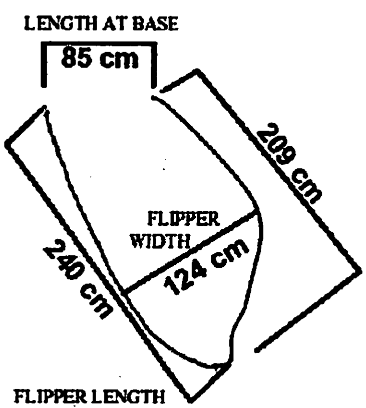
## Appendix 4: External Morphometrics

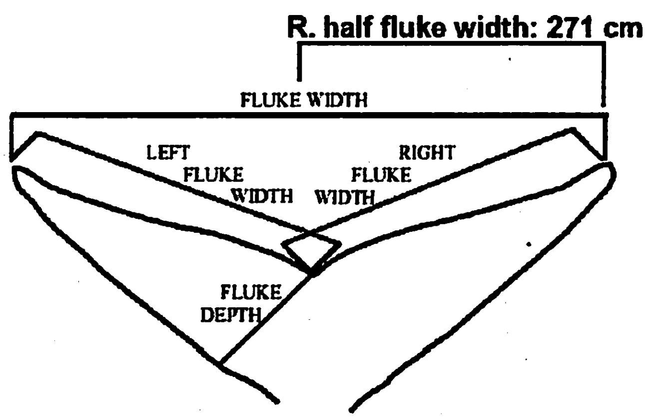
# Right Whale External Morphometrics

WRITE MORPHOMETRICS ON LINES




**Right flipper measured:**



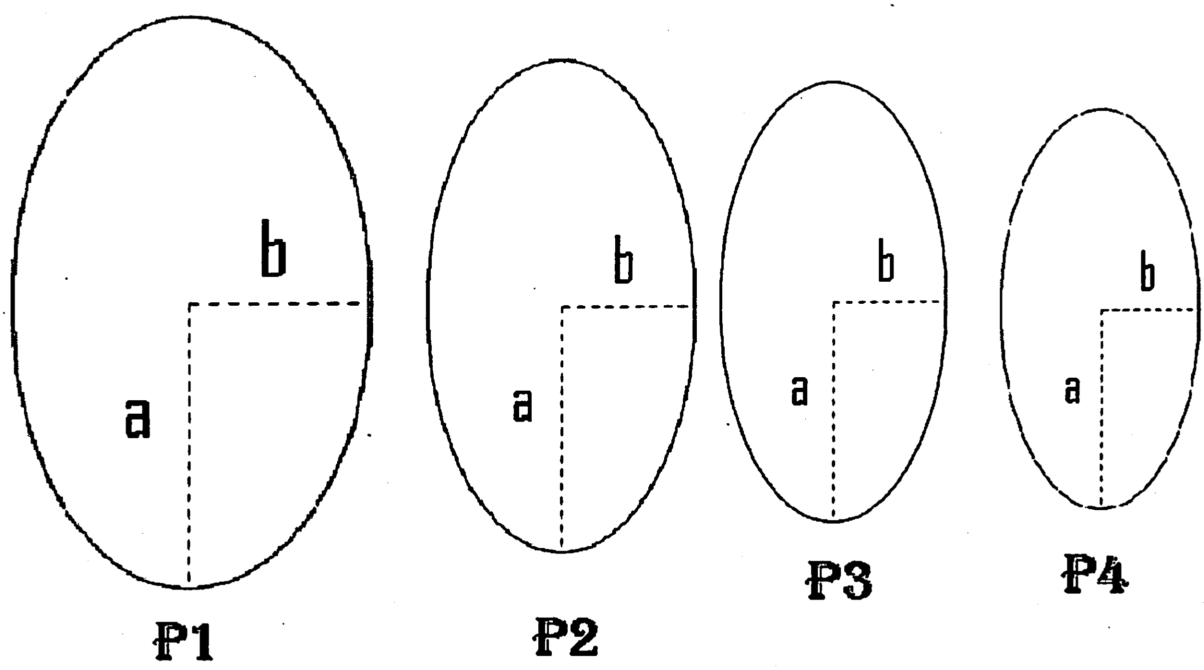




Fluke insertion

**Peduncle girths measured every 20 cm, measurements in cm:**

| | | | | | | |
|---|---|---|---|---|---|---|
| 365 | 332 | 296 | 262 | 230 | 215 | 207 |

## *Appendix 5: Calculations for the design of the peduncle*




| Ellipse calculations in meters | | | | | |
|---|---|---|---|---|---|
| | **Perimeter** | **a(unscaled)** | **b(unscaled)** | **width** | **height** |
| P1 | 3.65 | 0.64407 | 0.51 | 1.02 | 1.28814 |
| P2 | 2.96 | 0.546297 | 0.3813 | 0.7626 | 1.092594 |
| P3 | 2.3 | 0.4386 | 0.275 | 0.55 | 0.8772 |
| P4 | 2.07 | 0.376099 | 0.275 | 0.55 | 0.752198 |

## *Appendix 6: Body cross section measurements*

| Body section | length from point A to point B (m) | |
|---|---|---|
| | un-scaled | scaled |
| A | 2.71 | 0.344564526 |
| 1 | 3.05 | 0.387794024 |
| 2 | 3.56 | 0.452638271 |
| 3 | 3.7288 | 0.474100445 |
| 4 | 3.7288 | 0.474100445 |
| 5 | 3.686 | 0.468658614 |
| 6 | 3.644 | 0.4633185 |
| 7 | 3.5 | 0.445009536 |
| 8 | 3.305 | 0.420216147 |
| 9 | 2.711 | 0.344691672 |
| 10 | 2.2 | 0.27972028 |

## *Appendix 7 : Towing Structure Calculations*

Tow structure is 80 inches tall - 12 inches across tow carriage, 26 inches to water, and 42 inches to whale. Calculation on front beam uses this measurement.

$Lbeam := 80in$ $\quad Fdrag := Fclosed$ $\quad Fdrag = 38.24lbf$

$Moment := Lbeam \cdot Fdrag$

$Moment = 345.643N\,m$ = 3060 in-lb

## *Appendix 8: Purchase estimates for Camera*

Quote 905207 on April 5, 2005 by UNDERWATER PHOTO-TECH LLC Derry, NH.
Cost: $12,032.95

# Quotation

UNDERWATER PHOTO-TECH LLC
16 MANNING STREET
SUITE 104
DERRY, NH 03038
USA
603-432-1997

**Quote Number:** 905208
**Quote Date:** Apr 5, 2005
**Page:** 1

**Quoted to:**

UNIVERSITY OF NH
ACCOUNTS PAYABLE
11 BOOKWAY
DURHAM, NH 03824-3561

**Ship To:**

UNIVERSITY OF NH
DEPT OF ZOOLOGY-LARRY HARRIS
FIRST FLOOR- RUDMAN
DURHAM, NH 3824

| Customer ID | Good Thru | Payment Terms | Sales Rep |
|---|---|---|---|
| UNH | 5/5/05 | Prepaid | FRED |

| Quantity | Item | Description | Unit Price | Extension |
|---|---|---|---|---|
| 1.00 | SODCR-HC1000 | SONY HC-1000 MINI DV CAMCORDER 3 CHIP | 1,699.00 | 1,699.00 |
| 1.00 | 852-0094 | L&M BLUEFIN HC1000 HOUSING | 2,999.00 | 2,999.00 |
| 1.00 | 802-0177 | UWA100 WIDEANGLE LENS | 4,000.00 | 4,000.00 |
| 1.00 | 802-0122 | BLUEFIN REMOTE MONITOR | 1,699.00 | 1,699.00 |
| 1.00 | 680-0070 | REMOTE MONITOR EXT. CORD 50' | 350.00 | 350.00 |
| 1.00 | 680-0083 | VIDEO OUT WHIP | 250.00 | 250.00 |
| -0.10 | | PACKAGE DISCOUNT | 10,997.00 | -1,099.70 |
| | | | **Subtotal** | 9,897.30 |
| | | | **Freight** | |
| | | | **Total** | 9,897.30 |

Quote 905208 on April 5, 2005 by UNDERWATER PHOTO-TECH LLC Derry, NH

***Cost: $9,897.30***

## *Appendix 9: Data sheet*

**North Atlantic Right Whale Model Testing**

**General Information**
Date:______________________
Time: ______________________
Trial: ______________________

**Tow Characteristics**
Depth in water: ______________________
Travel speed: ______________________
Rotation (in turns): ______________________
Speed of rotation: ______________________

Observations: ______________________

Problems associated with tow:

## *Appendix 10: Tow on April 22, 2005*

Testing
Friday, April 22 2005

The tow structure was attached without incident to the tow carriage at 7:30 am. The camera was turned on before the tow structure was put in the water, but it was not set to record. The whale was then attached to the bottom of the tow structure by two divers. When they finished attaching it, one of them warned that the pole was no longer fixed inside the whale, meaning that the whale could now rotate on the pole. It was not considered a big problem because the tow carriage would be pushing it, and the pole could only be removed through the back of the whale.

The camera was then checked to make sure that it was on. It was not. This required taking it out of the underwater housing and turning it back on. The underwater housing must be removed from the towing structure and brought up to the surface to be opened, which turned out to be a bit of a chore, even with it designed so only two bolts had to be removed. After the camera was turned on again, it was reinserted into the housing, and replaced on the towing structure. This time, it was also set to record so that it would not shut off if it had a battery-saving shutoff timer.

The tests needed to be run at 4 knots, but to make sure that the tow structure and whale were sturdy enough to take this speed; it was decided to make a run at 1 knot, then 2 knots, then 3 and 4 knots. The run at 1 knot went without incident. At 2 knots, the whale slipped a little ways off the pole when the carriage rapidly decelerated at the end of the tank. A long tank hook was used to try pushing the whale back onto the pole, but to no avail. After trying to accelerate it at a high rate to try to slide it back onto the pole that way, the carriage decelerated at a high rate and the whale slid the rest of the way off of the pole. It was interesting to note that the whale sailed off nicely, making a slight turn to the left as it slowly floated to the surface. Once it reached the surface, only the top of the tail and a bit of the back of the whale were above the water; it was only slightly buoyant, which is exactly what it should have been.

One diver was called back at this time to reinsert the pole into the whale. After this was done, the whale was lashed to the tow structure using the peduncle to prevent any further slipping off of the pipe. The three knot run was abandoned, because the tow structure and whale seemed adequately stable enough to undergo 4 knots. The first run at 4 knots broke the tow carriage system, however. At the startup acceleration, the carriage jiggled a bit and caused the steel cable drive train to jump off its track. One hour passed before this was completely fixed. After the cable was replaced on the track, the tension in the system was increased to compensate for any bumpiness caused by the acceleration.

Once the carriage was fixed, a second test run at 4 knots was attempted. This time, the carriage worked fine, but the drag force on the front of the whale caused the whale to be pushed back onto the pipe, and the pipe to break through the nose. Luckily, there was a two-foot section in front of the 8-foot section that could be easily removed so that testing could continue without interruption.

The test runs were now complete, and a real run was setup using fluorescent pink mason line as the model fishing gear. An eighteen-pound weight was attached to the bottom of the line as an anchor, and the top was suspended at the water's surface using a scaled lobster buoy. The line was 11 feet, 3 inches long. After this was put in the water, a run was attempted, but the line had floated away from the center of the tank, and the whale missed it. To avoid this, the line was shortened by two feet. The test was then run again, and this time the whale was caught in the rope by the flipper. It was observed that the line cut all the way through the neoprene on the flipper, down to the fiberglassed wood.

This was the last run due to time constraints - the camera had to be returned at noon, and it was 11:15. After the camera was removed from the tow tank, it was discovered that the tape inside only had 100 minutes of film time, which had been used up shortly after the whale slid off the pipe, so the actual run was not taped. There are still pictures of the actual run, however.