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Development of two automated feed buoys for submerged fish aquaculture net-pens

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DEVELOPMENT OF TWO AUTOMATED FEED BUOYS FOR SUBMERGED FISH AQUACULTURE NET-PENS

BY

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THESIS

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DEDICATION

I would like to dedicate this work to my wife, Amy Fullerton, and to my parents, Robert Fullerton and Cindi Curtis, for the encouragement they gave me to finish this writing.

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I would like to thank a few key individuals who contributed to this project and helped me complete this research and thesis work. Thank you:

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NOMENCLATURE

Symbol	Description
a	amplitude
b	damping coefficient
B	buoyancy force
c	restoring force constant
C_d	drag coefficient
D	depth
f	frequency
g	gravitational constant
gm	metacentric height
H	wave height
Hs	significant wave height
I_v	virtual mass moment of inertia
k	spring constant
K	wave number
L	wavelength
m	mass or meter
m_v	virtual mass
n	cycle
r	radius
R	logarithmic decrement
S	water plane area
t	time
T	period
T_d	damped natural period
V	Volts
x	position/displacment
x	velocity
x	acceleration
x_n	amplitude, n
ζ	damping ratio
ρ	density
η	water surface position
ω	angular frequency
ω_n	undamped natural frequency
ω_d	damped natural frequency

ABBREVIATIONS

AGM	Absorbed Glass Mat battery type
CAD	computer aided design
cm	centimeter
COTS	commercial-off-the-shelf products
FAQ	frequently asked questions
FEA	finite element analysis
gph	gallons per hour
gpm	gallons per minute
GPS	Global Positioning Systems
hp	Horsepower
JACOE	Jere A. Chase Ocean Engineering laboratory and building
kN	kilonewton
kW	kilowatts
MCU	microcontroller unit
NH	New Hampshire
NDBC	National Data Buoy Center
NEC	National Electric Code
NOAA	National Oceanic and Atmospheric Administration
OOA	Open Ocean Aquaculture
OPIE	Optical Positioning Instrumentation and Evaluation System
PLC	Programmable Logic Controller
PNS	Portsmouth Naval Shipyard
PVC	Polyvinylchloride
RAO	Response Amplitude Operator
rpm	revolutions per minute
SCUBA	Self-Contained Underwater Breathing Apparatus
SS	Ocean Spar's SeaStation™ fish cage
SSC	Seacoast Science Center
UNH	University of New Hampshire
VDC	Volts Direct Current
WHOI	Woods Hole Oceanographic Institution

Units of Measure:

Note: The author attempts to use scientific (SI) units when possible. However, due to the nature of commercial products available in the United States market, English units are supplemented when necessary.

ABSTRACT

DEVELOPMENT OF TWO AUTOMATED FEED BUOYS FOR SUBMERGED FISH AQUACULTURE NET-PENS

by

Brett Fullerton

University of New Hampshire, May 2007

Two prototype research feed buoys, designed with a feed capacity of a quarter-ton and one-ton respectively, were designed, modeled, constructed and field-tested to support raising aquaculture finfish in submerged cages at the University of New Hampshire's Open Ocean Aquaculture Demonstration site. These two buoy systems consisted of a surface buoy, moorings to a submerged fish cage mooring, feed dispensing machinery, feed transfer hose and buoy telemetry and control systems. Numerical finite element analysis and physical model scale wave tank testing were performed on both feed buoys. Various mooring concepts were also tested. Both buoys were moored close to the aquaculture cages using compliant mooring members, which allowed motion through tidal, current and storm wave conditions. Feeding mechanisms consisted of feed dispensing equipment and centrifugal pumps to actively force a feed and seawater mixture down to fish in the submerged cages.

The first buoy, with a quarter-ton feed capacity, was battery-powered and recharged by both a wind generator and two solar panels. A control system managed the operation of the feed equipment, and telemetry sent diagnostic and system status information back to shore to the project manager. The quarter-ton feed buoy was deployed to the University's aquaculture site in early December 2002. After correcting initial start-up problems, the buoy operated for many years enabling beneficial, metered and regular feeding to the caged fish.

To meet immediate needs of an expanding aquaculture operation, a larger one-ton capacity feed buoy was designed, built and deployed to the aquaculture site within a ten-month period. This buoy had a similar design to the quarter-ton feed buoy, but was scaled larger to hold a greater amount of fish feed. One significant innovation on this buoy was the onboard diesel generator, which was necessary to power industrial feed equipment, as well as to charge the buoy's battery bank. In case of generator failure, the buoy's control system received its own power from an internal battery bank, which was charged from solar panels and/or the generator.

The larger one-ton feed buoy was deployed to the aquaculture site in early December 2003 and, after overcoming the complexity of remotely starting and controlling the diesel generator, the buoy supplied greater amounts of feed to the fish cages than was previously possible. After operating for just one year, the one-ton feed buoy sank during a Nor'easter storm in late December 2004. On examination of the salvaged buoy seven months later, it appears a weld failure in the feed system was the root cause of flooding and the ultimate sinking of the buoy. Despite the unfortunate loss of the one-ton feed buoy, the research discussed in this thesis will likely serve as a basis for developing future commercial aquaculture feeding systems suitable for an open ocean environment.

CHAPTER 1 -

INTRODUCTION

1.1 Purpose

As finfish aquaculture inevitably moves offshore away from sensitive and valuable coastal regions, one significant hurdle to successful open ocean finfish aquaculture is the ability to supply an adequate amount of feed to the caged fish in a scheduled and cost-effective manner. Feed and feeding schedules are both crucial factors to the viability and economics of raising healthy, marketable aquaculture finfish. For these reasons, two prototype feed buoys were developed by University of New Hampshire's (UNH) Open Ocean Aquaculture (OOA) Demonstration Project to contain and dispense large amounts of pelletized fish feed to submerged cages, containing either haddock, halibut or cod fish species at the time. The two research prototype feed buoys were designed, modeled, fabricated and field-tested to support the UNH OOA project, a National Oceanic and Atmospheric Administration (NOAA) funded research project to study the feasibility of and promote an offshore aquaculture industry in the Gulf of Maine. The first feed buoy developed had a feed storage capacity of approximately 250 kilograms (approx. 550 lbs) and hence took the title of the "quarter-ton" feed buoy. This buoy was battery-powered with charging from both wind and solar power generation units. Based on the successful learning experience of this quarter-ton feed buoy design and deployment, a second feed buoy was developed to have a larger, one thousand kilogram feed storage capacity. This "one-ton" capacity feed buoy contained a five-kilowatt diesel generator to meet the feed system's greater power demands. Control of the feeding systems, including frequency and volume of feed dispensed, was all accomplished remotely from a computer onshore. The feed buoys saved both time and money and were safer for researchers since they did not have to be onsite during feed times. Before the feed buoys were deployed feeding the caged fish was not always possible because of bad weather, personnel and boat schedules. Remote operation and communication to the feed buoys was achieved using radio telemetry systems between the buoy and a shore station. Once on shore, or vice versa, the signal traveled via the internet allowing access and control to the project manager virtually anywhere in the world.

1.2 Background

Current aquaculture practices and methods, such as the raising of farmed salmon in the Gulf of Maine, normally occur in bays and harbors relatively close to land and protected from damaging waves and current. The UNH OOA Demonstration Project was initiated in 1997 to research the feasibility and possible promotion of an offshore aquaculture industry in New England. The advantage of offshore finfish aquaculture is that abundant deep water and currents provide a cleaner and therefore healthier environment to raise fish, while at the same time, minimizing the environmental pollution and impact of fish farming. Since 1998, UNH has used the OOA Demonstration research site, seen in Figure 1, which is approximately ten kilometers from the New Hampshire coast and two kilometers south of Isles of Shoals of New Hampshire in the Gulf of Maine. Approximate coordinates of the UNH OOA Demonstration site are 42° 56.55' North and 70° 37.94' West.

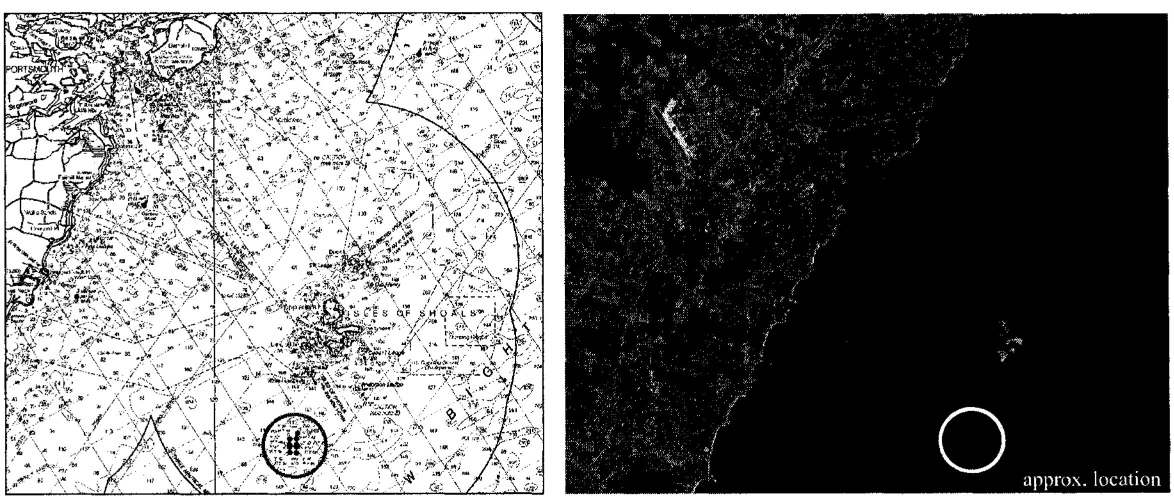


Figure 1: NOAA chart #13278 (left) and aerial view from Google Maps (right) showing the relative positions of the permitted OOA site to the Isles of Shoals and the coast of NH.

Permitted through the State of New Hampshire, this research site is used to explore the engineering, biological, environmental and operational aspects of offshore fish aquaculture (Muller, 2002).

To contain the aquaculture fish, two 600 m^3 Ocean Technologies SeaStation™ cages (SS600) were deployed at the UNH OOA research site in 1999. (Fredriksson et al., 2000 and Baldwin et al., 2000). Each cage had its own independent grid mooring system as shown in the schematic of Figure 2. The mooring system was held in place by a total of eight one-ton embedment anchors, which had an average depth of 52 meters and a generous three-to-one scope. The fish cages were held in position by four bridle lines, which were attached to the corners of the submerged, square grid. Tension of the grid corner was maintained by submerged buoy floats, which averaged 18 meters in depth. Finally, the vertical position of the cage is held fixed by a taut pendant, which is attached to a dead weight on the bottom. These two central spar fish cages were the focus of an intense engineering and operational analysis for many years to prove that such systems could survive conditions of the open ocean. Numerical finite element analysis modeling and physical wave tank model testing were conducted to better understand submerged fish cage and mooring dynamics with the goal that suitable engineering methods and equipment could be developed to cost-effectively deploy open ocean aquaculture fish cage systems (Palczynski, 2000; Tsukrov et al., 2000; Tsukrov et al., 2003; Fredriksson et al., 2003).

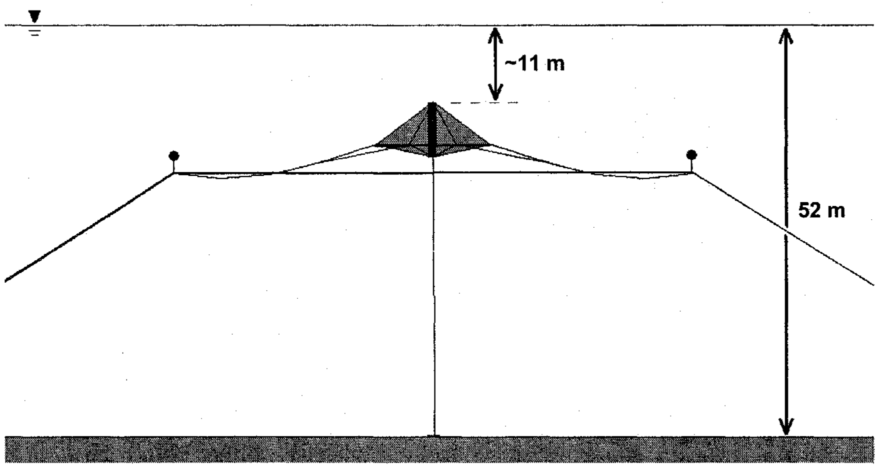


Figure 2: Schematic of single cage grid mooring system

By the year 2003, the OOA project expanded with a larger Ocean Spar SeaStation™ 3000 m^3 (SS3000) central spar fish cage shown in Figure 3. This cage was added because the existing SS600 fish cages were considered small, due to the limited number of fish each SS600 cage could contain. The motivation behind adding this additional cage was to increase the project's finfish bio-mass closer to that of a commercial aquaculture scale so that a proper commercial economic assessment could be investigated. Although offshore aquaculture techniques and methods were being developed at a smaller scale, new engineering challenges existed, including feeding systems, which must be overcome to prove the viability of commercial-scale open ocean aquaculture.

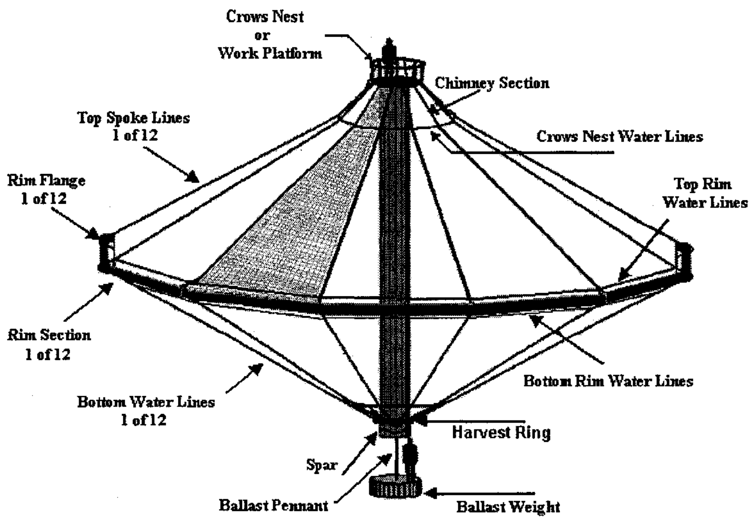


Figure 3: Schematic of SeaStation™ 3000 cage

To incorporate this new cage, the two individual fish cage grid mooring systems, which had been deployed at the OOA site since 1999, were dismantled and replaced by a new four-cage grid mooring system depicted in Figure 4.

Figure 4: Schematic of four-cage grid mooring system over seafloor topography.

The four-cage mooring also enabled the deployment of a possible fourth fish cage in the future should the OOA project grow larger (Fredriksson et al., 2004). However, along with greater fish populations and bio-mass, the immediate need for larger surface feeding platforms and feeding systems became apparent (Rice et al., 2003; Fullerton et al., 2004).

Supplying sufficient and regular doses of fish feed to species contained in a submerged aquaculture cage has always been a major challenge to successful offshore finfish aquaculture. It has been shown that a regular feeding schedule, along with ample amounts of feed, are crucial to the growth rate of cultured fish (Chambers, 2003). Conversely, any uneaten feed pellets that pass through the cage are a significant economic loss and introduce waste into the environment.

Dependable and automated feeding systems must be developed for open ocean aquaculture to grow and become a success. Such systems built for the open ocean environment and supplying feed to submerged fish cages were not commercially available at the time. This includes multiple components which make up the mechanical systems; many of which are commercial-off-the-shelf (COTS) products that are modified to work in the harsh offshore marine environment. Pioneering work in the concept design and development of offshore feeding has been reported by Willinsky et al. (1994, 1995, 1997). Offshore radio telemetry techniques have also been addressed by Kimura et al. (1993). Although specialized feed boats, buoys and barges are currently used in aquaculture farms, where large surface cage arrays are located in relatively sheltered waters, rather little research or work has been accomplished on feeding submerged cages in extreme offshore environments (Swanson, et al., 2004). Typically the companies who fabricate inshore and near-shore aquaculture feeding systems claim their commercial systems will handle offshore conditions; however, these designs are relatively untested and unproven for true open ocean environments. The location of the UNH OOA Demonstration site in the Gulf of Maine is capable of experiencing severe open ocean storm and wave conditions.

Gael Force Ocean Technologies, a Scottish company, builds large circular concrete feed buoys, called C-Cap buoys, shown in Figure 5. These systems have very large feed storage capacities between fifty and three hundred tons. However, as previously mentioned, these feed buoys are usually located in bays and harbors protected from large storm waves. Even if the C-

Cap buoys could survive the OOA project's site conditions, a shortcoming of this system is that the feed pellets are conveyed via high-velocity air forced through a floating PVC hose from the buoy to the surface cage. A sprinkler is used above the cage to spread feed through the air as it sinks inside the cage. Because the OOA fish cages are typically submerged, usually around ten meters to evade damaging surface wave energy, such an air-conveyed system would not work for the OOA project. It would be nearly impossible and impracticable to force air and feed down to the cage due to the pressure of seawater pushing against it. It was also well-known that air bubbles, usually from SCUBA divers, frightened the caged fish. A second disadvantage to the Gael Force feed system involved the risk that the hose at the surface may become entangled in boat traffic or among other feed hoses in varying surface conditions.

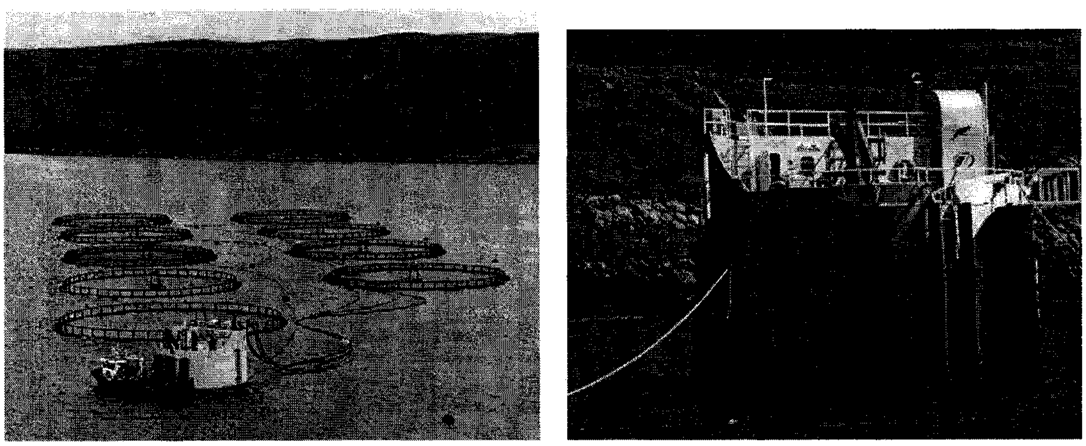


Figure 5: Gael Force C-Cap™ feed containers **(Gael Force™ website)**

Earlier in the UNH OOA project, without an automated way to feed caged halibut or haddock, fish were fed by hand with SCUBA divers sprinkling food pellets either outside or inside the submerged fish cage. A later solution, that did not require divers in the water, was via a three-inch flexible PVC hose bolted to the top of the fish cage. The other end of the hose was kept at the water's surface with a mooring float. In order to feed the fish, the hose was pulled onboard a support vessel and connected to a gas-powered trash pump, which pushed water down through the hose to the cage. Feed pellets were added from a hopper into the stream of water and forced down to the submerged cage. This feeding method worked well in calm seas and has remained a backup method for feeding in case of a feed buoy system failure or clogged hose. The disadvantage to this method of feeding is that feed schedules depend greatly on the cooperation of decent marine weather, due to the exposed location of the OOA site. This severely restricts the window for feeding, which is particularly difficult during the winter months when marine sea conditions tend to be worse. During the winter months, it would be typical to feed the fish only once a week if at all. With the UNH vessels available, it is only possible to feed in Sea States two or less. This generally means waves less than 1.2 meters and winds forty kilometers per hour or less. Another disadvantage to manual feeding is that it is logistically dependent on the boat's schedule and personnel availability.

To address the problem of feeding fish in submerged cages, the Massachusetts Institute of Technology (MIT) was tasked, with support from the UNH OOA project, to develop a submersible feeding system for the SS600 cages. The MIT system developed, known as the "Robo-Feeder", was bolted directly to the top of the Sea Station™ fish cage platform as shown in Figure 6.

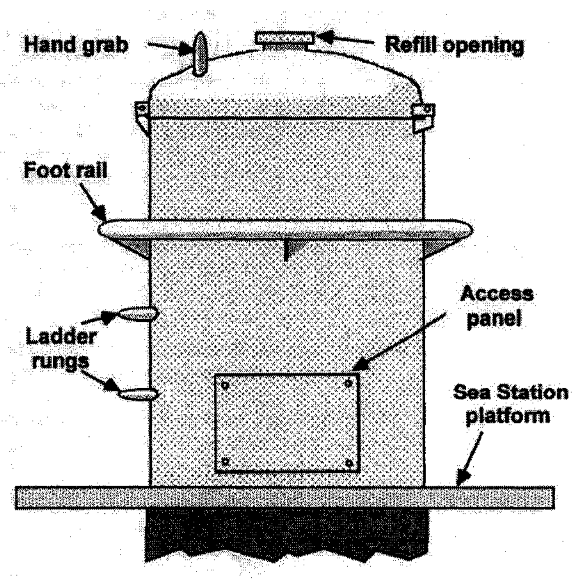


Figure 6: Schematic of MIT Robo-Feeder

Using simple digital timers, the pneumatically-operated system would open a knife valve at the base of a feed hopper for a user-set time duration to dispense the desired amount of feed. Though the Robo-Feeder system worked in the laboratory, it was not reliable while at sea due to the frequency with which the system clogged. Also, despite the initial design criteria of being able to operate submerged, the components used in the Robo-Feeder were not meant to be fully submerged underwater. Ignoring this deficiency, the real limiting factor to the Robo-Feeder design was its small feed capacity. The prototype could only contain a maximum of one hundred kilograms of feed pellets.

Driven to alleviate the frequency of feeding trips to the aquaculture site and to overcome the shortfalls of the MIT Robo-Feeder, in 2000 the UNH OOA engineering group was determined to build its own feeding system for the open ocean environment. The initial design and concept of this surface feed buoy was generated and reported by Rice et al., (2003). UNH teamed with Matt Stommel, a commercial fisherman from Woods Hole, MA who had a personal interest in aquaculture. Matt Stommel fabricated the aluminum buoy structure over the winter of 2000 and 2001. The buoy structure was then transported to the UNH Jere A. Chase Ocean Engineering (JACOE) high-bay, where it was outfitted with simple COTS equipment and tested in the JACOE six-meter deep tank. The buoy, shown in Figure 7, was deployed at the OOA site in late October 2001 off the stern of the UNH *R/V Gulf Challenger*. (Note: the red anti-fouling paint in Figure 7 marks the approximate waterline of the buoy, which was only inches from the buoy's single side access hatch.)

This buoy's feeding system, similar to the MIT Robo-Feeder, relied on gravity and sinking feed pellets to deliver feed to the submerged fish cage. Because the system lacked positive flow, the feed hose, which carried feed to the cage, would periodically become clogged. The frequency of blocked hoses, compounded by timer malfunctions, were setbacks to an operational feed system. Humidity inside the buoy also plagued the digital timers and feed equipment, which prevented the buoy from operating as it was intended. In late spring of 2002, after being deployed for seven months, the feed buoy mysteriously came loose from its mooring. The buoy drifted in the Gulf of Maine for several weeks before being reported to the US Coast Guard by a passing by fishing vessel.

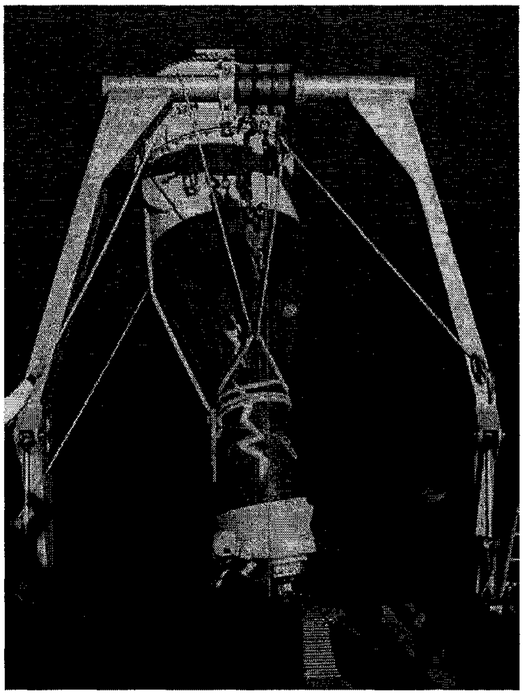


Figure 7: Photo from the original quarter-ton feed buoy deployment
(prior to the author's involvement)

It became apparent, after the drifting buoy was brought to Portland, Maine by the US Coast Guard in mid-July and retrieved by UNH, that a major overhaul to the buoy was necessary. The buoy's hull and structure were in good shape, but a complete re-design of its interior workings and feeding system design was essential. The author's involvement with the OOA feed buoy project began at this point.

1.3 Objectives

To address the challenges of feeding finfish contained in submerged offshore aquaculture cages, the following objectives were pursued for the quarter-ton capacity feed buoy:

- modify the existing quarter-ton capacity feed buoy, particularly internal feed dispensing equipment and operation
- improve the three-point mooring design
- perform field-testing at the OOA site and troubleshoot any problems or deficiencies

and for the one-ton capacity feed buoy:

- design a one-ton capacity feed buoy using knowledge and techniques learned from the previous quarter-ton buoy design
- apply finite element modeling techniques and conduct physical scale wave tank model testing
- design and analyze the buoy's mooring system
- oversee construction of the one-ton feed buoy
- procure and install all the buoy's mechanical components
- deploy the system at the OOA site for field evaluation and operational use

Generally these objectives were addressed in chronological order as written above; however, due to time constraints and aggressive deployment schedules, many objectives were worked on concurrently. The feed buoys described in this thesis may be regarded as a series of two feed buoys, each increasing in size and feed capacity as design methods and knowledge of the systems improved.

1.4 Approach

The approach for developing both feed buoys began by defining general design criteria, such as feed capacity and system voltage. Since the quarter-ton buoy structure was already constructed, the design was constrained to working with available hull structure and refurbishing the buoy's feeding systems. The one-ton capacity feed buoy, on the other hand, had to be designed completely from scratch and therefore had a greater all-encompassing scope compared to the quarter-ton feed buoy.

The general approach to designing the feed buoys was to first develop the general concept of the buoy; that is, design the basic generic hull shape, i.e. a discus, spar or boat hull or other intermediate shape. Once the hull shape was established, critical components, such as the feed hopper or feed hose connections, were located. After the general design of the buoy's hull was determined, the hydrostatics for this design were to be investigated analytically. Through an understanding of the buoy's hydrostatics, the layout of internal components like feed dispensing equipment, power supplies and circuit panel box, as well as ballasting could then be considered. As the buoy's design was finalized, the arrangement of other internal components was investigated. During the buoy's fabrication, concepts and methods for mooring the feed buoys were devised. Each mooring design underwent computer numerical and/or physical scale modeling techniques to test and validate the design. Results from numerical finite element (FE) modeling approximated the buoy and mooring system dynamic range of motion, mooring force loads and safety factors. This was an iterative process used to develop feasible mooring configurations and specifications. Physical modeling and wave tank testing was conducted to characterize the buoy's heave and pitch response characteristics as well as to detect undesirable conditions not seen in numerical models, such as mooring line chaffing, "snap-loadings" or possible buoy and cage collisions. After finalizing the mooring design, focus was placed on procuring parts for the buoy and mooring in preparation for outfitting and eventually deploying the buoy.

The basic design concept behind both feed buoys was to store a large amount of dry, pelletized fish feed above the waterline in a well-ballasted, surface spar buoy. Feed was stored above the waterline in attempts to keep it as dry as possible and minimize the chance of getting wet, since wet feed clumps easily and is likely to clog the dispensing equipment. The spar buoy was perceived as the optimal design because its small waterplane area is thought to decouple the buoy's excitation from the water's surface effects, i.e. waves. Both UNH OOA feed buoys had a low center-of-gravity, spar-like design. Due to decoupling the wave response, spar buoys generally make good vertically stable platforms. This characteristic was deemed advantageous to the OOA project and its operation. For the OOA project, the ideal buoy platform would be stable in daily typical sea conditions, like short period, wind-wave chop. If the buoy were to heave or pitch excessively in such conditions, it would be considered unsafe for the support vessel and, most importantly, to personnel to work on or near the buoy. A stable platform was also necessary for good radio telemetry links to shore. Other generic buoy shapes were considered like the discus or boat hull; however, since these designs tend to contour wave slope and amplitude, they were not given much consideration (Berteaux, 1991).

One disadvantage to the spar buoy design is that certain frequencies can excite buoy resonances creating greater amplitudes than the amplitude of the wave itself. This characteristic of spar buoys can make mooring them difficult. Large and quick excitations can cause "snap-loading," resulting in quick, high-tensile loads on the mooring and its components. Physical modeling techniques were essential to predict and possibly avoid the destructive events of snap-loading.

A second drawback to the spar buoy design is its limited interior volume. Due to the nature of the spar buoy's small cross section, the diameter limits the amount of fish feed that can be stored. The feed capacity and interior space of these feed buoys was deemed adequate for the

OOA project. However, it was noted that larger capacity feed buoys in the future would unlikely be able to store all the feed above the waterline and still remain a spar design. It is expected that larger feed buoys would have a more squat shape like the C-Caps buoys shown in Figure 5.

The following describes the approach that was used to dispense fish feed from the buoy. Feed pellets stored in the hopper were dispensed into a smaller hopper, which worked as a mixing chamber, where feed pellets mixed with seawater before being actively pumped down through a pipe in the center of the buoy. Leaving the buoy, the feed pellets and water mixture traveled through the feed transfer hose to the submerged fish cage. In an attempt to reduce the size of the centrifugal pumps, as well as to minimize the risk of clogging, the feed hose was as short and straight as possible to the fish cage. The short feed hose required that the buoy be positioned above and relatively close to the submerged cage. However, positioning the buoy too close would run the risk of its collision with the fish cage during storm conditions. To achieve the shortest feed hose possible and still minimize the chance for collision, each feed buoy was taut-moored to the submerged cage mooring grid using two or three compliant mooring members. With the robustness of the fish cage mooring, the buoy moorings were attached to grid corners of the cage moorings. Feed buoy moorings and their components were designed to be strong enough to survive severe storms, yet were sufficiently compliant not to damage the fish cage, its mooring grid or the feed buoy itself. Figures 8 and 9 show two schematics, an elevation and plan view, of the original single cage mooring grid used to moor the quarter-ton feed buoy. The quarter-ton capacity feed buoy had an elastic feed hose, which allowed the buoy to be positioned almost directly above the fish cage. The one-ton capacity feed buoy, on the other hand, because of its deeper draft, had to be moored further away from the fish cage it supplied. Later, when the individual cage mooring system was replaced with the four-cage mooring, shown in Figure 4, the quarter-ton buoy was transferred to this new cage mooring using the exact same arrangement as the single cage configuration.

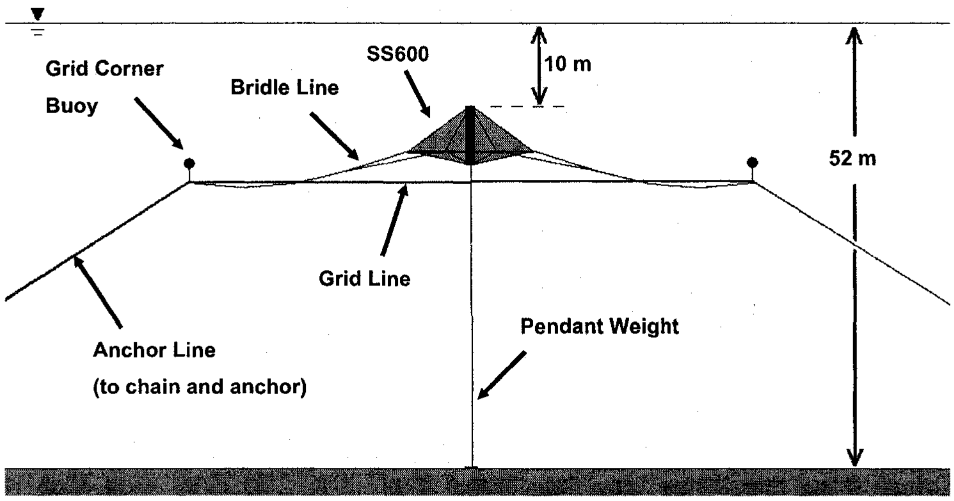


Figure 8: Elevation view of submerged cage and mooring grid at the OOA site (one of two at the site).

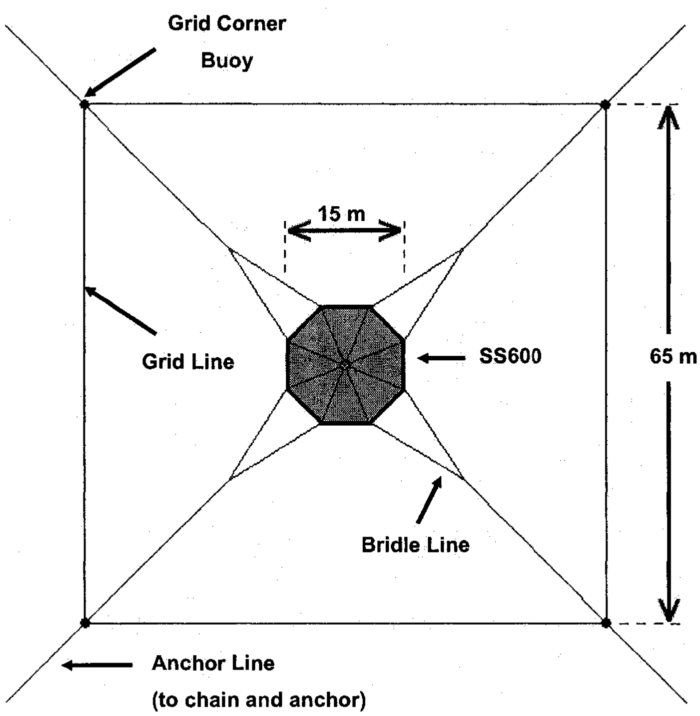


Figure 9: Plan view of the submerged cage and mooring grid at the OOA site (one of two at the site).

Construction of both feed buoys took place in Woods Hole and Bourne, Massachusetts by Stommel Fisheries. Following completion of the buoy's hull structure, each buoy was transported to UNH, where mechanical and electrical components were installed. Once ready for deployment, the feed buoy was trucked from UNH to the NH Port Authority, where the buoy was floated pier-side until final installations and modifications could be completed. The UNH *R/V Gulf Challenger*, a 50-foot aluminum research vessel, was used to transport the buoys to the OOA research site. The quarter-ton feed buoy was small enough that it was carried on the stern of the *Challenger*. The one-ton buoy was too large to have on the deck of the boat, so it was towed to the site. Once at the OOA site, each buoy was connected to its moorings and the feed hose was attached to the cage. The buoys were then prepared for field testing and operation.

Lessons and experiences learned from the development of the quarter-ton capacity feed buoy had served as the basis for the one-ton feed buoy design and development. This thesis is organized in chronological order to focus on the development of the feed buoys and their systems. This arrangement also facilitates use of this thesis as a reference, because information about each buoy is grouped together. The modifications and re-deployment of the quarter-ton feed buoy are described in Chapters 2 through 6. The design development, construction and deployment evolution of the one-ton capacity feed buoy is contained in Chapters 7 through 11.

CHAPTER 2 - QUARTER-TON FEED BUOY

GENERAL DESIGN

2.1 Design Rational / Criteria

The quarter-ton feed buoy hull structure was taken from the existing feed buoy design described in Rice et al. (2003). Basic design criteria for the quarter-ton feed buoy included the ability to store and dispense dry fish feed while operating remotely at the OOA research site. The buoy should operate remotely without assistance between feed hopper refills and periodic maintenance trips to the buoy or cage. Feed storage and conveying equipment, power supplies, and control and communication systems were necessary for the buoy to function correctly and accomplish the objectives. These systems were all contained inside the structure of the feed buoy. Feed storage capacity for this buoy was approximately five hundred pounds and, hence, became known as the "quarter-ton" buoy. Because the feed was contained above the waterline, ballasting in the form of lead was necessary to lower the buoy's center of gravity.

The quarter-ton feed buoy was built to supply a single six SS600 fish cage moored in a submerged mode approximately ten meters below the surface as seen in Figures 8 and 9. Because the fish cages were usually submerged, feed pellets had to be delivered to the cages by actively pumping seawater mixed with feed pellets to form a seawater-and-feed slurry. Conveying feed pneumatically, as practiced in commercial aquaculture farms, was not feasible for the UNH OOA project because the cages were submerged.

The quarter-ton feed buoy had a small waterplane area due to its spar-like buoy design, hence, the buoy lacked adequate reserve buoyancy to house the weight being added by the feeding system and power/control system upgrade. To overcome this buoyancy problem, an external flotation collar, discussed later on in more detail, was fabricated to slide over the outer diameter of the feed buoy. This foam collar provided enough additional buoyancy to the buoy to compensate for added weight, as well as provide an extra amount of reserve buoyancy. During construction of the buoy, described in Rice et al. (2003), the side access hatch was located lower than was originally planned, due to an interference with the main buoy flange. This created freeboard between the waterline and hatch of only a few inches.

2.2 Design Configuration

The external appearance and major dimensions of the feed buoy are shown in Figure 10 (left), while the internal arrangement of the hopper, batteries, pumps and other internal systems is illustrated in Figure 10 (right). Major design parameters, such as general dimensions and weights, are summarized in Table 1.

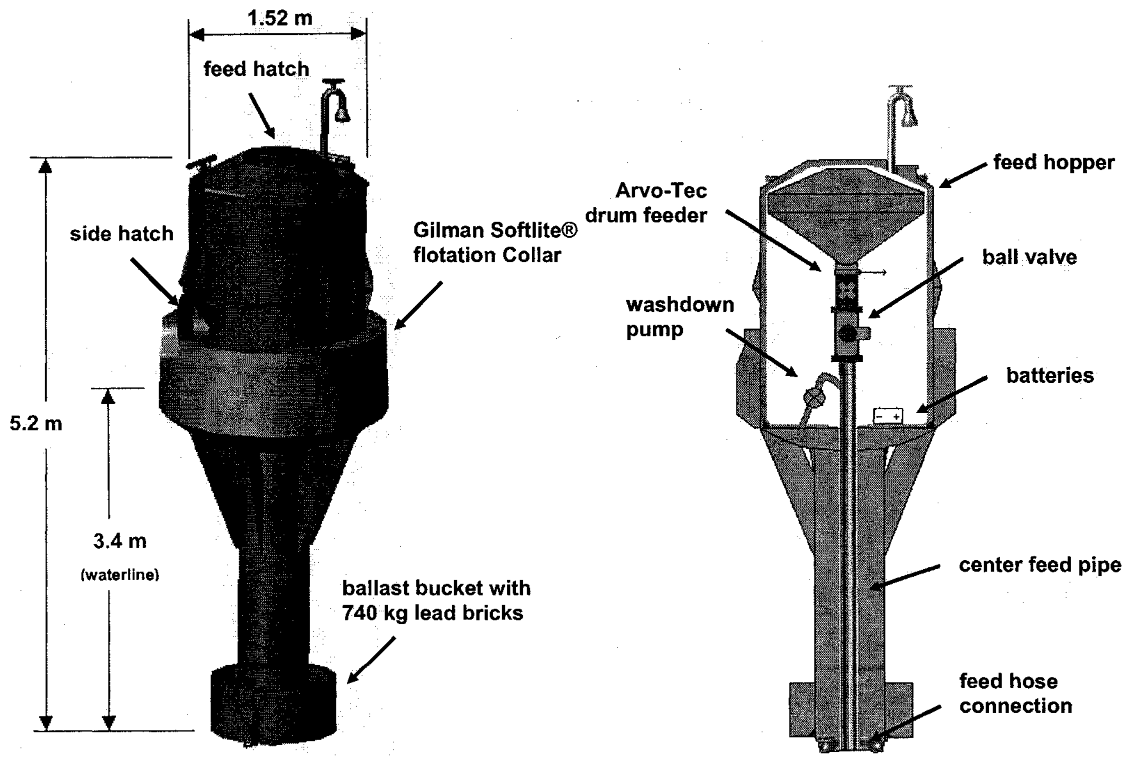


Figure 10: Schematic of buoy's external features (left) and buoy's cross-section showing internal feeding systems (right)

Table 1: Principal dimensions and weights of the quarter-ton feed buoy

Diameter (buoy structure)	1.52 m
Outer Diameter (flotation collar)	1.93 m
Overall Height (excluding antennas)	5.20 m
Draft	3.40 m
Material	aluminum
Feed Capacity	>250 kg
Ballast Weight	740 kg
Overall Mass	2040 kg
Metacentric Height	0.488 m
ratio of feed capacity/ overall buoy mass	12.3 %

From the original construction of the buoy, described by Rice et al. (2003), the main body consisted of a 1.52 meter diameter aluminum cylinder. At the base of the main body, a scrapped 1.5 meter discus buoy hull was used. The discus buoy had both a top and bottom section. The bottom served as the bottom hull base of the buoy and the top created the false deck floor inside the buoy. Below the center of the main cylinder, a 0.610 m diameter pipe section extended approximately three meters downward to the open 1.067 meter diameter ballast "bucket". This bucket held the buoy's necessary ballast in the form of brick-shaped lead ingots. Due to concern over using lead as ballast and its close proximity to fish raised for human consumption, the lead ingots were rubber-coated with a product similar to Plastisol™. The coated lead bricks were arranged evenly in the four compartments of the bucket to ensure they would not slide around and change the weight balance. Also, to make sure the bricks would not fall out in case the buoy heeled over severely; the ingots were retained by an aluminum grate fastened over the top. The large pipe used between the main cylinder of the buoy and the ballast container was heavily gusseted with six supports to stiffen the structure.

Supplemental and reserve buoyancy was provided by a 20.32 cm thick Softlite® foam flotation collar custom-built by the Gilman Corporation of Gilman, CT. Softlite® is a durable closed cell foam made of low-density Surlyn® ionomer material that is commonly used on navigational and research buoys, markers and fenders. The outermost layer of the flotation collar was heated, rolled and pressed by the manufacturer to create a hard, dense shell that increased the foam's durability. A detailed CAD drawing of the buoy's flotation collar can be found in Appendix A.

Because the design of the buoy positioned the feed hopper above the waterline, approximately 740 kilograms of lead ballast was used in the buoy's lower ballast bucket. This significantly lowered the buoy's overall center of gravity. Calculations of center of gravity, center of buoyancy, righting arms/moments and other hydrostatics using MathCAD® software can be found in Appendix B. The calculated center of gravity of the overall system, which had an overall mass of 2040 kg, was 14.4 centimeters below the center of buoyancy. These calculations yielded a metacentric height of 48.8 centimeters, indicating that a sufficient reserve righting moment was present. The extra buoyancy the flotation collar added and the calculated righting moment were viewed as essential features for survivability and safety of the buoy in the event of severe storms, icing conditions or loss of its watertight integrity. A more detailed look at the quarter-ton buoy hydrostatics is located in Appendix B.

CHAPTER 3 - QUARTER-TON FEED BUOY

INTERNAL SYSTEMS

3.1 Feed Storage, Dispensing and Distribution

For the fish species being raised, feed pellets ranged from three to fourteen millimeters in diameter, depending on the species and their age or size. These pellets were loaded through the top center hatch of the buoy and were stored in the feed hopper shown in Figure 10. This custom-built feed hopper was made of Sun-Lite® fiberglass material and held up to 250 kilograms of feed. The buoy's feed system assembly was made of multiple components as arranged in Figure 11. A four-inch manual Valterra knife valve was directly beneath the funnel opening of the feed hopper. This valve was necessary to hold back the feed in the hopper should the lower feed assembly or any components need to be disassembled and removed, i.e. to clear a clog or for periodic cleaning. The knife valve was normally left in the open position, but if necessary, was shut by sliding a manual T-handle. A rubber Fernco coupling was used to increase the diameter from the four-inch knife valve above, to a larger diameter valve below. This valve was an Arvo-Tec rotary drum feeder that was used to dispense the desired amount of pellets per feeding from the feed hopper. The feeder/valve had interchangeable plastic drums with dispensing cups of various sizes cut around the solid cylinder. The feeder's motor spun the drum at a constant rate. Thus, by changing the duration of feeding (and/or the cup size), a specific amount of feed will be dispensed from the feed hopper. Bench tests were conducted in the Jere A. Chase Ocean Engineering (JACOE) laboratory to determine the amount of seven millimeter diameter feed that was dispensed for the different dispensing cup sizes. This allowed the project manager to determine the time to run the feed system for the desired amount of feed. More information about this drum feeder/valve and its interchangeable dispensing cups can be found in Appendix C.

After the drum feeder, pellets passed through a special PVC reducing coupling back to four inches diameter to a Hayward ball valve. This electrically-actuated ball valve was a critical piece of equipment that was programmed to open at the start of every feeding sequence and close at the end. This was an important step because the ball valve prevented seawater from entering the buoy in large seas and consequently soaking internal feed or other system components.

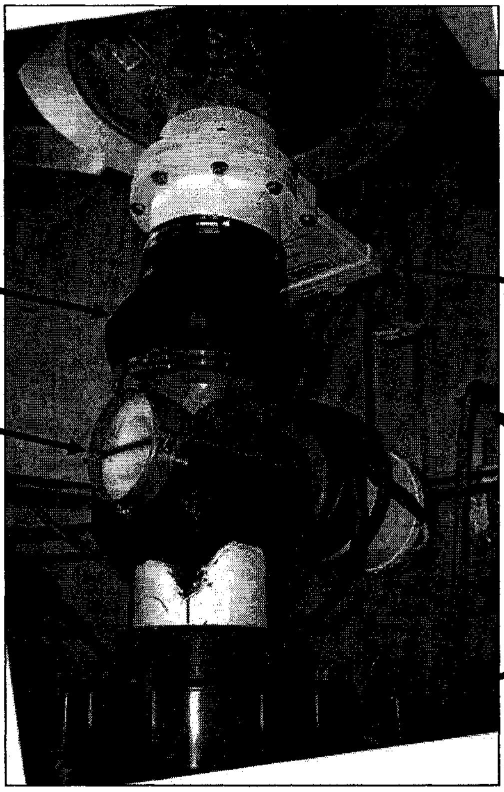


Figure 11: Internal feed system components

The ball valve was also opened and closed multiple times during a feed cycle to prevent the dynamic head of the seawater pump from rising to the dispensing feeder/valve. This was a concern because the feeder was not sealed to pressure below and seawater and salt on the dispensing cups would likely make them sticky and clog more easily. Because the ball valve was cycled during feeding, pellets left the buoy in batches or slugs. Though clogging was an initial concern, the pump was powerful enough to keep the feed pellets moving through the hose and to the cage.

Below the ball valve was a four-inch PVC 'Y' fitting, which served as a mixing chamber for the feed pellets and seawater to mix. Seawater was pumped in from the 'Y' and forced the water-and-feed slurry down through the buoy's center feed pipe, then through the feed hose to the fish cage. The seawater pump was a Rule Industries Model 16A, 24 volts DC (VDC), general purpose pump. This centrifugal pump had a maximum-possible flow rate of 3700 gallons per hour (GPH), which is about 230 liters per minute. Experiments in the JACOE deep tank, replicating the buoy's feeding system arrangement and fluid dynamic pressure head, yielded about 170 liters per minute (approximately 2700 GPH). More information and manufacturer's specifications on this centrifugal pump can be found at: http://rule-industries.com/.

Other non-feeding equipment internal to the buoy and essential to its operation included two 24-VDC Rule Industries bilge pumps. These pumps each had a maximum flow rate of 1,100 GPH and were mounted inside a 25-centimeter round bilge well, which was the lowest point inside the buoy for water collection. The size of the bilge pumps was increased from the buoy's original deployment of 500 GPH to ensure that the bilge water was making it out of the buoy and at a quick rate. These bilge pumps featured automatic, computerized water-sensing, which meant a float switch was not required. An automatic bilge pump operates by turning itself on every 2½ minutes and, if resistance is sensed by spinning the impeller, i.e. meaning that water is present, the pump will continue to run until all the water is removed. As the bilge pump ran, bilge water was forced up one meter vertically through a one-inch flexible PVC hose and out the side of the buoy, approximately eighty centimeters above the buoy's waterline. Due to the nature of the bilge area, containing spilled feed and debris, the screen filters on the bilge pumps had to be periodically checked and cleaned, if necessary, to ensure the pumps would operate efficiently when needed. Additional information on these bilge pumps can also be found at the company website mentioned above.

3.2 Power Supply

The buoy was powered by two Lifeline 12-volt, 105 amp-hour batteries, which were connected in series to form a 24-VDC battery bank. The battery type selected was an absorbed glass-mat (AGM) battery. These batteries were chosen because they are completely sealed with little to no chance of battery acid spillage and minimal hydrogen or other chemical off-gassing. These features were ideal for the tight confined space inside the buoy. Note: the quarter-ton feed buoy had a single snorkel vent on top of the buoy, which was necessary for ventilation of the interior. This snorkel vent can be seen in Figure 10. More information on the buoy's batteries is contained the Appendix D.

The charge on the buoy's batteries was maintained by both solar and wind energy generation, shown in Figure 12. Solar panels provided electricity during sunny periods, while the wind generator provided electricity during times with moderate to heavy winds, particularly during the winter months. These two systems seemed to complement each other well, since typically when solar was strong, the wind was weak and vice versa. Two 60-watt BP solar panels, model SX-60U 12-VDC, and two SunSaver SS-20L-24V solar charge controllers were purchased from Atlantic Solar Products. The two solar panels were wired in series to generate 24-VDC. The wind generator, a Ampair Pacific 100 24-VDC, and its charge controllers were acquired from Jack Rabbit Marine. Both these electrical power generating systems provide a trickle charge to the 24-VDC battery bank maintaining them at a near full-capacity. In case the solar or wind power generation was not enough to keep the batteries charged, a backup set of charging cables was made to attach to the buoy's charging circuit. This allowed for emergency charges of the battery bank via a tethered support vessel. The charging cables were used on occasion while working out a few initial bugs in the system; however since then the buoy's own energy generation has been self-sustaining and the backup charging cables have not been needed.

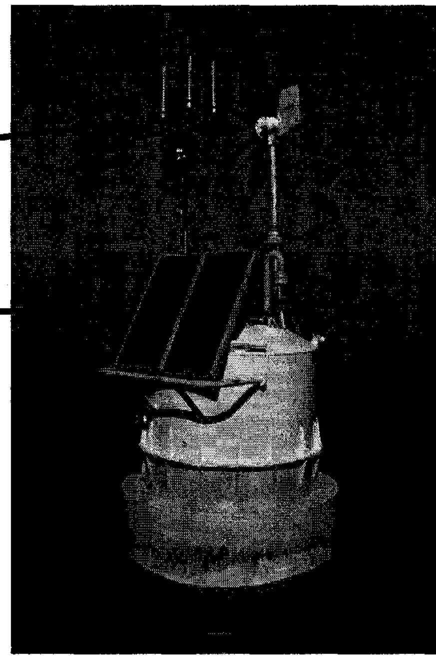


Figure 12: Buoy's solar and wind power generation and telemetry antennas

3.3 Control and Telemetry

The quarter-ton feed buoy's electronics and control system were designed and built primarily by Stanley Boduch with assistance from Jim Irish of the Woods Hole Oceanographic Institution (WHOI). Control of the quarter-ton feed buoy was handled by a Persistor Instruments CF-1 microcontroller (MCU), which was programmed using Persistor's PicoDOS functions and macros. More information on the Persistor CF-1 MCU can be found in Appendix E. This single board computer was mounted inside a watertight aluminum pressure cylinder, along with a load distribution panel. Both the pressure cylinder and the distribution panel are shown in Figure 13. A schematic diagram of the buoy's instrumentation is shown in Figure 14. A flexible control system was designed to allow the MCU to control every aspect of the feeding operation as well as to monitor the system's voltages and current drains. The controller was interfaced with two spread-spectrum radio systems to allow for land-based remote control and data acquisition. The first of these systems contained two 900 MHz serial radios that allow for direct monitoring, telemetry and control of the CF-1 controller. An advantage to the CF-1 MCU was that the system was also programmed to allow for remote program upgrades and feeding schedules without the need to travel offshore. The second radio system included a set of 2.4 GHz, 802.11b radios, known as the popular Wi-Fi. These radios allowed for live video monitoring from two waterproof cameras used to view feeding behavior within the fish cage that the feed buoy was supplying. The two cameras were strategically placed; one camera viewed across the fish cage and the other looked upwards from the fish cage spar. Initially the second video system did not work from land; however, the video capability proved invaluable for monitoring while onboard a nearby research vessel. Underwater video allowed for observation of the aquaculture fish without needing SCUBA divers to enter to water.

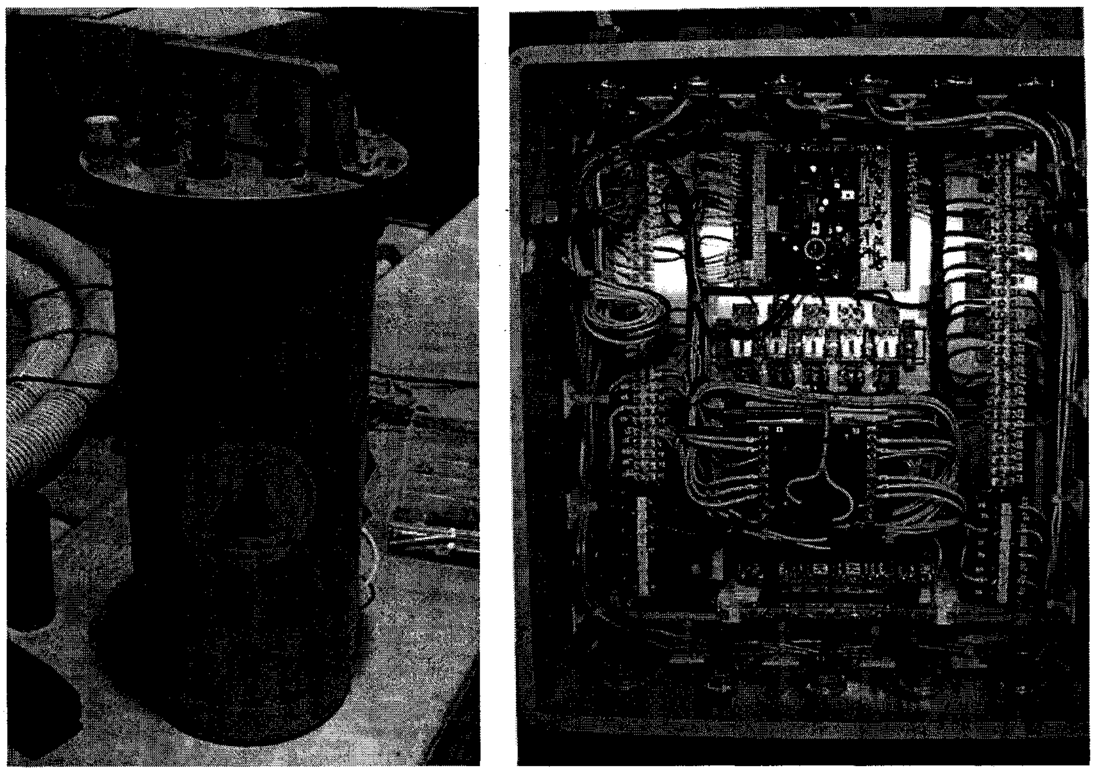


Figure 13: Waterproof pressure cylinder (left) and distribution panel wiring (right)

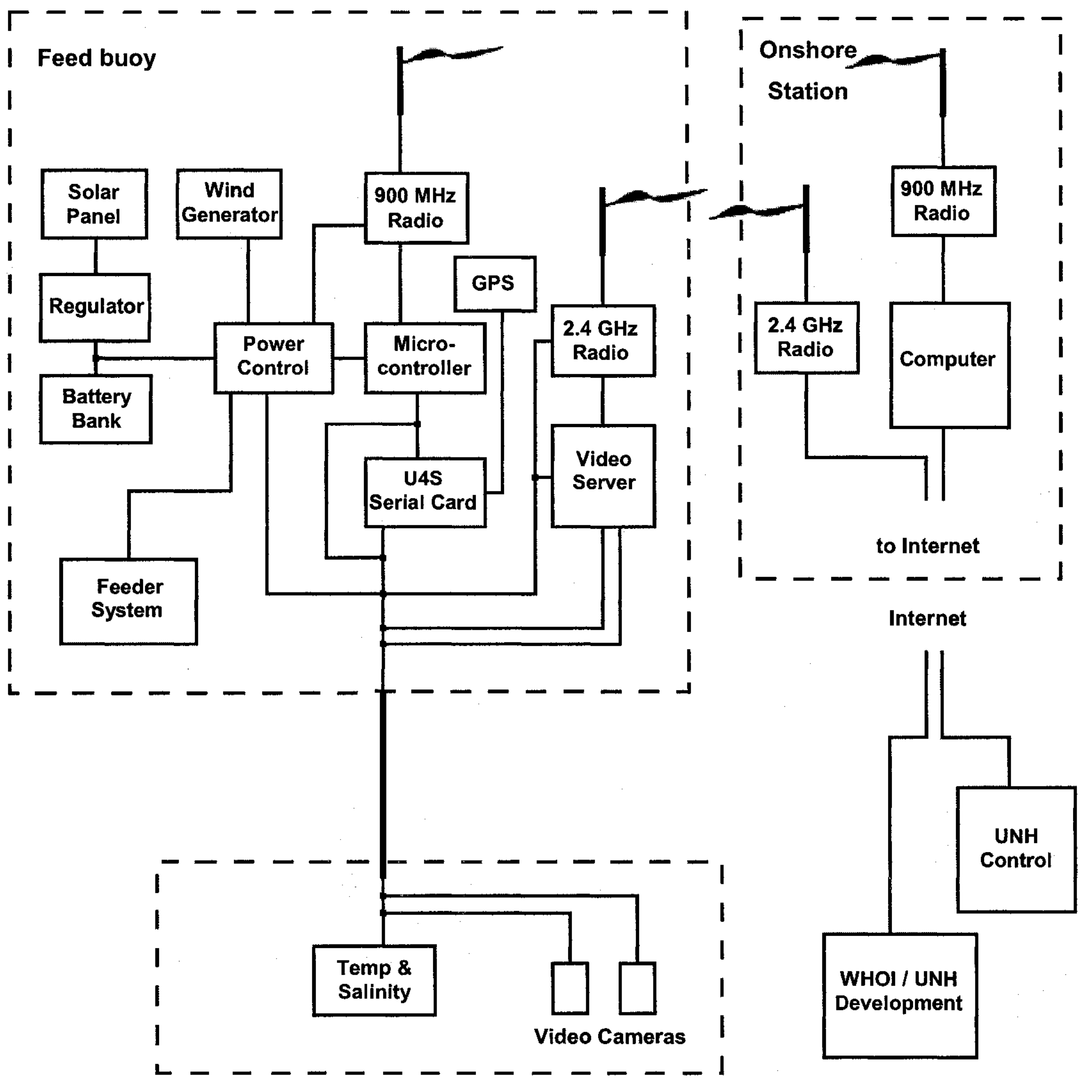


Figure 14: Block diagram of buoy's instrumentation

Additional monitoring of the cage environment was done using a Sea-Bird Electronics SEACAT, a conductivity-temperature instrument. The SEACAT was installed on the center spar of the submerged fish cage. It interfaced with the CF-1 MCU system to allow fish biologists to monitor temperature and salinity from within the cage with a 15-minute sampling resolution. Both the SEACAT data and the cameras' video stream were transmitted to the feed buoy via sets of copper wires embedded in the wall of the high-stretch feed hose. This custom-fabricated feed hose is discussed in greater detail in section 4.1. Telemetry proved to be very useful for acquiring remote feed buoy system data and environmental site data. It is recommended that a similar system be employed in future feed buoy systems.

CHAPTER 4 - QUARTER-TON FEED BUOY

MOORING SYSTEM AND WAVE RESPONSE

4.1 Mooring Design and Motion Range Analysis

The quarter-ton feed buoy and its mooring system were both designed to restrain the buoy and still survive certain severe storm conditions predicted for the UNH OOA research site. These "worst-case" conditions included storm wave heights of nine meters combined with daily tidal fluctuations around three meters and a current of 1.0 m/s at the water's surface down to 0.25 m/s on the seafloor. These design parameters were determined by Fredriksson et al. (1998) and validated by actual measurements during an early March 2001 storm, which contained significant wave heights up to eight meters (Fredriksson, 2001). The ability to successfully moor the feed buoy was a challenging task due to the extreme design conditions and the unknown kinematics of two large bodies, the fish cage and feed buoy, responding dynamically to environmental forcing. Numerical finite element modeling and physical modeling techniques were employed to better understanding the systems' behavior and dynamics. The resulting feed buoy mooring design consisted of an elastic feed hose, which was bolted directly to the top of the cage, and two very compliant rubber tethers connected to the fish cage mooring grid corners. A schematic of the quarter-ton feed buoy mooring is depicted in Figure 15. Originally designed for the single fish cage mooring, the same quarter-ton feed buoy mooring was used in the identical configuration on the expanded four-cage grid mooring deployed one year later. This four-cage mooring system is shown back in Figure 4.

The buoy's feed hose, used to transfer feed from the buoy to the fish cage, was the main strength member of the mooring and was bolted directly to the top of the fish cage. This specialized hose was designed by Walter Paul of WHOI and built to UNH OOA specifications.

The feed hose was made of a highly-stretchable, vulcanized rubber wrapped over spirally wound reinforcing nylon cords for strength. Vulcanization is the process of treating rubber using heat and sulfur to improve the rubber's elasticity and strength. This specialized elastic feed hose could stretch up to 220% of its unstretched length before possibly causing damage to the hose. The feed hose had a safe working load of around 4.5 kilonewtons (kN) and an estimated ultimate breaking strength of 29.8 kN. The hose had an inside diameter of 7.62 cm and a wall thickness of approximately 1.60 cm in the middle compliant section. A cross-section of the feed hose construction, an estimated load-elongation curve and photos of its construction can be found in Appendices F and G.

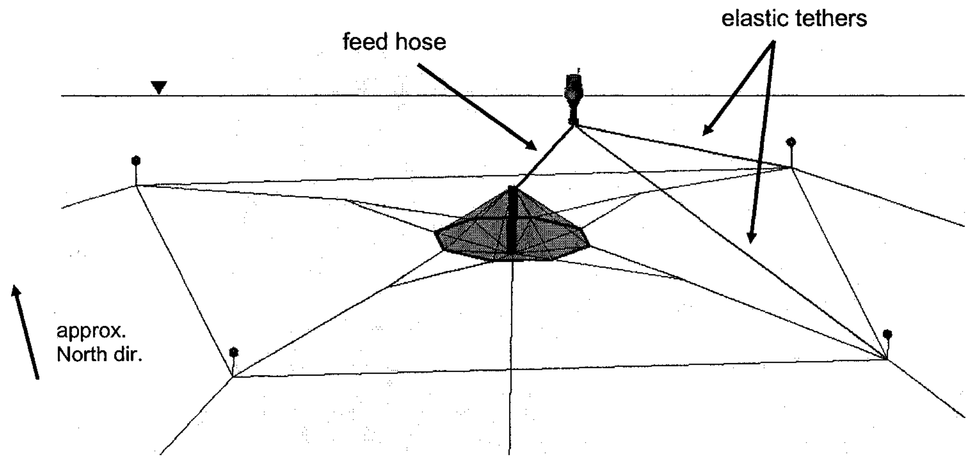


Figure 15: Compliant feed buoy mooring to SeaStation™ 600 m^3 fish cage

Two pair of elastic mooring tethers were used to position the feed buoy to one side of the cage. This helped reduce the chance of collision between the feed buoy and cage. Each mooring tether consisted of two 2 ½-cm (one-inch) diameter elastomeric members in parallel for part of the overall tether length from the grid corner to the buoy connection. The remaining length of mooring beyond the rubber tethers, was taken up by a braided marine Polysteel® rope with breaking strength of 89 kN. Polysteel® is an extruded copolymer fiber made of polypropylene and polyethylene. The stretch of this Polysteel® rope was negligible, however, since the rubber tether was the weakest link and extremely compliant. The force on a single elastomeric member should not exceed its safe working load of 890 N. More information on the quarter-ton feed buoy mooring and its specifications can be found in Appendices F, G and H.

Initial values and lengths for the mooring design were calculated by preliminary static and kinematic analyses using known site parameters and the design wave and tide conditions. Component lengths of the feed buoy mooring system were calculated to be slightly taut in the trough of the design wave at low tide and, at the same time, within the maximum operational limits for the hose and tethers on the crest of the design wave at a high tide. The mooring tethers could be made stiffer with more tethers in parallel; however, the trade-off would be reducing the range of motion of the buoy and greater mooring loads would be generated. Another option would be to shorten the length of the elastic tethers, possibly reduce slack or snapping tendencies; however this would increase the amount of pretension in the system and possibly damage the tethers when stretched to the maximum excursion of the buoy. The process of determining the ideal mooring tether lengths and stiffness therefore became an iterative one, where either forces in the system or range of motion were compromised. Finite element analysis allowed quick changes to the design parameters to be made, which enabled an optimal buoy mooring system to be identified. After evaluating several computer model predictions of the feed buoy/cage and grid mooring storm response, the final specifications and lengths of the feed buoy mooring system were determined. There were two eleven-meter mooring tethers in parallel with the remaining length to the buoy made of 20.1-meter braided Polysteel® rope. Details of the numerical computer modeling and physical wave tank testing are provided in the following sections 4.2 and 4.3.

4.2 Finite Element Analysis

The quarter-ton feed buoy mooring design was modeled and simulations were performed by Oleg Eroshkin and Judson DeCew using the UNH finite element analysis program called Aqua-FE. The purpose of using the Aqua-FE program was: 1) to determine an optimal feed buoy mooring configuration and 2) to characterize its motion and forces to the system as it underwent average daily and design storm wave/current conditions. The Aqua-FE finite element computer program was developed primarily for, but not limited to, applications of the OOA project. The software development was described by Gosz et al. (1996) and Tsukrov et al. (2000, 2003). Validation studies involving comparisons between predictions, field observations and wave tank data were performed by Fredriksson (2001) and Fredriksson et al. (2003). The Aqua-FE model uses nonlinear Lagrangian formulations to account for large displacements of structural components, such as buoys or fish cages which are constructed of trusses and other structural elements. Fluid dynamic forces on structures are determined using the Morison equation, which is modified to represent relative motion between the element and the surrounding fluid. The Morison equation estimates combined fluid drag on the submerged object and the added mass of the object due to its surrounding entrained fluid. The Aqua-FE program had recently been modified to solve nonlinear equations for material behavior and motion. This was a significant improvement to modeling the high-stretch feed hose and elastic mooring tethers of the feed buoy mooring system. In building the finite element model of the feed buoy and its mooring, many decisions in the length, diameter and density of its comprising elements were made so that the computer model would have the same fluid drag, inertia and/or buoyancy as the as-constructed feed buoy design. Figures 16 and 17 are screen captures of the Aqua-FE finite element model.

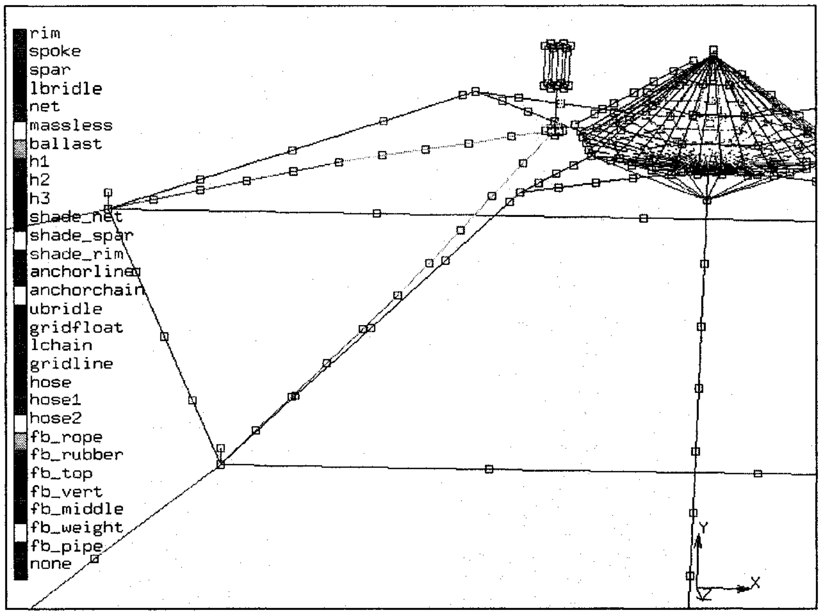


Figure 16: Modeling nodes in Aqua-FE

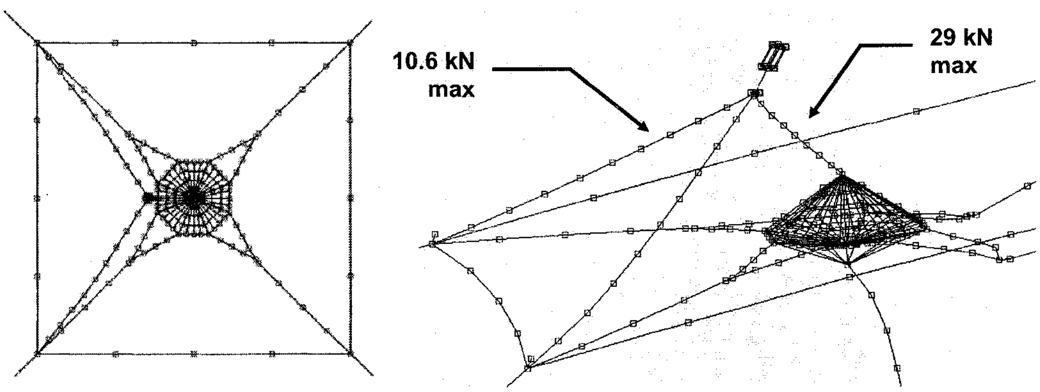


Figure 17: Plan view of FEA model of the feed buoy/cage/mooring (left) and feed buoy/cage/mooring system responding to extreme storm conditions (right)

The dynamic performance of the feed buoy and various mooring designs were investigated for both typical daily and extreme environmental storm conditions. Average daily conditions were approximated to be wind waves of 1.20 meters and a 25 cm/s uniform-with-depth current. The extreme condition consisted of a nine-meter tall wave with a period of 8.8 seconds in combination with a 100 cm/s current at the surface and decreasing linearly to 25 cm/s at the ocean's bottom. Again the design wave was based on wave statistics for the region in the Gulf of

Maine as described by Fredriksson (1998). The current profile was inferred from measurements made at the OOA site, which were doubled to include a factor of safety for storm conditions. The modeled wave and current directions were collinear. Modeling tests were performed in perpendicular (from the left and right direction in Figure 17 (left)) and diagonal to the fish cage mooring grid

The results for the typical site conditions in Aqua-FE proved that the forces of the feed hose and tethers were well below their safe working levels and maintained a significant margin of safety. These results also showed that the position of the buoy to the cage was suitable in these conditions for feeding operations. And tension in the feed hose never went slack; suggesting that the chance of the feed hose getting kinked or forming a loop was reduced. Finally these average conditions tests showed that the feed hose would not stretch significantly enough to constrict the inside hose diameter. In larger storm conditions, it was expected that the inside diameter of the feed hose would constrict significantly as its length was stretched. Both of these situations had been a concern as they increased the risk of feed pellets becoming clogged in the hose.

In design storm conditions, the feed buoy invariably set back on the mooring due to the force of the current and drag of the wave's water particles around the buoy. Once an equilibrium setback distance was achieved, the buoy's motion nearly matched the trajectory path of the wave's fluid particles; see Figure 18. These excessive buoy excursions induced large loads on the elastic tether and hose moorings. Figure 17 (right) is the same analysis of the buoy's response to the design wave and current traveling from left to right on the page.

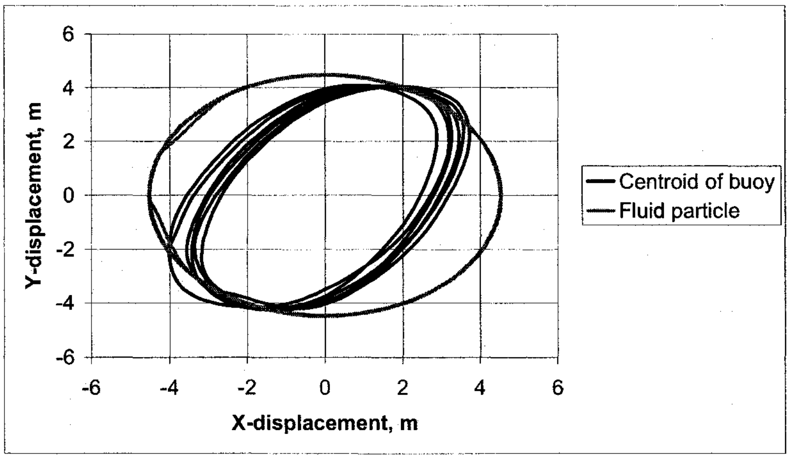


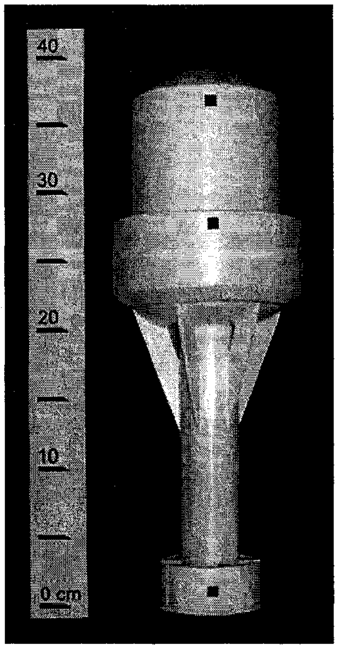
Figure 18: Motion analysis of design wave in Aqua-FE

Maximum loads in the mooring tethers were 10.6 kN, and in the feed hose, 29 kN. This was well beyond the breaking strength of the tethers, by nearly twelve times, and only slightly greater than that of the stretch feed hose. Through more FEA testing, it was determined that increasing tether stiffness had no significant affect on the buoy's movements and only further increased forces on the tether moorings.

Results from the finite element modeling effort indicated that the compliant mooring hose and tether concept, though excellent for positioning the feed buoy relatively close to the fish cage, was at risk for failure during large, but rare, storm events. The mooring system was sufficiently compliant, able to absorb large displacements; however through FEA modeling, it appeared not strong enough to withstand its worst-case design conditions. In view of the benefits the quarter-ton feeding system would have and the immediate need to feed haddock already occupying the SS600 fish cage, the risk of losing the feed buoy was assumed. FEA results were thought to be quite conservative and there was a low probability of encountering such a severe storm. It was further reasoned that, if the mooring should fail, the elastic tethers would break first, leaving the feed buoy anchored by just its feed hose. Since the feed hose was significantly stronger than the tethers, it was felt that unless the storm reached the conservative design conditions, the feed hose would likely survive the storm. The OOA project had a spare set of tethers, so that, once fair weather returned, the mooring tethers could easily be replaced onsite.

4.3 Physical Model Testing

To complement the computer finite element modeling effort, a 1:15.2 scale physical model of the feed buoy, shown in Figure 19, was built by for Froude-scaled wave tank testing. Froude scaling methods (see for example, Chakrabati, 1994) were used to model the buoy, its mooring and the environmental test conditions, which were acting on the system. FEA modeling, discussed in the previous section, was used to estimate the buoy's response due to large storm wave and current conditions. The intent of wave tank testing was to examine the feed buoy's seakeeping response over the spectrum of wave excitations as well as to provide a visual assessment of potential mooring problems, such as line snapping and chafing. At the 1:15.2-scale which the physical buoy model was built, the equivalent nine-meter design storm waves could not be replicated or generated by JACOE wave tank. Froude-scale physical modeling held an advantage over finite element modeling in that the physical modeling better represented the distribution of buoyancy, inertia and drag of the feed buoy. For this reason, the physical model was used to determine the system's natural frequencies and other characteristics. Separate free-release tests for heave and pitch were conducted to establish heave and pitch natural frequencies and their respective damping ratios.



Note: the small black squares are targets for the optical positioning and tracking system.

Figure 19: 1:15.2 scale feed buoy physical model.

The buoy model and a previously built SS600 fish cage model, made by Michael Palczynski and shown in Figure 20, were used together for feed buoy and cage wave response experiments (Palczynski, 2000). The feed buoy and cage models were arranged in the wave tank to simulate the actual mooring configuration designs. A series of single frequency wave tests were carried out on the quarter-ton feed buoy and cage mooring in which the motion of the feed buoy was captured by a video camera. Post-processing of the video images focused on the buoy's heave and pitch motions. Normalized results, presented in the form of response amplitude operators (RAO) or transfer functions, characterized the wave response over the wave frequency range.

Physical modeling experiments were conducted in the UNH JACOE 36.6 m long by 3.66 m wide and 2.44 m deep wave and tow tank. The wave tank has the ability to generate waves with periods between 0.5 and 5.0 seconds and wave heights up to 36 centimeters (Michelin, 2000). Tank experiments were carried out adjacent to the side observation window, so an Optical Positioning Instrumentation and Evaluation (OPIE) system could view and record buoy motion.

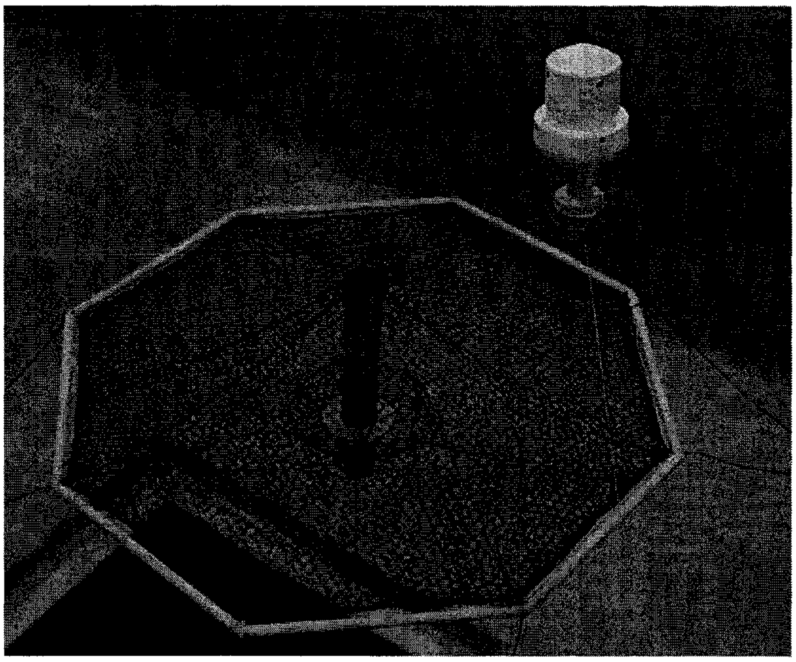


Figure 20: Physical modeling wave tank testing

As described by Michelin and Stott (1996), the OPIE system consists of a Pulnix® progressive-scan digital video camera that records images at a user-set frequency and a dedicated computer with frame-grabber and processing software programmed in MATLAB®. Small black target dots were placed on the white-painted model, and the model was illuminated with additional lighting, so that the black dots stood out from the lighter colored background. The software worked by tracking the black dots on each succeeding image. Each video recording was calibrated so the number of pixels could be converted to units of conventional distance. By knowing the distance and time, the MATLAB® program was able to calculate the displacements, velocities and accelerations of the tracked objects. All video images for the feed buoy experiments were recorded at the maximum thirty frames per second. Results of physical model testing are reported at full-scale values.

The free-release experiments were conducted only on the buoy model itself; that is, without mooring connections. For free-release tests, the buoy model was positioned approximately half a meter away and in front of the tank's observation window. This distance was adequate for minimizing wave reflections from the buoy model to the window and back to the model. In heave tests, the model was raised millimeters from its equilibrium position, not breaking the same cross-sectional surface area, then released from rest. The model oscillated vertically with decaying amplitude as indicated in the typical free-release time series shown in Figure 21. Approximately twelve seconds of data was recorded, yielding approximately 360 individual frames, to capture the decaying response. Pitch free-release testing was conducted in a similar manner to heave, except the model was tipped sideways (without changing its vertical elevation) and released from rest. At least three replicates of heave and pitch free-release tests were performed to ensure test consistency.

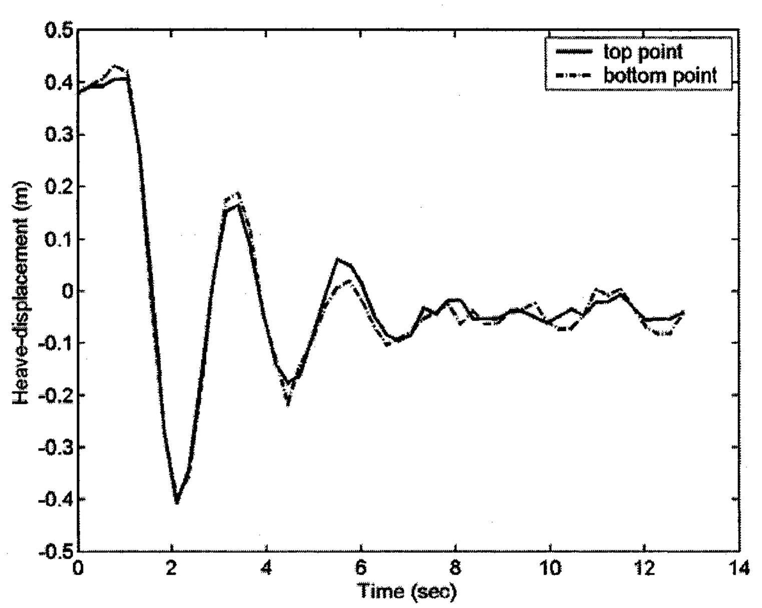


Figure 21: Typical time series of free-release heave motion

Free release time series for heave and pitch were both analyzed assuming motion could be represented by the following linear, second order, damped harmonic oscillator equation,

$$\ddot{x} + 2\zeta\omega_o\dot{x} + \omega_o^2 x = 0 \tag{1}$$

for which x is the generic dependent variable (either heave displacement or pitch angle), ζ is the damping ratio, and ω_0 is the undamped natural frequency. Undamped radian frequency for heave and pitch may be expressed by

$$(\omega_o)_{heave,pitch} = \sqrt{\frac{\rho g S}{m_V}}, \sqrt{\frac{B \cdot gm}{I_V}} \tag{2}$$

respectively. In equation (2), ρ is the fluid density, g is the gravitational constant, S is the waterplane area, m_v is the virtual mass, B is the buoyancy force, gm is the metacentric height and I_v is the virtual mass moment of inertia. Additionally, the virtual mass is defined as the sum of the actual mass and the added mass of the buoy. The undamped natural frequency ω_0 is related to damped natural frequency ω_d according to

$$\omega_d = \frac{2\pi}{T_d} = \frac{2\pi}{\omega_o \sqrt{1-\zeta^2}} \tag{3}$$

for which, T_d is the damped natural period. For this linear model, the damping of the generic response over one period follows the relationship

$$\frac{x(t)}{x(t+T_d)} = \exp(\zeta \omega_o T_d) \tag{4}$$

In processing the free-release data, the damped natural period was found from corresponding zero crossings and the ratio of response over one period was evaluated. Equations (3) and (4) were then used to solve for damping ratio ζ and undamped natural frequency ω_0. Virtual mass m_v and virtual mass moment of inertia I_v were then determined using Equation (2). Parameters were averaged over the number of replicate time series, usually three replicates, and Froude-scaled up to full- scale values.

The heave damped natural period for the quarter-ton feed buoy was determined to be 2.35 seconds. Since this result is somewhat shorter than the period range of the normal wave environment (3 to 10 seconds), wave-contouring behavior could be expected for vertical heave motion. The damping ratio of heave motion was 0.129, indicating moderate heave damping. The virtual mass was calculated to be 3,926 kg and is 192% of the actual buoy mass. The pitch damped natural period was 6.46 seconds putting the pitch resonance condition (buoy only) in the middle of the wave energy range during storms. The damping ratio of pitch motion was 0.0545 indicating light pitch damping. The virtual mass moment of inertia was calculated to be 677 kg-m^2. For the model, this was 198% of the actual mass moment of inertia. Results from the free-release experiments are summarized in Table 2. There was no attempt made to adjust heave or pitch frequencies by re-ballasting the buoy, since the reserve buoyancy and reserve righting moment attributes previously achieved were regarded as the highest priority for the buoy's survivability.

Table 2: Quarter-ton buoy characteristics determined through physical modeling

Characteristic	Value
Heave damped natural period, (T_d)	2.35 sec
Heave damping ratio, (ζ)	0.129
Pitch damped natural period, (T_d)	6.46 sec
Pitch damping ratio, (ζ)	0.0545
Actual mass, (m)	2045 kg
Virtual mass, (m_v)	3926 kg
Percent of Virtual/Actual Mass	192%
Virtual mass moment of inertia, (Iv)	677 $kg \cdot m^2$

Due to the wave tank's width and depth limitations, the full-scaled fish cage mooring grid could not be modeled in the feed buoy wave response experiments. Instead, the grid corners were mounted to the tank walls using four wooden clamped fixtures. It was assumed that the feed buoy's own dynamics would be most influenced by directly connected feed buoy mooring members, while fish cage mooring components, such as cage grid anchor lines, would play a diminished and negligible role on the feed buoy. The central spar fish cage model was anchored by its pendant weight to represent the cage in its submerged mode, as shown in Figures 20 and

22. Bridle lines to the cage were connected to the grid corners; however these lines were slack like the actual fish cage bridle lines. The quarter-ton feed buoy model was moored to replicate the Figure 15 configuration with two tethers to the grid corners and an equivalently elastic feed hose connected to the top of the cage. Elastic string, purchased from a fabric store, was used to represent the tether and feed hose members. The elastic characteristics of these members were also Froude-scaled and carefully matched to correspond to the actual deployed feed buoy moorings. As an example, the effective spring constants (force/length) of the model were scaled to be $(1/15.2)^2$ of the corresponding full-scale values.

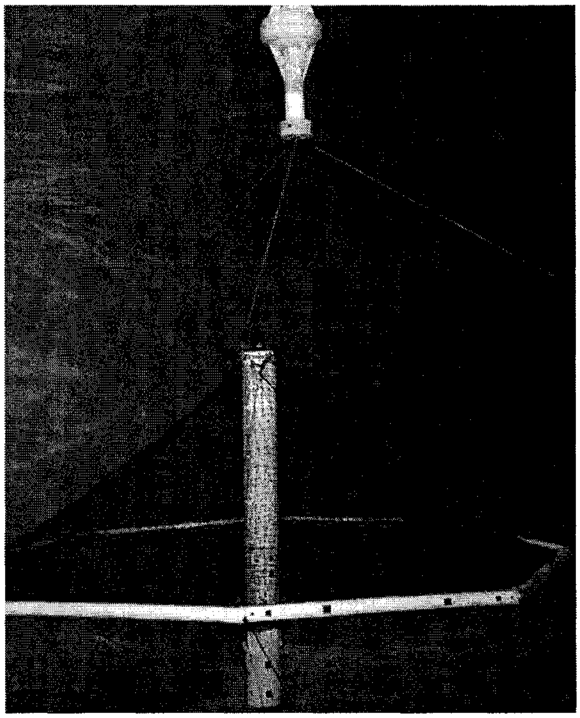


Figure 22: Buoy and fish cage interaction wave tank experiments

To measure water surface elevation during wave experiments, a light, approximately five-centimeter diameter, Styrofoam ball, which had a small hole through it, was used as a float that slid along a taut, vertically-held fishing line. The Styrofoam float had a thin black stripe around it horizontally for tracking its motion with the OPIE system. The fishing line was positioned in the tank on nearly the same wave front plane as the feed buoy model when the buoy set back in the waves. It was presumed that conditions acting on the buoy were the same as on the float. Also, it was assumed that the float behaved as a near-perfect wave-follower and the fishing line had little to no frictional effects to dampen the float. Surface elevations, i.e. the wave conditions, were determined during post-processing separately from the buoy by tracking the float's black strip.

Motions of the feed buoy model and the float, mentioned above, were recorded by the OPIE video system through the side window of the wave tank. Figure 23 contains one frame using OPIE, which shows the calibration circle, the wave-follower float and the buoy model's two tracking targets. Regular, single frequency wave experiments were conducted at full-scale periods ranging from 2.4 – 14.7 seconds, thereby spanning the range of expected wave energies and bracketing the heave and pitch damped natural periods determined by the free-release tests. Experimental wave heights in the tank converted to full-scale ranged from 0.48 meter wind-waves to 4.80 meter moderate storm conditions.

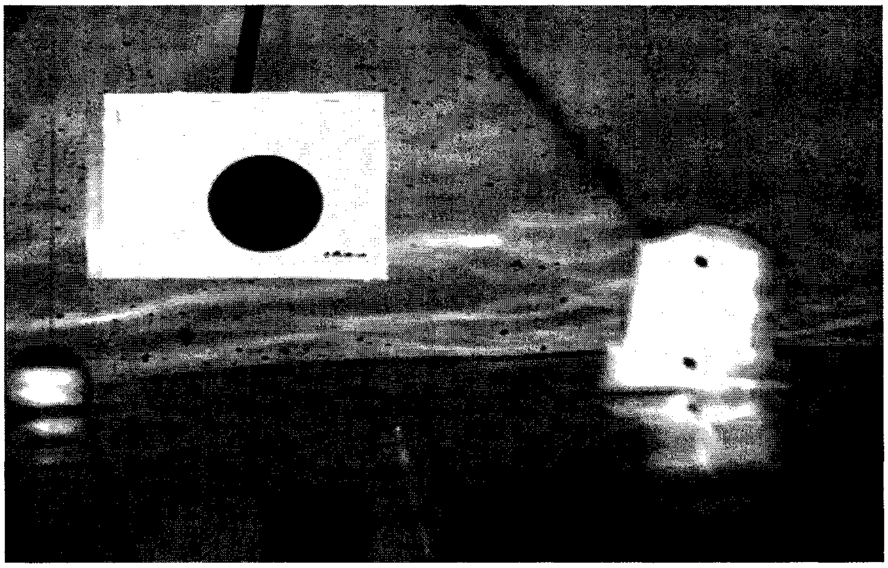


Figure 23: Single frame of OPIE system's tracking

The response amplitude operator is the input/output relation of the forcing and response of the model either in heave, pitch or surge. RAOs are defined as:

$$RAO = \frac{amplitude_{response}}{amplitude_{forcing}} \tag{5}$$

Results for heave and pitch, normalized by dividing by wave amplitude, are shown in Figures 24 and 25. The heave response shows the resonance at the heave damped natural frequency of 0.426 Hertz with a drop-off in response at higher frequencies and wave contouring behavior at low frequencies. This suggests that the mooring does not significantly affect the buoy's heave motions.

Pitch response, on the other hand, did not show a pronounced resonance at 0.155 Hz, the pitch damped natural frequency determined during free-release experiments. It was likely that the buoy's mooring altered the feed buoy's pitch response. Visual observations and analysis of the individual time series suggested that wave drag and inertial forces on the bucket, as well as mooring restraining moments on the bottom of the bucket, played a dominant role to the system. During the cycle of a passing wave, periodic hose slackness followed by snapping mooring lines was observed for all but the highest wave frequencies.

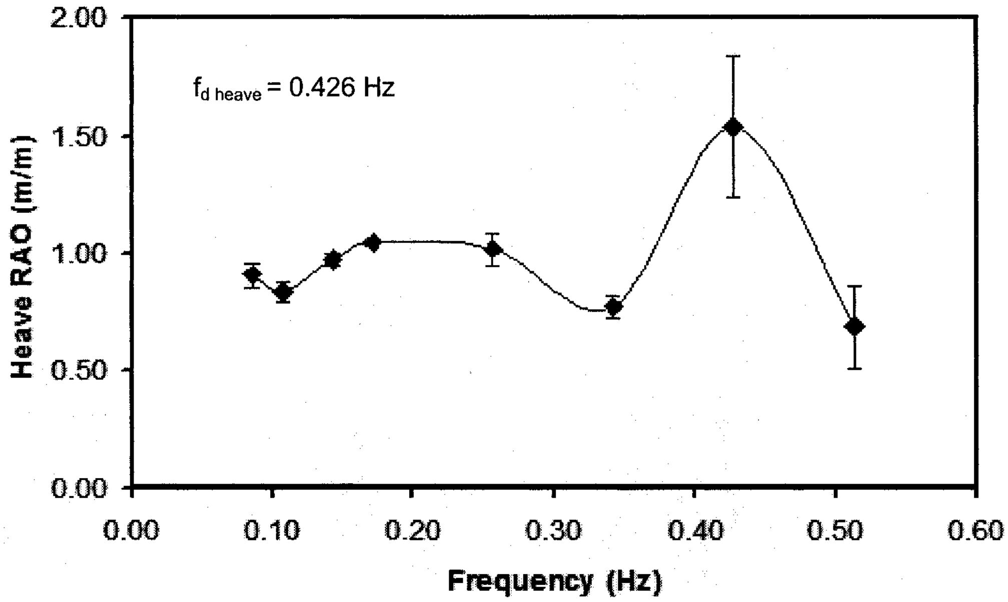


Figure 24: Average heave response amplitude normalized by wave amplitude
(Heave RAO full-scale). Error bars indicate ±1 standard error (SE) = standard deviation / (# of replicates)1/2.

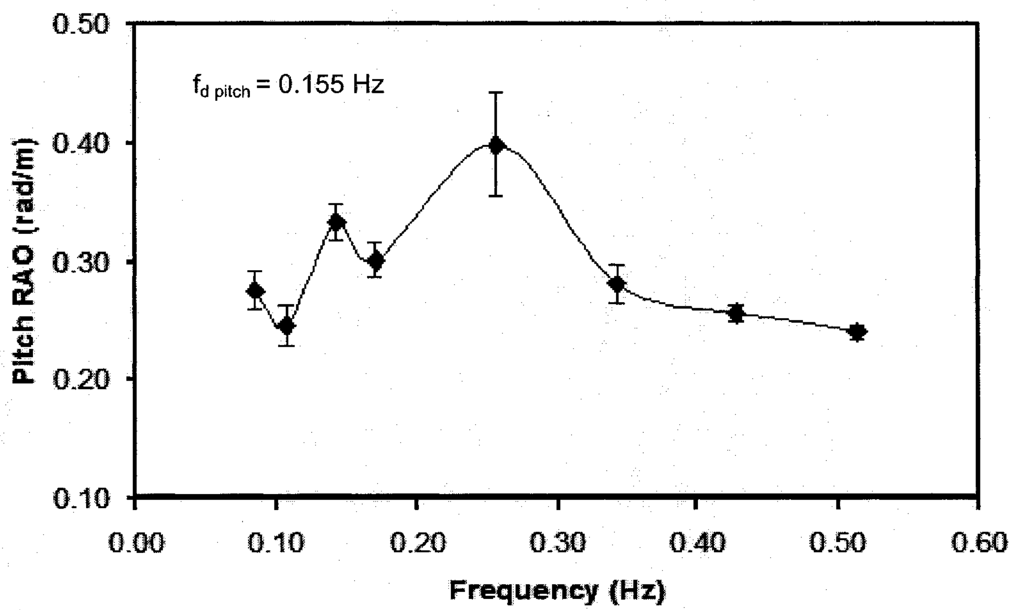


Figure 25: Average pitch response amplitude normalized by wave amplitude
(Pitch RAO full-scale). Error bars indicate ±1 standard error (SE) = standard deviation / (# of replicates)1/2.

CHAPTER 5 - QUARTER-TON FEED BUOY

CONSTRUCTION AND DEPLOYMENT

5.1 Structure Fabrication

Prior to the author's involvement, the quarter-ton feed buoy shell was fabricated by Stommel Fisheries in Woods Hole, Massachusetts in the spring of 2001 (Rice et al., 2003). The buoy's structure consisted of two major components: an upper and lower buoy section split by a flange above the waterline. This flange is shown in the schematic of Figure 10 or the photo of Figure 12. The upper buoy section extended from the flange to the buoy's top deck; the lower section reached from the flange to the ballast container. Buoy parts were made of 5000- and 6000-series aluminum alloys. These alloys were chosen for the feed buoy for their good corrosion resistance and ease of forming and welding. The two buoy sections bolted together with forty-eight ½-inch stainless steel bolts in the 1.75-meter outer diameter flange, approximately sixty centimeters above the waterline. The quarter-ton feed buoy has two Bomar hatches: one twenty-inch round hatch located on top to access the feed hopper and the other hinged 15" by 24" oval hatch located on the side to access the buoy's interior. Both hatches were cast aluminum and watertight using four-dogs to compress the hatch's seal against its aluminum frame.

The lower buoy section had the single access hatch to enter inside the buoy. Space inside the quarter-ton buoy was tight. The feed pipe and equipment used to dispense feed were located directly in the center of the buoy. Distribution and circuit panels were mounted between the framing of the buoy structure. A pressure cylinder, which contained the buoy's onboard MCU computer and its own batteries, was strapped in vertically to the framing. Any free space inside the buoy was filled blocks of cut-to-fit Styrofoam billets, which were used as reserve buoyancy in case the buoy flooded. To keep the blocks in place, they were individually strapped between the buoy's frame sections using nylon webbing. Across from the access hatch on the deck floor was the bilge well, a built-in lowest spot to collect water inside the buoy. The discus shape at the base of the hull was salvaged from an old discus buoy. A void beneath the deck floor to the hull was pressurized and capped for additional buoyancy. A pressure gauge was added to monitor the pressure within the void cavity. If the pressure changed in this void, it could indicate a leak in the buoy and the buoyancy of this cavity would be lost.

The main spar of the buoy was the 0.610 meter (24-inch) pipe from the main body of the buoy to its base. Besides being structural for the buoy, the spar held the feed pipe, which transferred the feed from the buoy's interior down to the feed hose connection. The spar was otherwise an empty void. At the base of the spar was a ballast container. This one-meter round compartment was divided into four sections to hold ballast in the form of lead bricks. The volume of the ballast containment was built to hold at least 750 kilograms of rubber-coated lead ballast.

The upper buoy housed the feed hopper cradled by a bolted aluminum-angle frame. Access to the feed hopper was located in the center top deck of the buoy. This 20-inch round hatch was the only access to the feed hopper. The wind generator mast slid into a welded post and was through-bolted to keep the wind turbine in place (see Figure 12). Solar panels were mounted in a frame that was bolted to welded pad-eyes on the top of the buoy. Since the solar panels extend over the edge of the buoy, a frame was built around the solar panels to protect them from possible collisions and damage from support vessels. Four cleats were spread across the top deck of the buoy to tie-up vessels. Also on the buoy's deck was an inverted snorkel vent to allow air exchange/ventilation within the buoy's interior.

5.2 Installation of Internal Components

Internal components of the buoy consisted of multiple mechanical and electrical systems as shown on Figures 10, 11 and 14. Refer back to section 3.1 for a description of the mechanical systems, including all feed system components and bilge pumps. Installation of most internal components was done at the UNH JACOE laboratory prior to being deployed at sea. The quarter-ton feed buoy was small enough that it was placed in the JACOE deep tank and floated most of its time at UNH. Feed systems were fit-up inside the buoy, and if necessary tested to ensure proper operation. Prior to leaving JACOE, all feed systems were removed. This was done to prevent any damage while in transport, either on the road for eighteen kilometers or in the water as the buoy was brought thirteen kilometers to the OOA site. Once the feed buoy was moored at the OOA site, all systems were re-installed.

The electrical systems, outlined in sections 3.2 and 3.3, included the MCU single-board computer, the 24-volt battery banks, power generation equipment, two radio telemetry systems and all power control and distribution systems. The MCU computer and other circuit boards were built and tested at WHOI, then assembled into the waterproof pressure cylinder or watertight circuit panel cases arranged and built at UNH. Other electrical work conducted at UNH JACOE included routing all the wires and cables, installing the proper connectors, making penetrations through the buoy to pass cables and ensuring their watertightness, and then finally testing the systems. Like the mechanical systems, the electrical equipment was installed in JACOE to ensure proper fit and function, but for the most part, all the electrical components were removed again for transport.

5.3 Deployment

Deployment of the refurbished quarter-ton feed buoy began the first week of January 2003. The feed buoy was loaded on a flat bed trailer at the JACOE building and was driven to the NH Port Authority under the Sarah Long Route 1 Bypass Bridge. With a hired crane service, the buoy was lowered from the pier to the stern of UNH's R/V *Gulf Challenger*. The flotation collar of the buoy doubled nicely as a bumper between the hull of the Challenger and the buoy. After safely rigging the buoy for transport, the feed hose was bolted to the hose flange at the base of the buoy. The remaining feed hose was coiled and lashed onboard for the duration of the tow.

Installing the hose was done pierside in order to spare one task that needed to be performed at sea.

On January 8, 2003, the quarter-ton feed buoy was brought to the OOA site for deployment, field testing and feeding operations. Full deployment of the buoy entailed transporting the buoy to the site, connecting its feed hose to the cage and the two mooring tethers from the buoy to the grid corners (see Figure 15), installing the internal equipment necessary to operate the buoy, and then installing the external equipment, including antennas, solar panels and the wind generator. Because it was the winter season with generally rough seas, it took approximately seven weeks to complete all of these steps.

The first day of deployment had an early start to get the buoy to the southern haddock cage and connect it to its mooring before the afternoon winds picked up. The R/V *Gulf Challenger* held position over the southern cage as the feed buoy was released from its stern. The feed hose was cut free from its lashings and divers took the free end of the hose to the top of the cage. The feed hose absolutely had to be connected first, because it was the main, and least compliant, part of the mooring. It was also necessary to attach the feed hose relatively close to low tide, due to the high spring constant and large tension it would take at high tide to get the feed hose attached. Predicted low tide at the nearby Isles of Shoals' Gosport Harbor was 8:52 AM and high tide was 3:06 PM. Sunset was around 4:25 PM. Three divers brought the feed hose to the top connection on the submerged fish cage. Two divers muscled the hose in the general direction needed, while the third diver attached a come-along winch to bring the two bolted flanges together. Four 5/8-inch stainless steel bolts were used to finish the connection. After the feed hose was connected, the two elastic mooring tethers were connected to the respective northeast and southeast grid corners as shown in Figure 15. Compared to the feed hose, connecting the tethers was accomplished with relative ease. Again the come-along winch was used to draw the tethers to the grid corner shackle connections.

Once the buoy was on its mooring, the focus shifted to installing the two large batteries. This was the first priority, so that the bilge pumps could run if needed. As expected, the seas had picked up in the afternoon, so that the R/V *Gulf Challenger* could not get close enough to the oscillating buoy for fear that it could strike the boat or someone aboard. It was unsafe to pass the buoy's two 32 kg batteries from the *Challenger*. To get the batteries to the buoy, the *Challenger*'s inflatable Zodiac was put in the water and was able to safely ferry the batteries and equipment to the buoy. The batteries were installed and connected, so that the bilge pumps could run overnight, if necessary.

The second day of deployment focused on installing the feed equipment and antennas. The feed equipment was installed rather quickly in the morning; however the buoy would not fully run until the antennas for communication were connected. Note that individual components of the buoy could be operated from inside the buoy, but in order to operate the control system inside the pressure cylinder, communications must be made. The small Garmin GPS antenna was first to be installed, approximately two thirds up the mast. Next to be installed was the multi-spectrum radio antenna. This was the antenna necessary for buoy communications. Figure 26 shows the author installing a directional video antenna, which sent the video signal to a similarly looking receiving antenna at the Seacoast Science Center (SSC) in Rye, NH. However, due to increasing seas in the afternoon, that was all that was accomplished onsite that day. Installing solar panels, wind generator, telemetry, GPS and video relay antennas all occurred onsite.

On subsequent trips to the feed buoy, the feeding system installation was completed and a few bags of feed were added to the hopper. At this point testing of the feed system began. Divers around the fish cage reported that feed pellets were making their way through the feed hose and to the fish in the cage. Because of recent rough seas, the fish had not eaten in some time. Following this success, the feed hopper was filled with approximately eight bags, approximately 200 kg, and daily, remotely-operated feeding cycles began.

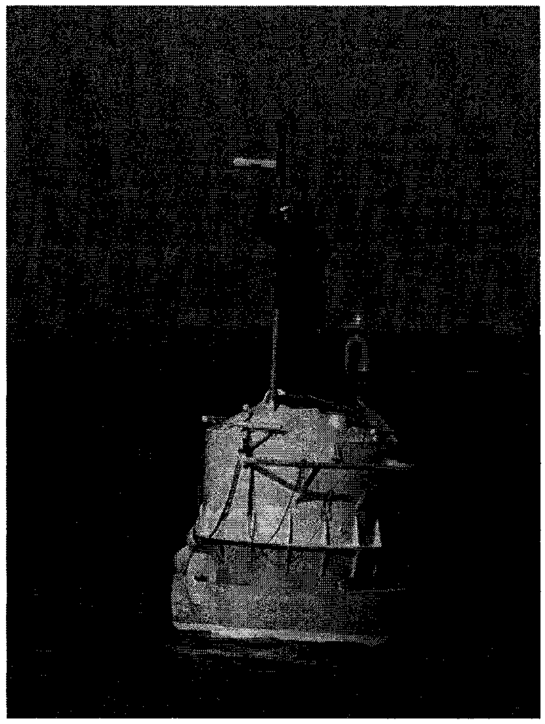


Figure 26: Installing the directional video antenna

Again, due to the season's weather, it was weeks before the seas were calm enough to install the buoy's solar panels and wind generator. In the meantime, the underwater video cameras had been mounted inside the fish cage. Though the video signal did not reach the shore as planned, the video was useful to have available when at or traveling to the OOA site. Because divers usually frighten the fish, the cameras were able to monitor the haddock's behavior, particularly during feeding. This allowed the fish biologists to determine when the fish were done eating, so that wasted, uneaten feed was minimized. From this information the feeding cycle of the buoy was changed. Because the project did not have the *Gulf Challenger* scheduled on the day the seas calmed down, OOA project's *Bluefin* jet boat was used to install these last remaining parts. Figure 27 is a photo of the completed buoy and the *Bluefin* taken later in the spring. Once the solar panels and wind generator were both installed, the deployment of the quarter-ton feed buoy was complete. At sea field trials began.

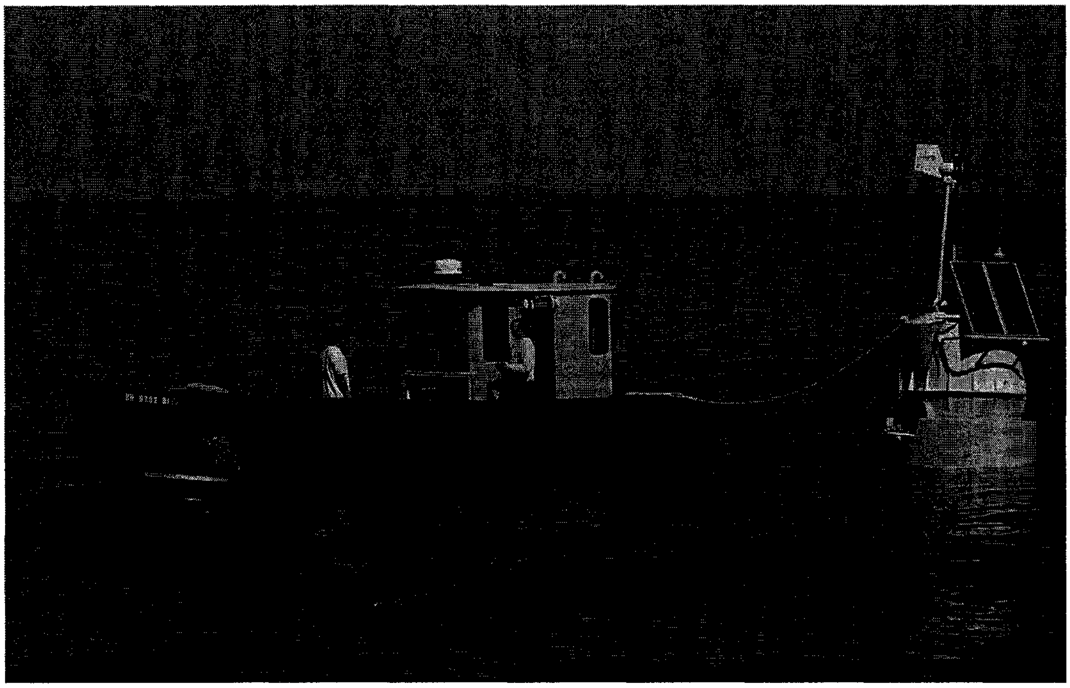


Figure 27: Deployed quarter-ton feed buoy and UNH support vessel, *Bluefin*

CHAPTER 6 - QUARTER-TON FEED BUOY

FIELD TRIALS

6.1 Field Trials

Prior to the installation of the solar panels and wind generator, the feed buoy had already begun feeding the haddock in the submerged cage. However, without the energy generating equipment, the buoy's batteries were unable to automatically recharge. At this point most systems were performing as they were intended. Within one month of deployment, before the power generating equipment could be installed, a winter storm unfortunately coated the feed buoy with a thick and heavy layer of ice. The added weight of the ice and a damaged hatch, mentioned later, caused the feed buoy to take on water, and it slowly began to sink. The severity of the freezing spray ice and its affect on the feed buoy is shown in Figure 28 (left). Ice around the exterior of the buoy blocked the bilge water outlet, so that any seawater that had entered the buoy had no way of being pumped out.

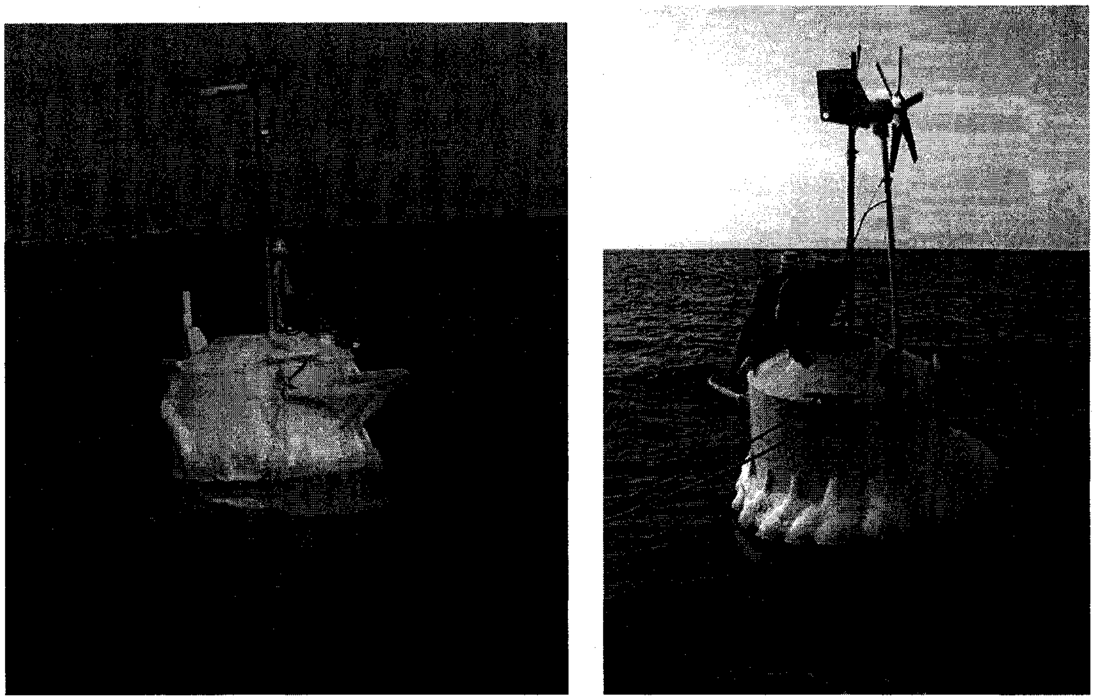
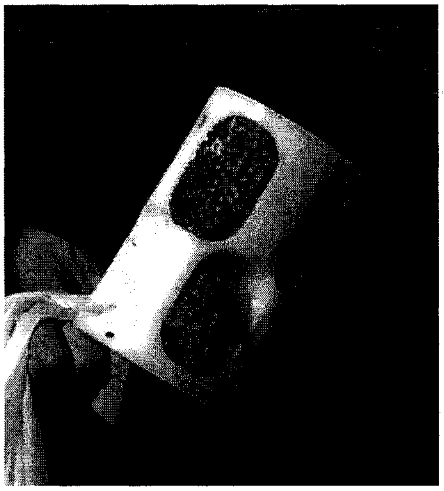


Figure 28: Freezing spray on the feed buoy

Freezing spray had never been observed on the first deployment of the quarter-ton feed buoy. The ice and its effect on the buoy had been unanticipated and therefore had not been designed for. Frozen seawater adds a significant amount of weight, particularly above the buoy's center of gravity. If compounded by a full feed hopper and a leaky hatch or blocked bilge water outlet, the risk of losing the feed buoy is increased. The feed buoy's righting moment and its newly installed flotation collar were instrumental to the buoy's survival. With the flotation collar fully submerged, the buoy was not taking on any more seawater and was not sinking any further. The buoy had reached equilibrium. A gasoline-powered trash pump, the same used to feed the fish from the surface hose, was used in reverse from the support vessel to draw the water out.

Water inside the buoy had shorted the batteries and damaged other electrical components. When both batteries were replaced and the electrical circuits were fixed, the feed buoy seemed to be back in operation. However, increased humidity inside the buoy, due to the intake of seawater, caused the feed inside the hopper to become clumped together and form a rather solid mass. This was evident when disassembling the drum feeder's dispensing cups as shown in Figure 29. The cups had become clogged with moistened feed that had turned into a thick paste. The contents of the feed hopper had to be shoveled out of the buoy through the top access hatch.



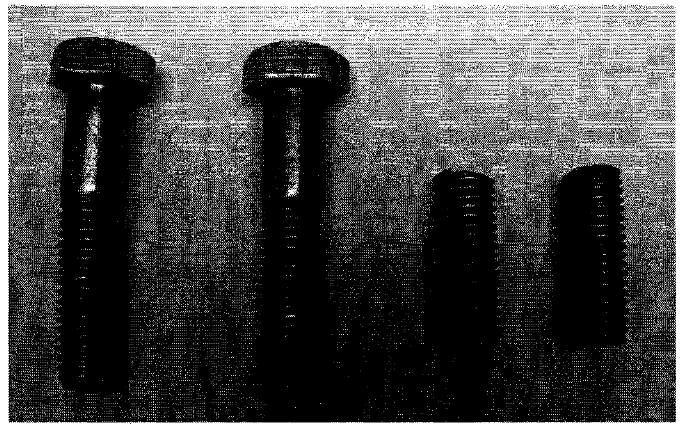


Figure 29: Clogged feed dispenser cups (left) and broken feed hose flange bolts (right)

When the multiple problems, all originating from the freezing spray, were fixed, the feed buoy resumed operation to provide feed pellets to the haddock in daily feed schedules. Regular nourishment was beneficial to the growth rate of the fish, which would be paramount for an actual commercial aquaculture venture (Chambers, 2003). Use of the quarter-ton feed buoy reduced the urgency and frequency of trips to the OOA site. Manual feeding was, however, still necessary for the halibut in the northern fish cage. Though the UNH OOA research site had perimeter buoys with radar reflectors to mark the corners of the site, the feed buoy established a significant presence to the aquaculture site. The location of the submerged southern fish cage was clear by locating the feed buoy. Without these surface buoys, the submerged fish cages would go unnoticed, though the site's location was published in the Notice to Mariners.

Five months into the feed buoy's operation at the OOA site, termination splices on the mooring tethers leading northeast, the dominant storm direction, were found to be overstretched, see Figure 30. The southwest tethers, for the most part, were undamaged. These mooring tethers had been in-use from January 8th, 2003 to June 10th, 2003 - a period of 153 days. The condition of the damaged tethers was discovered, prior to failure, when the feed buoy was taken off its mooring for the four-cage grid mooring expansion. Figure 30 shows a pair of tethers; the photo on the left is the northeast mooring and the photo on the right is the southeast mooring. The other ends of the tethers were in similar condition. The curling of the northeast tethers shows that the splice termination had slipped around the eye thimble, causing the curling effect. This is a telltale sign of the tether being overstretched. Built by David Wyman of Buoy Technology Inc., the tether splices were made by Scotch®-gluing the tethers around the thimble, then wrapping the splice with a heavy adhesive tape, similar in appearance to an electrical tape. The damaged feed buoy tethers were built properly, but they had simply been stretched greater than they were meant to. Since a spare full set of tethers was available at JACOE, the damaged tethers were replaced with new tethers and monitored for signs of overstretching.

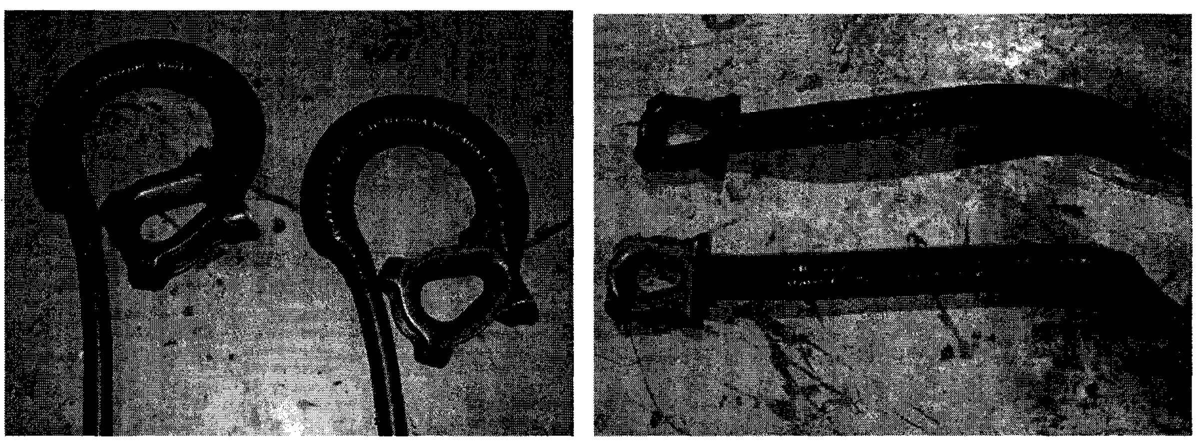


Figure 30: Examples of the NE mooring terminations (left) and SE terminations (right)

Other difficulties in the field, which did not affect feed operations, included broken feed hose flange bolts, a damaged access hatch close to the waterline and a persistent grounding problem in the buoy's charging circuit. The broken feed hose bolts were caused by approximately one year's worth of cyclic wave loads on the 5/8-inch, 316 stainless steel bolts. These bolts fastened the feed hose flange and fish cage flanges together. Figure 29 (right) contains a photo of the four flange bolts. It appeared that two locknuts had backed off and stripped the last remaining screw threads on the pair of bolts on the left. Once one side of the flange was not held together, the other pair of bolts broke due to bending at their weakest spot, the transition between the thread and unthreaded shaft diameter. No damage to the feed buoy, the fish cage or the feed hose was caused by the hose separation. This issue was corrected by installing tougher coated marine-grade steel bolts of the same diameter as the previous softer stainless steel bolts. These fasteners may, however, be an item that needs to be periodically inspected and maintained.

The problem with the feed buoy's damaged hatch was caused by a bullet, which created a significant dent in the hatch. The bullet's impact near an edge warped the aluminum hatch, making it no longer watertight. This was the buoy's single access hatch, which happened to be very close to the waterline. Waves slapping on the hatch was common, a near daily occurrence, and seawater entered the buoy. The amount of incoming water was small; however, this put a greater and unnecessary demand on the bilge pumps and the electrical and charging systems. It is assumed that the feed buoy was shot by a passing boat because it made a good target and not out of anger towards or in protest to the UNH OOA project.

Finally, the problem with the feed buoy's charging circuit took some time to diagnose and correct. A slow drain of the buoy's batteries destroyed one set of batteries by drawing their core charge below the batteries' ability to recover and maintain a charge. This electrical drain was likely caused by the battery charging circuit for the wind and solar generators, which was not detecting the correct incoming voltage. This, and possibly stray electrical currents, prevented the circuit from charging the buoy's batteries properly. Once the problem was pinpointed to the battery charging circuit, the circuit was replaced and the problem was solved.

GPS data from the feed buoy was averaged and broadcasted back to shore every hour. Figure 31 shows these hourly GPS positions over a thirty-day period. The quarter-ton feed buoy's mean equilibrium position was determined to be 42° 56.547' North and 70° 37.844' West and a watch circle of around twenty meters was estimated. Outlying data may be explained by severe weather events and/or erroneous GPS signals for example. This information could be used to quickly inform researchers onshore whether the buoy's mooring tethers or the feed hose had come loose in the event of a failure.

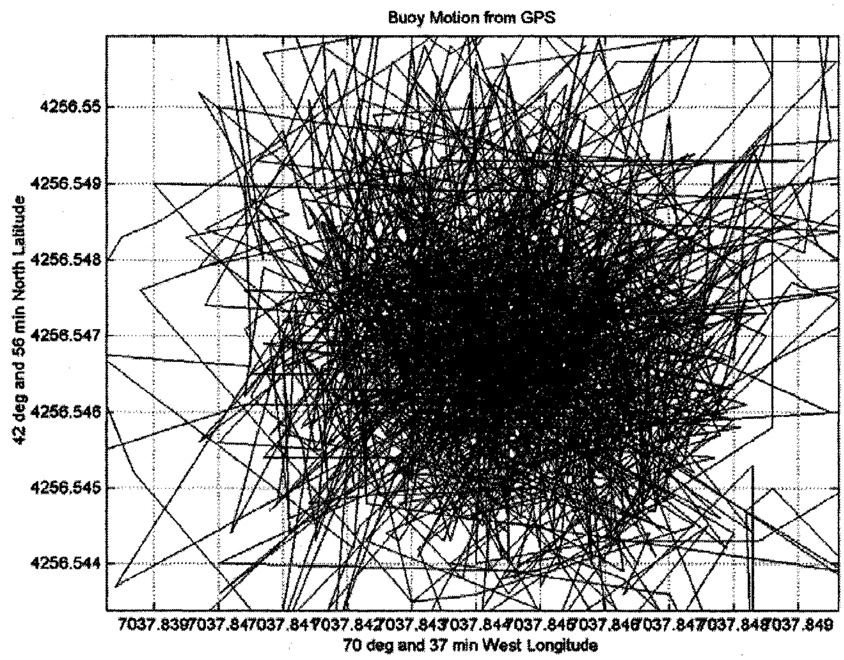


Figure 31: Buoy's watch circle from GPS positions over a 30-day period

Ultimately the quarter-ton feed buoy proved to be a valuable asset to the OOA program, because the buoy provided regular and metered amounts of feed to the caged haddock with less time and effort by the OOA operations staff or project members. In the height of the busiest feeding schedule for the SS600 cage, when the fish were grown and the water was warm, the feed buoy's hopper had to be refilled at least once a week. However, despite its small feed capacity, the quarter-ton feed buoy saved valuable time and expense by feeding the fish remotely. Based on this successful design, a larger one-ton capacity feed buoy and feeding systems were developed.

CHAPTER 7 - ONE-TON FEED BUOY

GENERAL DESIGN

7.1 Design Rationale and Criteria

A second, larger research feed buoy was designed in the spring of 2003 specifically to feed thirty-five thousand young cod fish in a new and also larger submerged SS3000 fish cage. The immediate need for this larger buoy was driven by hungry fish already purchased and contained in a nursery pen within the cage. The nursery is simply finer netting lashed inside the cage to prevent the young fish from escaping or gilling themselves in one-inch-square fish cage netting. From the feed buoy's initial design conception to its at-sea deployment, this feed buoy and internal systems were prepared and built in less than a single year. All together the feed buoy system consisted of a surface feed buoy, its moorings attached to the fish cage mooring grid corners, a feed transfer hose to the cage, industrial-sized feed dispensing equipment, and telemetry and control systems. It had been specified that this feed buoy be similar in design and operation to the quarter-ton capacity feed buoy, which had been proven to be a key improvement to consistent offshore submerged cage feeding. Design rationale and criteria for this buoy match those discussed in Chapter 2 for the quarter-ton feed buoy. The general design of the larger feed buoy was to increase the overall dimensions and scale of the quarter-ton feed buoy, and hence, increase its feed storage capacity. The hopper in the new feed buoy had a capacity of over two thousand pounds, and hence, became known as the "one-ton" feed buoy.

One major change to the feed buoy's design was the onboard diesel generator, which was a necessity due to the system's increased power requirements. It would have been nearly impossible to generate enough power via solar or wind generators and then store the DC power in large enough batteries. With the exception of a rotary airlock feed dispenser and two seawater pumps, all the buoy's equipment was powered by 24-volts, similar to the quarter-ton feed buoy. It was also planned that the new one-ton buoy would serve as a platform for other aquaculture-related research, including an acoustical fish tracking system to monitor fish biology. The increased space inside the buoy would serve as a work and storage area for these projects. The one-ton capacity feed buoy described here can be regarded as the second buoy in a series of feed buoys under development as the UNH OOA project progresses towards a commercial scale.

7.2 Design Configuration

The external appearance and dimensions of the one-ton feed buoy are shown in Figure 32 (left). The internal arrangement of the feed hopper, dispensing equipment, diesel generator, seawater pumps and other internal systems are illustrated in Figure 32 (right).

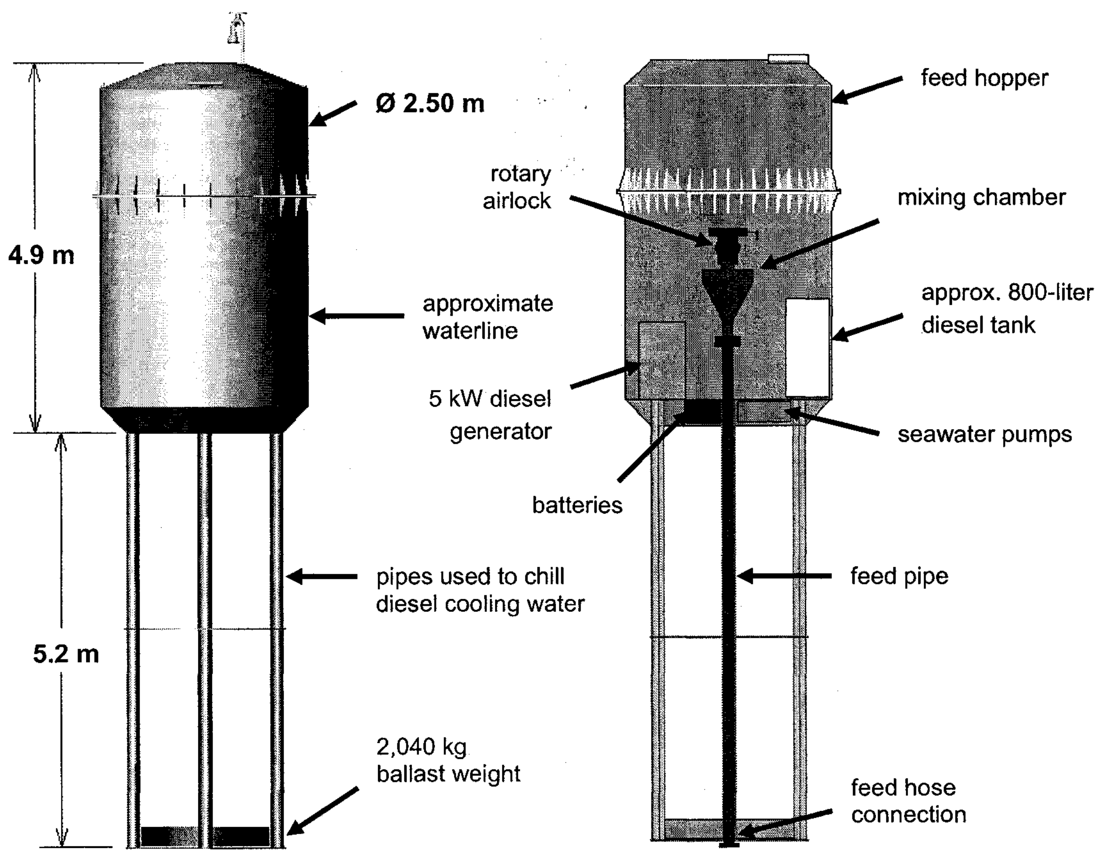


Figure 32: General schematic of one-ton feed buoy's external (left) and internal (right) features

The main compartment of the buoy consisted of a 2 ½-meter diameter cylindrical body approximately five meters tall. This cylindrical body was split into two parts; the lower section made of steel, and the upper section made of aluminum. Plain carbon steel plate and angle was used for the lower buoy section, because it was less expensive than aluminum, more durable and its heavier weight down low lowered the buoy's center of gravity. Aluminum was chosen to make the top of the buoy, primarily because it was lighter weight and had good corrosion resistance. A 6000-series aluminum-alloy was used again because it was easy to form into curved buoy shapes and it had good machining and welding characteristics. Two access hatches on opposite sides of the aluminum cylinder allowed entry to the inner workings of the buoy. [Two hatches were also installed for safety should the diesel generator catch fire or to ventilate the buoy.] Again a single hatch centered on the top deck of the buoy was used solely for filling the feed hopper.

One important difference between the one-ton buoy design and the quarter-ton buoy was the removal of the large diameter center pipe. This pipe on the quarter-ton feed buoy was a sealed empty void, which undesirably lowered the center of buoyancy of the buoy. On the one-ton design, this pipe was removed and replaced by four small diameter pipes, which again connected the buoy to the ballast container.

Hydrostatic calculations were done again in MathCAD® and are shown in Appendix I. The buoy design was such that the center of gravity was significantly lower than the center of buoyancy, offering a substantial 1.20-meter metacentric height. Table 3 lists the principal dimensions and weight for the one-ton capacity feed buoy.

Table 3: Principal dimensions and hydrostatic characteristics of the one-ton feed buoy

Characteristic	**Value**
diameter	2.2 m
overall height (not including antennas and vent pipe)	10.1 m
Fully-loaded draft	6.37 m
minimum draft (w/o consumables feed and fuel)	5.55 m
material of lower buoy section	Steel
mass of lower buoy section	2,380 kg
material of upper buoy section	Aluminum
mass of upper buoy section	465 kg
max. feed capacity	1,100 kg
mass of ballast	1,810 kg
overall mass	7,530 kg
metacentric height	1.20 m
ratio of feed capacity/overall buoy mass	14.6 %

CHAPTER 8 - ONE-TON FEED BUOY

INTERNAL SYSTEMS

8.1 Feed Storage, Dispensing and Distribution

The description of feed storage and distribution will follow the sequence that feed pellets undergo from entering the buoy through the top feed access hatch to finally reaching the submerged fish cage. The feed hopper, cradled by a bolt-in aluminum frame shown in Figure 33, was located in the top portion of the buoy. This was done again to keep feed storage well above the waterline, in an attempt to keep the feed as dry as possible. Access to the feed hopper was strictly through the center hatch on the top deck of the buoy. Opening this hatch revealed a second plastic hatch below it, which was part of the COTS polyethylene feed hopper. COTS hoppers available did not possess ideal dimensions to fit into the feed buoy, so modifications were made to an ACE Roto-Mold feed/grain hopper. A CAD drawing of the hopper before modifications is shown in Appendix J.

The height of the hopper purchased, was too large for the space available in the buoy. Approximately 1.80 meters was removed from the height of the hopper's center. The two parts of the hopper were plastic-welded back together on both the inside and outside. And since the COTS hopper came with only a side access hatch, an additional threaded hatch and hatch ring was added to allow on-center access to the hopper. The feed hopper held a maximum of 1,225 kg (approx. 2,700 lbs) of feed pellets. It should be noted that initially feed pellets were loaded by hand through the feed access hatch on the top of the buoy. Thirty-two kilogram bags of feed were heaved by hand from a support vessel to the top of the buoy, where the receiver would slash open the bags to empty the contents into the hopper. This was not an easy task, due to the height of the buoy off the water and the weight of the feed bags. This loading procedure was only to be temporary since a specially-made cyclone decelerator was being built, which would convey feed pellets from the support vessel to the buoy via high-velocity air blowers. A MiniMo™ acoustic level sensor was used inside the feed hopper to estimate the amount of feed remaining without having to be onsite or opening the hatch. This sensor measured the distance from a known position above the feed, then using a formula for the geometry of the hopper, the amount of feed pellets in kilograms was determined. This data was relayed to shore as part of the feed buoy's hourly data transmission.

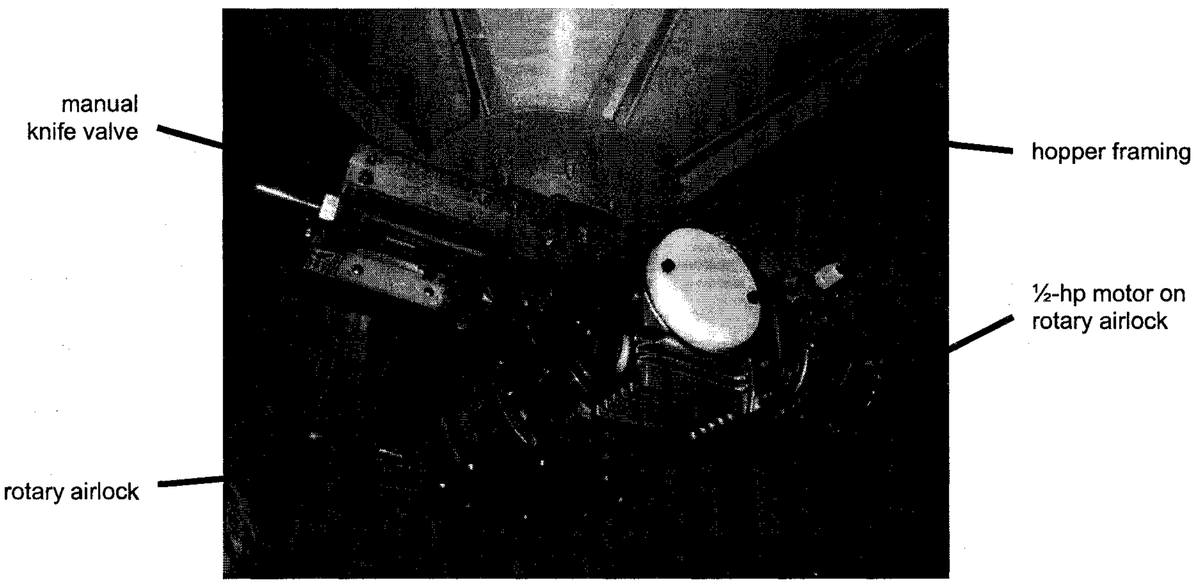


Figure 33: Upper feed assembly

Components in the upper feed assembly included: the feed hopper, a manual crank knife valve and a rotary airlock with its own ½-horsepower (hp) motor, which dispensed discrete amounts of feed from the hopper. The upper feed assembly parts were suspended by the hopper frames. Immediately below the feed hopper was a six-inch manual knife valve. This maintenance valve was used to keep feed pellets in the hopper when disassembly of components below the knife valve was necessary, either to clear a clog or for routine cleaning. The knife valve operated by manually turning its handle open or closed. Although not originally in the feed system design, the knife valve could be left partially open to reduce and regulate the flow of pellets into the rotary airlock.

The rotary airlock was suspended beneath the manual knife valve. This industrial, six-inch round rotary airlock was made by the Prater Corporation. The airlock valve served two functions: 1) to dispense discrete amounts of feed from the hopper and 2) to seal feed in the hopper from seawater backing up in the feed assembly. Experience from the quarter-ton feed buoy showed that any moisture on the feed pellets turned it into a thick pasty substance that would easily clog the hopper and other moving parts. The rotary airlock was made of cast 316 stainless steel material to handle the harsh saltwater environment inside the buoy. A ½ hp direct drive motor on the rotary airlock drove the eight vanes contained within the airlock housing. The rotary airlock and its motor are shown in both Figures 33 and 34. Information and specifications on the Prater Industries rotary airlock can be found in Appendix K.

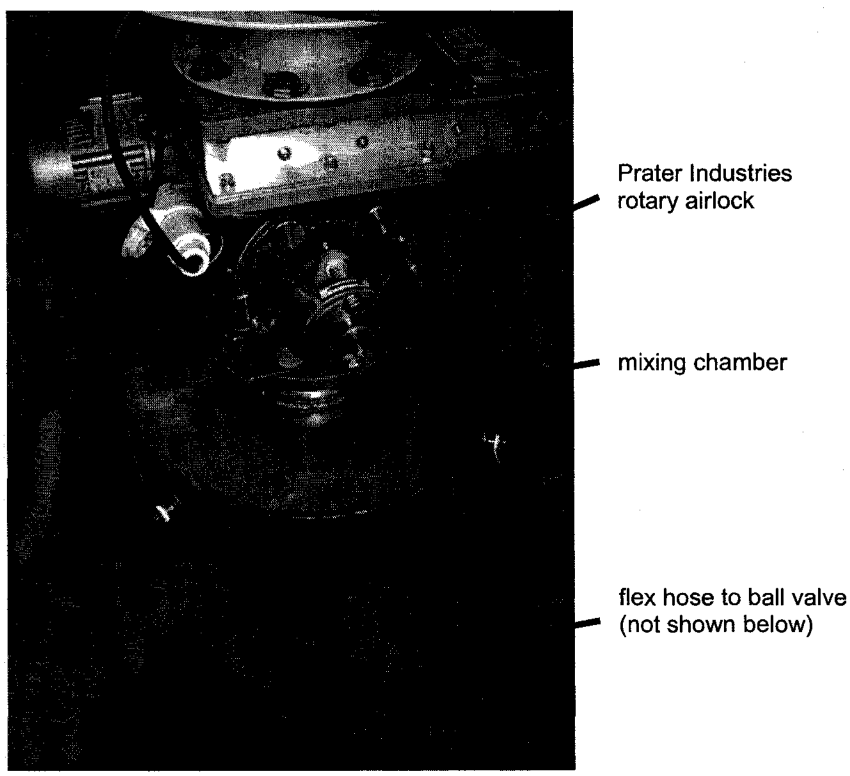


Figure 34: Lower feed mixing chamber

The rotary airlock's eight vanes rotate a constant ten revolutions per minute (rpm). Through experiments in the JACOE laboratory, this rotation yields approximately eighteen kilograms per minute. A variable speed motor controller for the rotary airlock was an optional accessory; however similar to the Arvo-Tec feeder, dispensing the desired amount of feed would be regulated by varying the duration of one feeding cycle. Accelerating the feeding cycle was not an option, since dispensing feed too rapidly could potentially produce a clog somewhere in the system, requiring a special trip to the buoy to clear the clog. Underneath the rotary airlock valve, the feed dropped into a specially-built stainless steel mixing chamber. As its description suggests, the mixing chamber was used to mix feed pellets with seawater prior to being pumped through the feed pipe and hose. Seawater was forced into the mixing chamber by two centrifugal pumps, which were piped together in parallel. These centrifugal pumps were mounted to a ½-inch PVC plate, which was bolted to the subfloor of the buoy. The pumps had a constant supply of seawater, which was drawn from nearly one meter below the buoy's waterline. Having a steady supply of water was necessary since these were not self-priming pumps. More information about these centrifugal pumps can be found in Appendix L. The water-and-feed slurry then travel down through the flex hose and ball valve. The flex hose was used to align and join the feed assembly to the buoy's lower steel pipe. The electrically-actuated Hayward ball valve was the same as the quarter-ton feed buoy's ball valve. After the ball valve, feed continued through the buoy's center feed pipe and then into the one hundred meter long feed hose. An advantage to this feed system design over the quarter-ton feed buoy design was that feeding occurred continuously versus in slugs or small batches like the other buoy. This was due to the rotary airlock and mixing chamber being higher above the waterline that the dynamic pressure head did not reach as high. More information and discussion on the one-ton buoy's feed hose is mentioned in section 9.1.

Other non-feeding equipment inside the buoy included two 24-volt bilge pumps made by ITT/Rule Industries. The primary bilge pump had a maximum flow rate of 1500 GPH and was able to automatically detect the presence of water without the use of a float switch. This was accomplished by computerized operation which sensed the resistance of the impeller if water was present. The second bilge pump did require a float switch and was backup to the primary bilge pump should it fail or its filter clog. This backup bilge pump had maximum flow rate of 2100 GPH. Both bilge pumps were hose-clamped to a stud in the base of a thirty centimeter square bilge well. The bilge well was intentionally the lowest spot in the buoy to collect water and/or other debris. Once enough water was present in the well to start either bilge pump, water was forced through an inline check valve, which was necessary to prevent reverse flow through the second bilge pump. After the check valve, water was forced up nearly two meters vertically through a flexible PVC hose and out the side of the buoy through a pipe coupling. The bilge outlet was intentionally lower than on the quarter-ton feed buoy to prevent freezing spray from blocking its outflow.

Ventilation inside the buoy was a major safety concern because of the diesel generator and battery charging taking place inside. Air exchange was supplied either by two two-inch snorkels on the top deck of the buoy or by the hatches left open when personnel were present. Attached to the inside of one snorkel end was a Rule Industries 12-volt ventilation blower. On the other end of the blower was a three meter long flexible vinyl duct hose used to draw air from lower inside the buoy to the outside. This blower was controlled manually by a switch inside the buoy. More information on the bilge pumps, mentioned above, and the ventilation blower can be found at: http://www.rule-industries.com/.

8.2 Power Supply

As previously mentioned, power for the one-ton feed buoy was provided primarily by its own onboard diesel generator. A Northern Lights five-kilowatt generator supplied 220-volt AC power (or less, if necessary) to run the rotary airlock and seawater pumps as well as to charge the buoy's battery bank. Figure 35 shows a photo of the installed diesel generator. The buoy's batteries powered all the remaining 12- and 24-VDC equipment, including the ball valve, bilge pumps, lighting and ventilation. These batteries were again two 12-volt, 105 amp-hour, AGM type batteries from West Marine, which were connected in series to produce 24-volts.

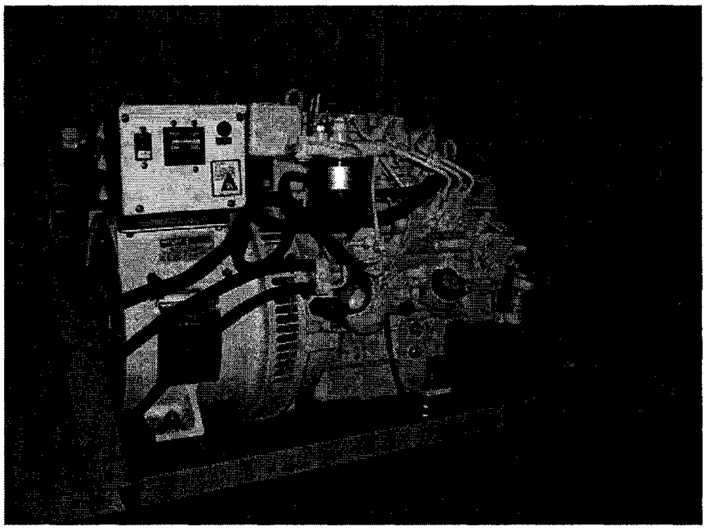


Figure 35: Northern Lights 5 kW diesel generator

Since the generator ran on diesel fuel, a custom fuel tank was built into the structure of the feed buoy. The tank held just under eight hundred liters (around 210 gallons) of diesel fuel when filled. Two different methods were used to estimate the volume of diesel remaining inside the tank. The first used a MiniMo™ acoustic level sensor, which measured the distance from the sensor to the surface of the diesel. Since baffles were installed inside the tank, a relatively accurate estimate was made. This data was sent to shore via the buoy's hourly data transmission, so the level of diesel fuel could be determined remotely. The second method for determining the tank's level was through a clear PVC hose used as a sight-gauge.

The diesel generator selected was a water-cooled generator versus an air-cooled generator, because water-cooled was quieter and, with the abundant amount of cold seawater available, it would be a more efficient method for cooling the engine. Stommel Fisheries came up with the idea to use the buoy's "legs", its four pipes supporting the ballast container, to chill the generator's cooling water. Two of the buoy's legs were joined inside the ballast container by a two-inch steel pipe. Warm water exiting the generator traveled down one leg of the buoy and would return up the other leg and back to the generator. Cooling fluid was half antifreeze and half freshwater for a total volume of approximately 200 liters (55 gallons). A small expansion tank was installed above the generator to keep a supply of cooling fluid present and to provide a volume for the fluid to expand as it heated up. It was estimated that, if the generator's coolant pump ran constantly, it would take just over one hour for cooling water to complete one cycle. This was deemed more than adequate time to cool the fluid. The exhaust of the generator was discharged from a flexible metal exhaust hose and pipe out the side of the buoy through a pipe coupling. Outside a stainless pipe exhaust pipe rose vertically above the top deck of the buoy. To prevent rainwater from entering the exhaust pipe, a 45-degree elbow was installed and the pipe end was undercut similar to many working boat exhausts. The interior exhaust piping was wrapped and taped with high-temperature resistant cloth to prevent anyone inside the buoy from getting burned by accidentally touching the pipe. For more information on the Northern Lights generator refer to Appendix M.

8.3 Control and Telemetry

Simultaneous to the effort of designing and building the one-ton feed buoy structure, Stanley Boduch, Jim Irish, as well as some WHOI staff, were working on the feed buoy's control and telemetry systems. Stanley Boduch was the primary designer and builder of the buoy's electrical systems, while Jim Irish and WHOI specialized in building the PLC unit and programming it to function and control other systems as desired. It was obvious adding the diesel generator for power also added new complexities to the control and electrical system of the buoy. For the quarter-ton feed buoy electronics, the feed programs were completely passive, meaning various aspects of operation did not have to satisfy specific conditions before proceeding with a different operation. For example, the seawater pump in the quarter-ton buoy did not check to see whether the ball valve was opened or not, prior to operating the pumps. This type of control, though simpler, was impossible to implement in the one-ton feeding system. This was mostly because the system had to be sure the generator was running before trying to operate the rotary airlock, for example. More data had to be acquired from multiple subsystems and analyzed properly in order to respond to various conditions that may exist. Incorporating this kind and amount of control into the system was one of the greatest hurdles to the design of the new control system.

In addition to the added complexity of the system, more safety precautions had to be put in place to keep its operators safe, since the generator was capable of producing voltages in excess of 240-volts AC. Such safety precautions include emergency shutoffs, accurate current-limiting circuits, wiring that complied with the 2003 National Electric Code (NEC), interior lighting, ventilation and a fire extinguisher. If a safety problem arose in the buoy, i.e. a circuit breaker tripped or an emergency stop was activated, this information was logged by the internal MCU computer and telemetered to shore. This allowed for a quick diagnoses and response if something in the buoy needed to be repaired.

The control system was designed and built to be modular. Due to the limited opening of the buoy's hatches, electrical panels were sized to be able to fit, forcing the electrical system to be split into multiple smaller boxes and panels. A waterproof pressure cylinder, shown in Figure 36, was used again to house the Persistor CF-2 MCU and its own internal batteries, in case the buoy lost its other power supplies. The Persistor CF-2 controlled and acquired data from all subsystems and was interfaced to shore via 900 MHz, RS-232 spread-spectrum radio transceivers.

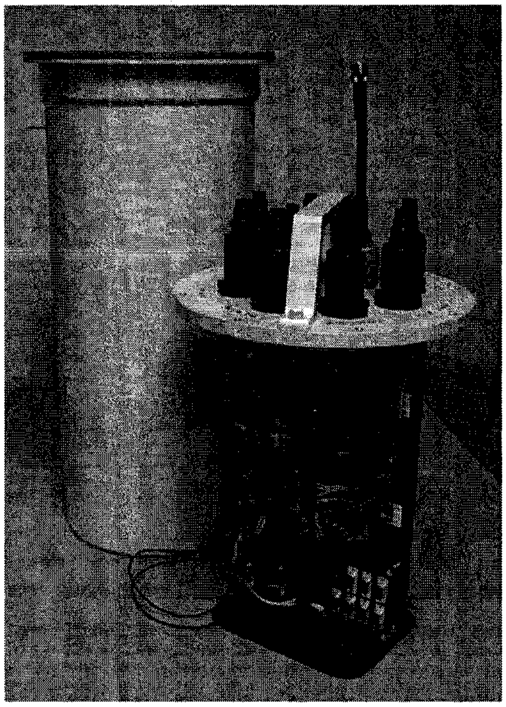


Figure 36: Pressure cylinder assembly

Five circuit panels, shown below in Figure 37, were built and installed onto flexible Unistrut® connectors. The panels were as follows: 1) a data acquisition/control panel for acquiring and multiplexing all data and control information back to the pressure cylinder; 2) a DC distribution panel for control and distribution of all 12 Volt power along with diagnostic interfacing to relay information back to the data acquisition panel; 3) an AC distribution panel for control and distribution of all high voltage AC power again containing more diagnostic interfacing; 4) a generator control and data acquisition panel to control and acquire detailed information about the status of the generator; and 5) a battery charging panel to keep the 12-Volt battery banks charged. The electrical system has three isolated battery banks to keep its subsystems functioning independently, if one should fail. Additionally, the system has been pre-wired for the addition of cage lighting and a host of biological monitoring equipment.

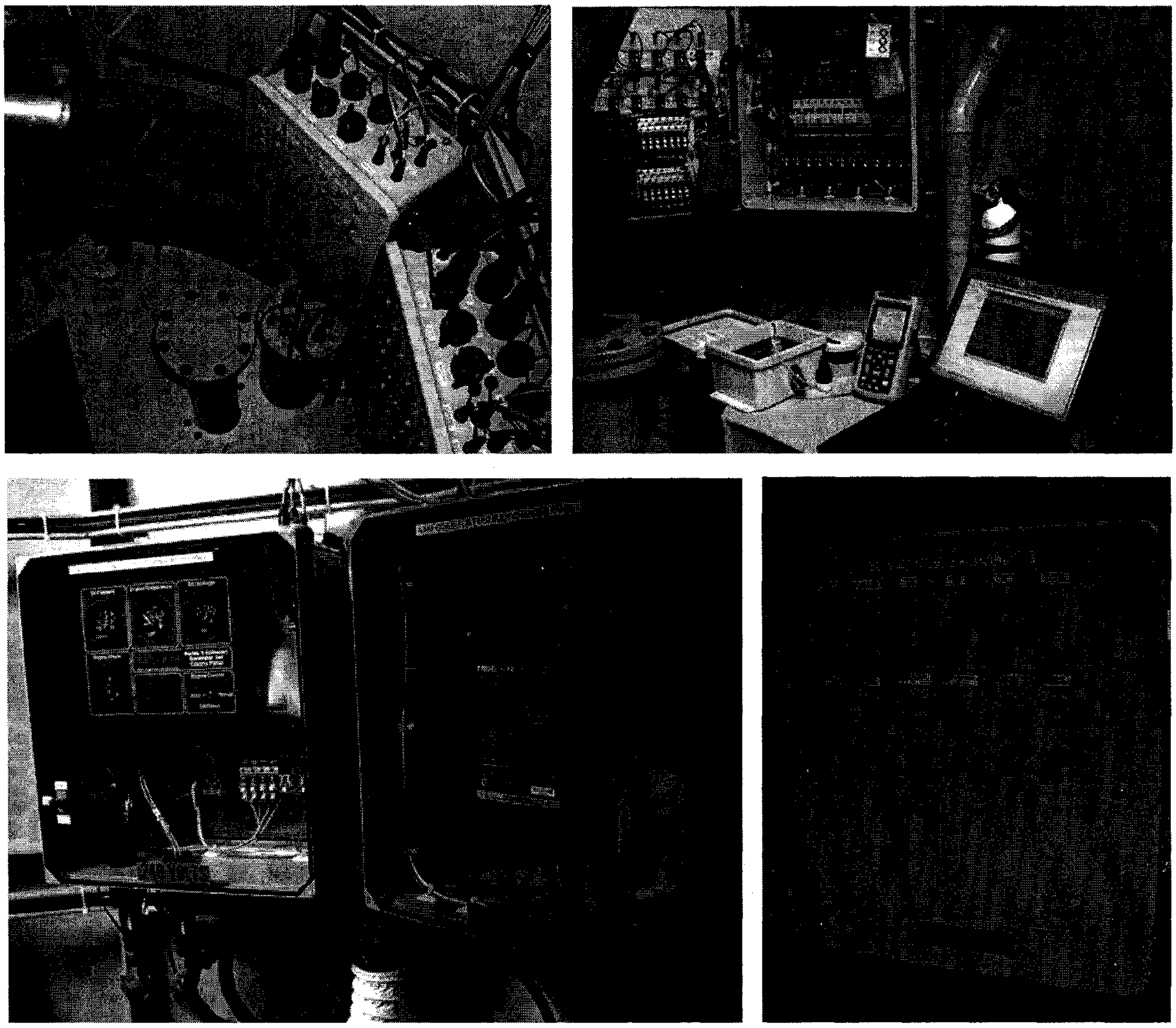


Figure 37: Clockwise from top left: 2 of 5 circuit panels and pressure cylinder, electrical system undergoing pierside testing, AC distribution panel, and generator control/acquisition and battery charging panels

The telemetry system allowed for full control and acquisition of all data from the buoy. Its manager had the ability to choose which days and hours they wanted the buoy to feed and to vary the rate at which the fish were fed. The control and telemetry system were developed to complement a web-based control center that allowed engineers/technicians, managers and certain personnel to be able to monitor and control every aspect of the operation.

CHAPTER 9 - ONE-TON FEED BUOY

MOORING SYSTEM AND WAVE RESPONSE

9.1 Mooring Design and Motion Range Analysis

The one-ton feed buoy was designed and built specifically to feed the new, larger submerged SS3000 fish cage, which at the time contained cod fish. The newly submerged four-cage grid mooring, shown below in Figure 38, would be used to moor the one-ton feed buoy, rather than mooring the feed buoy on its own anchors. This was decided because of the cage mooring's robustness and also for simplicity to minimize crossed or chafing mooring lines. Two different mooring designs for the one-ton feed buoy were investigated: 1) one concept with two high-stretch mooring tether-hoses, designed in collaboration with WHOI and 2) a second contingent configuration with two high-strength inelastic mooring lines each with a concrete center-weight to restore the buoy to its equilibrium position.

Figure 38: Expanded four-cage grid mooring system

The stretch tether-hose mooring design used two equal length, rubber tether-hoses, similar to the feed hose used for the quarter-ton feed buoy, to moor the one-ton feed buoy. The actual feed hose for the one-ton buoy would run slack from the buoy to the fish cage and would only provide mooring restraint in the most severe of conditions. The ideal position for a two-point mooring design was thought to be directly over the western submerged grid line of the new SS3000 cod cage, which the feed buoy would be supplying. Again this was to minimize the length of the feed hose to reduce the chance of the hose becoming clogged. The lower end of the buoy's mooring tether-hoses would connect to the grid corner junctions, shown in Figure 39, where submerged grid corner buoys are located. The mooring tether-hoses were designed to have an unstretched length of 14.6 meters with the remaining distance to the feed buoy, roughly 18.8 meters, made of high-strength, one-inch Yalon® rope.

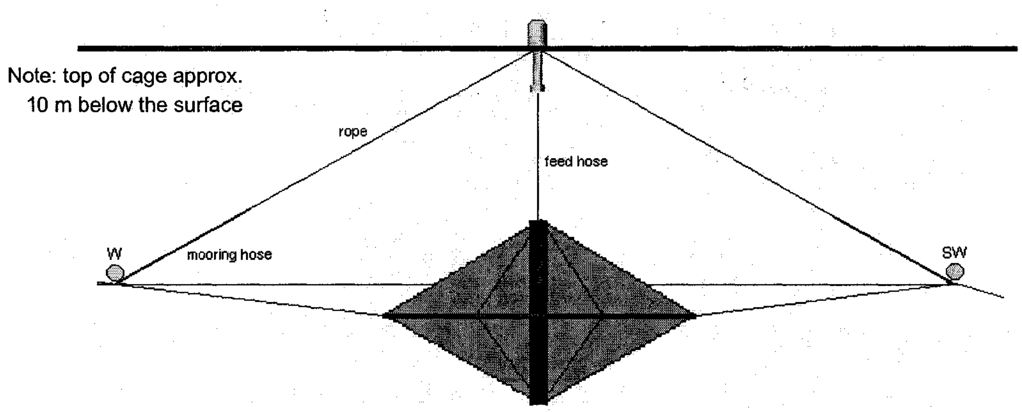


Figure 39: Elevation view of the elastic hose mooring concept

The elastic mooring tether-hoses were designed to stretch up to 32.3 meters before damaging or possibly breaking the mooring hose. This was 220% of the tether-hose's original 14.6-meter unstretched length. To prevent possible overstretching of the hose, in the case of the most severe storm conditions, the interior void of the tether-hose, a five centimeter inner diameter, would be packed with a 3/8-inch Vectran® rope. This high-strength, 12-strand rope would have a length of precisely thirty-two meters to prevent the hose from overstretching beyond its maximum 220% elongation. This was possible since the mooring tether-hoses would not be used to convey feed or any wiring unlike the feed hose. Figure 40 shows an exploded view of the flange tether-hose end showing from left-to-right: the strain-relief pipe, the neoprene gasket and the custom clevis pin end cap. The strain relief was ribbed so the molded rubber hose would remain in place when rubber was vulcanized to the metal fitting. One unanswered question in the mooring tether-hose design was whether or not to fill the tether-hose's inner volume with freshwater prior to capping it. With either end uncapped or with air inside the tether-hose, the tether-hose's inner diameter would decrease as the hose was stretched. However if the tether-hose was filled with water instead, it would likely not compress nearly as much since the water inside is incompressible. This decision was to be made during pierside elongation tests to prove the design. More specifications on the stretch mooring tether-hoses can be found in Appendix N. Also refer to Appendix G for photos of the construction of the quarter-ton buoy's feed hose.

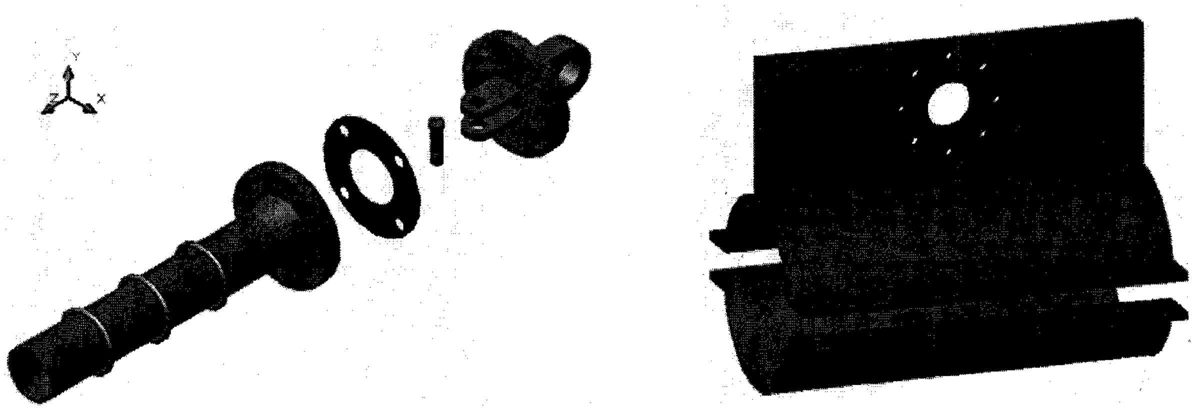


Figure 40: Exploded view of mooring tether-hose end (left) and feed hose connection to the fish cage (right)

The feed hose for the one-ton feed buoy would be built similarly to the mooring tether-hoses, however without as much concern over its ability to stretch, since the feed hose was not designed to actually moor the feed buoy. The inner diameter of this feed hose was 7.6 centimeters (3.0 inches). Up to eighteen copper conductors were to be spiral wound and embedded within the many layers of rubber of the hose wall. At both ends of the hose, the conductors would appear outside the hose wall and with a short pigtail section they would be terminated with the appropriate connector. Feed hose conductors had been a large success on the quarter-ton feed buoy because it allowed the ability to transfer power to and receive data back from instruments or cameras within the fish cage. Conductors wrapped on the outside of the hose tend not to survive long term wear and abuse. The conductors for the one-ton buoy feed hose could be used for: underwater video cameras, underwater lighting, environmental monitoring equipment and possibly a Hydroacoustic Technology Inc. (HTI) acoustic fish monitoring system requested by the fish biologists. A potential usage list for these conductors is in Appendix N.

The majority of the design and analysis effort was focused on the WHOI mooring concept; however when it came time for the project to purchase the mooring and feed hoses, these major components were too expensive for the project and required a few months lead time to manufacture and perform necessary acceptance testing. Due to this setback, a second feed buoy mooring concept was developed in a short time. This contingent mooring design took advantage of the empty fish cage mooring, since only three out of the four cage moorings contained fish cages, as shown in Figure 41.

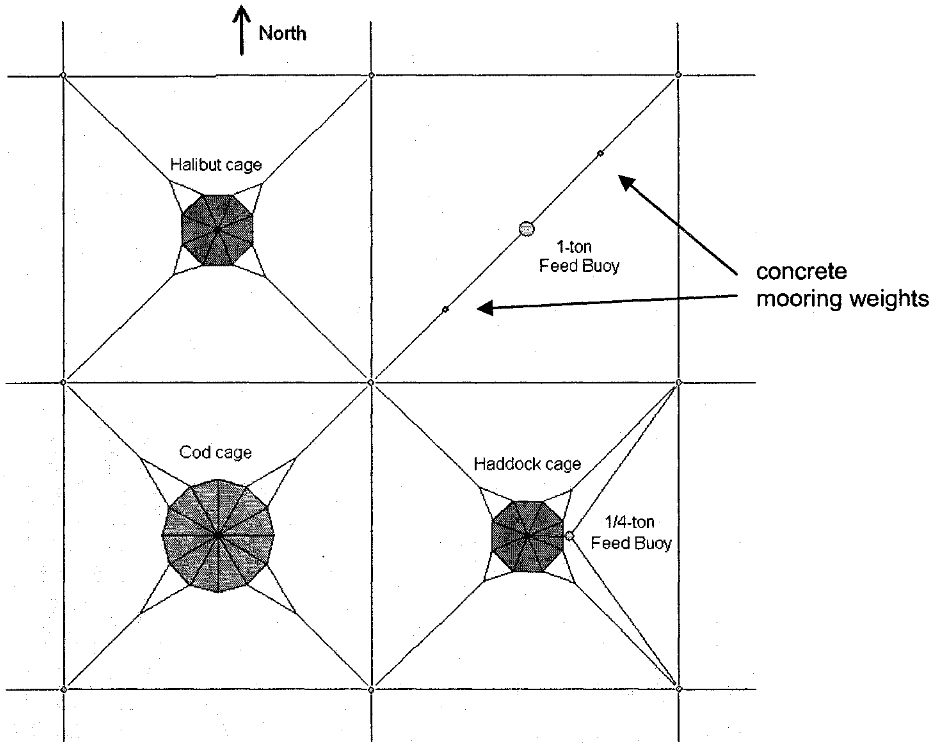


Figure 41: Plan view of the alternate one-ton feed buoy mooring concept

Without compliant mooring members, a second method of providing a restoring force from the mooring was needed. The resolution was a two-point mooring spanning the fish cage square with the feed buoy located in the center. Its restoring force was provided by two cylindrical concrete blocks which had an average mass of 280 kg dry. In seawater, the concrete blocks provided a weight force of 1.47 kN on average. These weights would be attached at the mid-span point on each mooring line. A CAD schematic of this mooring concept can be found in Figures 41 and 42.

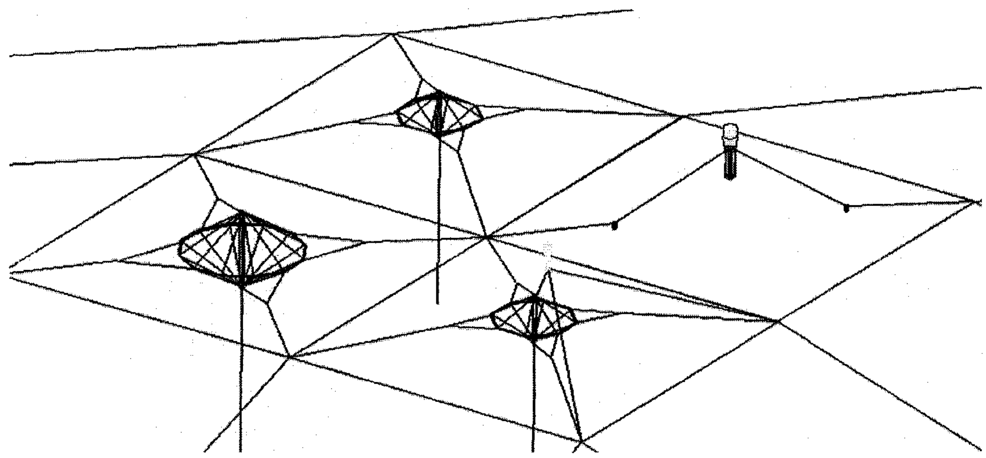


Figure 42: Schematic of alternate one-ton feed buoy mooring concept

The following sections discuss the finite element analysis and physical model testing conducted on the two different mooring designs. The WHOI mooring tether-hose design was modeled and analyzed using finite element analysis and physical modeling techniques. The contingent mooring design with the concrete center weight was evaluated using physical modeling for observational purposes only. No FEA was performed on this mooring due to the lack of time and available personnel.

9.2 Finite Element Analysis

Finite element modeling and analysis was performed by Judson DeCew with assistance from both Igor Tsukrov and Oleg Eroshkin. The WHOI two-point mooring concept, consisting of two highly stretchable mooring tether-hoses, was analyzed using the previously described (see section 4.2) finite element program, Aqua-FE. In the model, mooring tethers were connected to grid corners of the cod cage mooring grid as shown in Figure 39. The same OOA site and design conditions were applied to the one-ton feed buoy as were used on the quarter-ton buoy. The design storm conditions were nine-meter, 8.8 second waves and a 1.0 m/s to 0.25 m/sec current decreasing linearly with depth. These conditions were applied to the numerical model from multiple directions to determine worst-case loading scenarios. These scenarios were either inline with the moorings or perpendicular or normal to the moorings. The direction normal to both moorings had a bow string effect on the mooring. Under these extreme conditions, forces on the tether-hose moorings remained below the minimum ultimate breaking load, 120 kN, of the mooring tether-hose with the elongation-stopping rope inside. Results from FEA analysis in Appendix N show this inline force is 23,600 pounds, which is approximately 105 kN. Figure 43 (left) is a plan view of the four-cage mooring grid showing the one-ton mooring design. Figure 43 (right) is an example of the FEA storm-wave simulation.

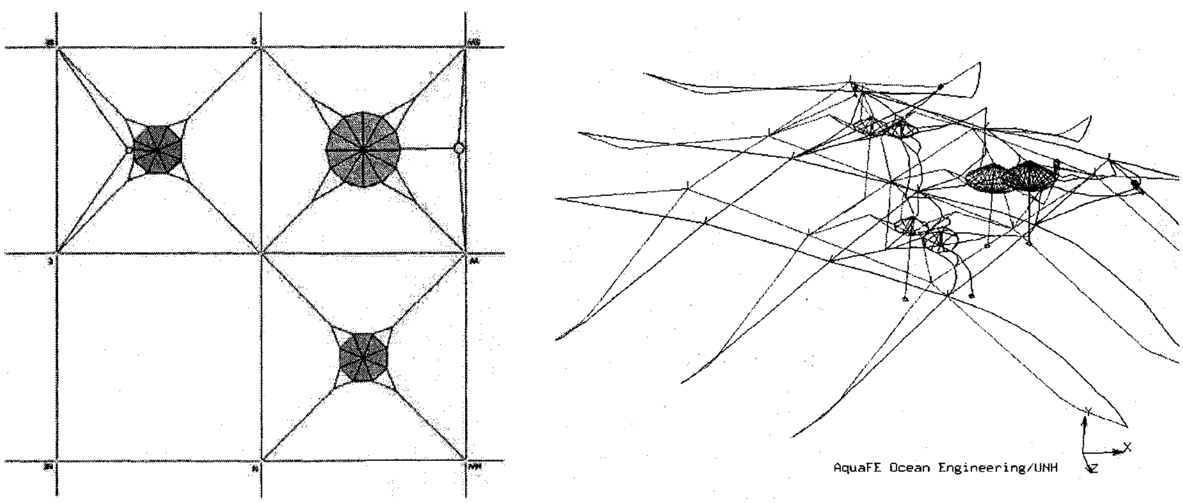


Figure 43: Top view of two-point mooring (left) and a FEA simulation in "storm" conditions (right)

9.3 Physical Model Testing

Early in the design and construction of the one-ton feed buoy, a 1:24 Froude-scale model was built in preparation for physical model testing similar to the experiments performed for the quarter-ton feed buoy in section 4.3. A photo of the one-ton buoy physical model is shown in Figure 44 (left). Physical modeling was conducted to help understand and characterize the one-ton feed buoy's seakeeping abilities and dynamics. Experiments conducted on the buoy model, included heave and pitch free-release tests, wave response tests and other tests for observational purposes.

In the first experiments performed on the buoy model, the buoy's ballast weights were varied to determine an optimal amount of ballast for the buoy. By changing the ballast weight, heave and pitch resonant periods were both affected. All free-release experiments were conducted using the same equipment and procedures employed in the quarter-ton feed buoy experiments; refer to Section 4.3 for more information on the process and analysis performed for free-release testing. Images from OPIE were calibrated for distance and pixel size and were recorded at thirty frames per second. All results of physical model testing are reported at full-scale values.

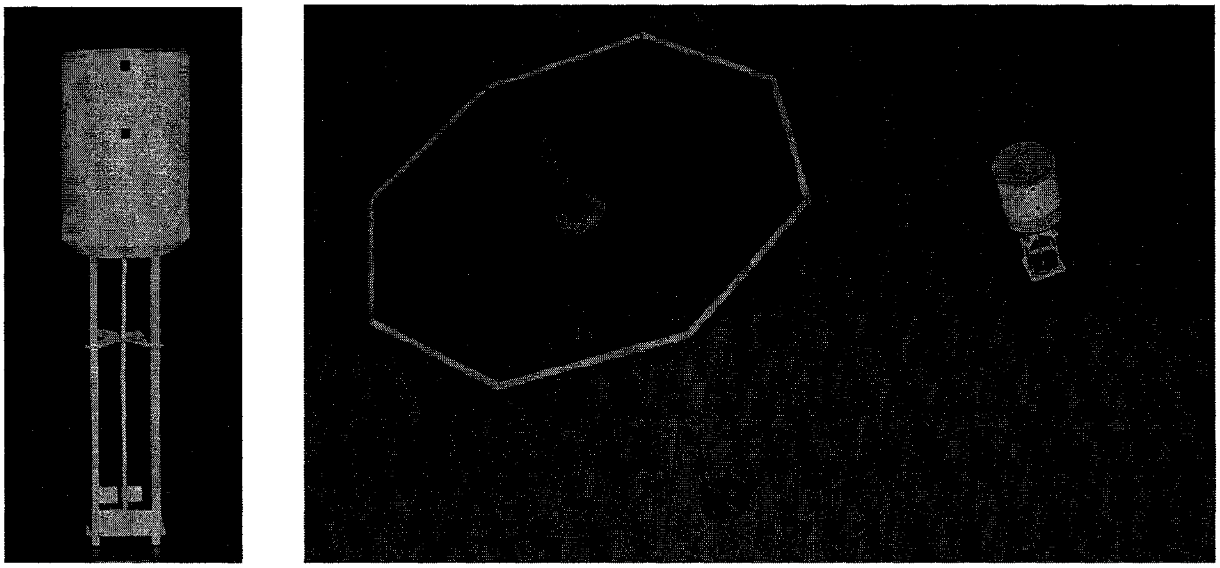


Figure 44: Scale model of one-ton feed buoy (left), feed buoy and cage wave tank testing (right)

Small pieces of lead were either added or taken away to observe how these changes in ballast weight affected the heave or pitch damped natural periods. For an equivalent of 1,360 kg of lead, the heave damped natural period was measured around 3.50 seconds, while the pitch damped natural period was 8.90 seconds. Heave resonance was rather favorable, since the buoy's maximum heave would occur in typical, low-amplitude, wind-wave conditions. Wave-contouring behavior would be expected for larger storm waves. Pitch tests, on the other hand, indicated a resonant condition precisely in the expected storm wave periods. This signified that the buoy would likely pitch severely in such conditions. As long as the buoy and its components survived excessive pitch in these conditions, this was not a safety concern, since UNH OOA operations were unlikely to take place in rough weather. Re-ballasting the buoy with 2,270 kg of lead, approximately 900 kg more than the previous experiment, reduced the resonant pitch period to 6.20 seconds, while the heave natural period increased slightly to 3.70 seconds. Overall it was encouraging that re-ballasting the buoy had a significant affect on the results. Following other ballast weight tests, the buoy's optimal ballast was determined to be around 1,800 kg. Through these experiments, the heave damped natural period was expected to be around 3.50 seconds and the pitch natural period around 8.30 seconds. A suggestion of drag-inducing baffles between the buoy's pipe "leg" sections to dampen pitch motion was also tested. Experiments on these baffles turned out to increase pitch natural period an average of about half of a second. The increase in pitch appeared to be caused by the wave particle drag and the long moment arm from the baffles to the system's center of gravity. Other feasible adjustments to the buoy appeared insufficient in shifting the pitch natural frequency away from the high-energy wave regime.

Later in the spring, the Dynamics of Moored Systems (OE 956 course) graduate students repeated free-release experiments of the 'as-constructed' feed buoy design. This was an exercise for the class and added repeatability and confirmation to the author's earlier free-release tests. Following free-release tests, students in the course also performed wave response tests on the feed buoy and a Froude-scaled WHOI buoy mooring. Eight different wave heights and periods were used to determine the feed buoy's heave, pitch and surge RAOs.

In preparation for OE 956 testing, the scale model was ballasted to represent the fully-loaded and as-to-be-deployed condition. Heave and pitch natural periods were determined from free-release experiments conducted on April 12, 2004 (McGillicuddy et al., 2004a) and are given in Table 4. Again a minimum of three replicates were performed for each test. Heave damped natural period was 3.5 seconds, which agreed with the results found earlier. The pitch damped natural period was 8.4 seconds; again putting the pitch resonance condition (buoy only) in the middle of the wave energy range during storms. Though attempts had been made while developing the design to alter pitch resonance by changing ballast and adding damping baffles, little advantage was deemed possible, and the maximized reserve righting moment attribute already achieved was regarded as the highest priority.

Table 4: One-ton buoy characteristics determined through physical modeling

Term	Value
Heave damped natural period, (T_d)	3.54 sec
Heave damping ratio, (ζ)	0.093
Pitch damped natural period, (T_d)	8.38 sec
Pitch damping ratio, (ζ)	0.086
Actual mass, (m)	7,900kg
Virtual mass, (m_v)	13,372 kg
Percent of Virtual/Actual Mass	169%

Wave response testing of the buoy model and its two-point compliant WHOI mooring took place on April 28th, 2004 (McGillicuddy et al., 2004b). This experimental setup is shown in Figure 44 (right). Due to tank width limitations, the entire buoy mooring and grid network could not be fully set up. Instead, the three mooring grid point attachments for the tether-hoses were mounted fixed at the tank walls. This assumed that feed buoy mooring dynamics would be most influenced by the directly connected, compliant members, while remote fish cage mooring components, such as grid anchor lines, would play a diminished role. A test plan for wave response testing is in Appendix O. Regular, single frequency wave tests were conducted to obtain normalized transfer functions in the form of RAOs. The maximum heave RAO (heave amplitude divided by wave amplitude) was 1.67 and occurred at the heave damped natural period of 3.5 seconds. Maximum pitch RAO (pitch amplitude in degrees divided by wave amplitude) was 11.4 degrees per meter and occurred at a period of 7.10 seconds. This is 1.3 seconds less than the expected pitch damped natural period of 8.4 seconds. This difference is likely due to the moorings effect on the feed buoy, since the damped natural period was determined without the mooring. RAO results revealed little to no danger to the buoy's ability to survive predicted OOA site conditions.

For the author, additional objectives of wave response testing were to observe designed mooring configurations to check for snap and chafe situations. As seen in Figure 44 (right), the concern was whether the slack feed hose could possibly make contact with or chafe the submerged grid line when the wave direction was normal to the two mooring tether-hoses. The rubber mooring tether-hoses were designed with a stiff spring constant to minimize snap shock-loading on all mooring members. During these tests, no unusual buoy or mooring behaviors were visually observed.

Following OE 956 course experiments, the one-ton feed buoy model was used again to test the alternate feed buoy mooring configuration. These experiments were setup for observational purposes only. Despite the advantages of the two-point compliant WHOI mooring, the design was not implemented due to its cost and the delivery time of the mooring tether-hoses. When procuring the WHOI components before the scheduled installation date became doubtful, an alternate feed buoy mooring was devised. This system consisted of two low-stretch Polysteel® mooring lines with mid-span concrete weights used to provide a restoring force. A drawing of this mooring is shown in Figure 42. Using only the fish cage grid mooring, this mooring design was assembled in the wave tank to observe whether the center weight provided an adequate restoring force and watch circle. Once again no unexpected or disconcerting reactions were observed. Other than by observation, it was never quantified how the mooring design affected the feed buoy's heave or pitch responses or RAOs. Due to pressures to feed the cod fish, the feed buoy and its mooring were deployed without further model testing or discussion about delaying the installation.

CHAPTER 10 - ONE-TON FEED BUOY

CONSTRUCTION AND DEPLOYMENT

10.1 Structure Fabrication

Stommel Fisheries was awarded the contract to build the one-ton feed buoy structure because of their knowledge of the OOA project, having built the first quarter-ton feed buoy. Stommel Fisheries was also the lowest-bid contractor out of three other quotes. Having recently purchased an old marina in Bourne, Massachusetts, Stommel Fisheries had the equipment and the facilities to handle construction of the one-ton buoy's large steel and aluminum parts. With crude drawings and an understanding of the design, Stommel Fisheries began ordering material in late March 2003. Fabrication of the main steel structure began in April with the tapered discus hull of the buoy. Once the discus was built, including the small reserve buoyancy under the floor and a bilge well, the buoy's "legs" were fit and welded into place with the ballast container. The photo in Figure 45 shows the buoy's base, its legs and the ballast container at far right.

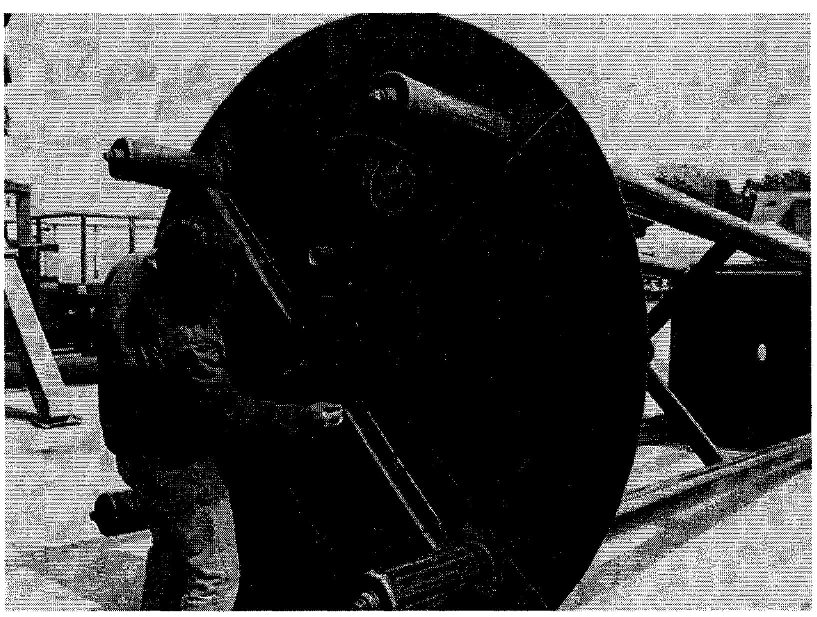


Figure 45: Buoy's steel hull fabrication at Stommel Fisheries

The 5.2 meter long legs were made of six-inch steel pipe, which supported the ballast container without adding unnecessary buoyancy like the smaller quarter-ton buoy design. This was done to lower the buoy's center of gravity, while keeping its center of buoyancy as high as possible. The difference between center of gravity and center of buoyancy contributed to the length of the righting arm. The buoy's legs penetrated the hull for both support and to use the pipe's interior volume to contain coolant fluid for the diesel generator. Two of the buoy's legs were joined inside the ballast container by a two-inch steel pipe. This was done so warm fluid would flow down one pipe leg, become cooled by the surrounding seawater and flow back up the other pipe leg. Enough volume of coolant fluid was contained in the pipes that the generator could run for hours with the coolant fluid remaining cold.

Simultaneously to the construction of the buoy's hull and legs, the main cylindrical body of the buoy was fabricated as a separate piece. The body consisted of 3/16-inch thick steel plate, which was bent into place using a come-along winch and clamps. Once in position, the steel plate was tack welded and eventually permanently welded in place. The buoy's round shape was maintained by 0.61 meter-spaced interior support framing. The photo in Figure 46 shows the framing looking inside the buoy. Other built-in internal parts are labeled in Figure 46.

Once this section was complete, the buoy's hull and legs were stood upright. The main cylinder was lifted approximately six meters and placed on top of the hull. A welder, standing inside the main cylinder, welded the two sections together. Once the inside seam was welded, the exterior was also welded to ensure a solid connection between the two main structural components.

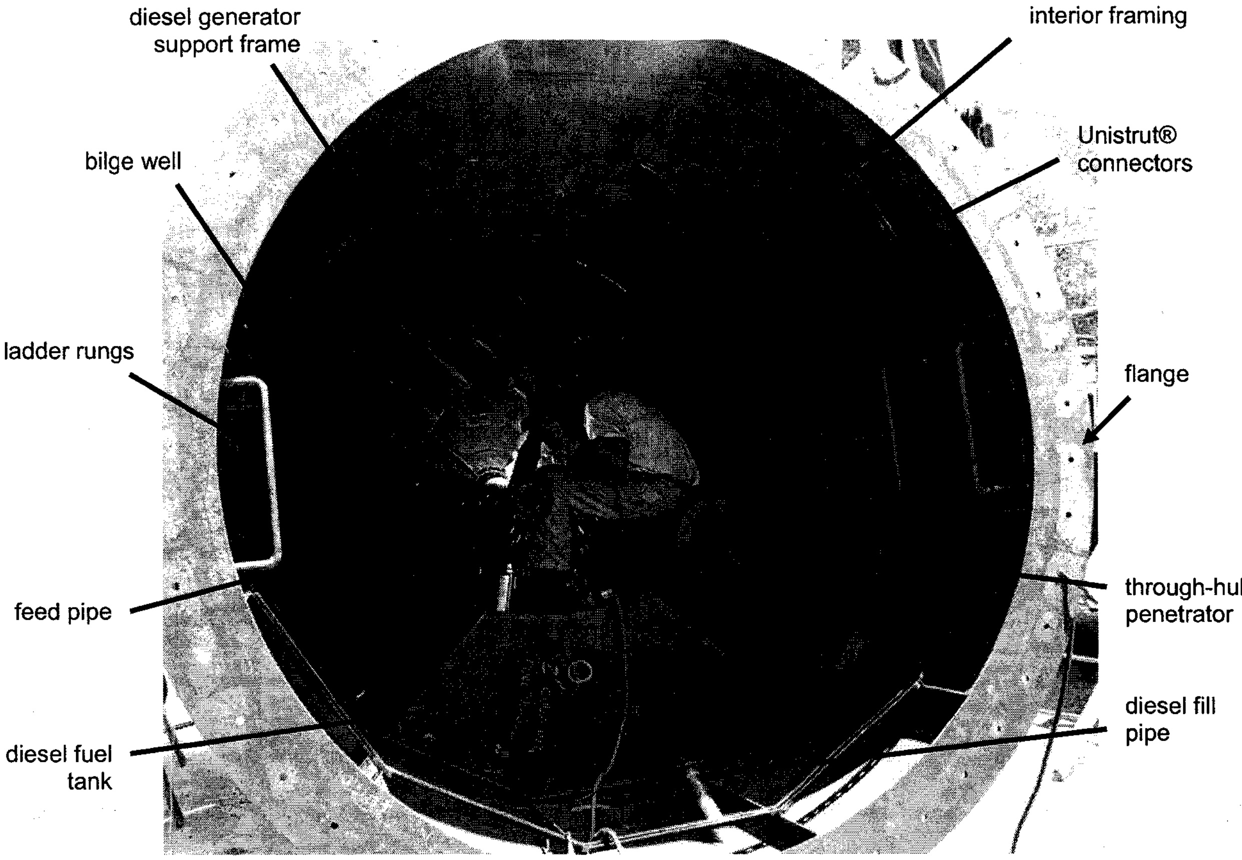


Figure 46: Internal view of the main cylindrical body

The aluminum buoy section, seen in Figure 47, was built in the marina's garage using a similar method to building the steel parts. This section contained the buoy's two access hatches, framework to support the feed hopper, railings, appendages and feed hatch on the top deck. The three hatches, built by Bomar Pompanette LLC, were made of cast aluminum with aluminum mounting rings. The mounting rings were welded directly and flush to the buoy structure. These hatches were hinged and watertight by compressing the rubber gasket with four tie-down dogs. The two side access hatches were 24-inch square hatches and the top hatch for filling feed into the hopper was a twenty-inch diameter round hatch. All hatches were modified to make them lockable with a marine-grade padlock. This was necessary to prevent unwanted people from entering the buoy and possibly harming themselves or the buoy systems.

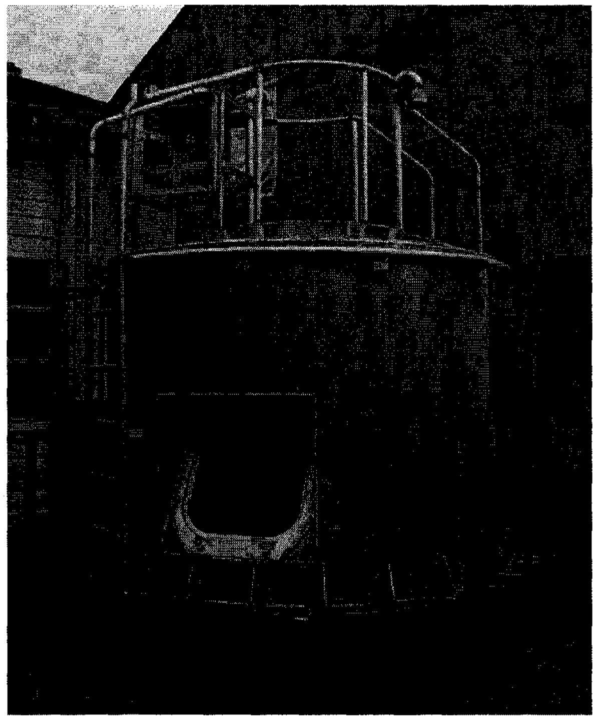


Figure 47: Top aluminum buoy at Stommel Fisheries

After the final touches, including installing the external ladders, handholds and numerous mounting brackets, the two main steel and aluminum structures were trucked from Stommel Fisheries in Bourne, MA to the Aulson Company in Somersworth, NH. Aulson prepared the buoy for painting by sandblasting the steel to get rid of the rust oxidization and provide a profile for the paint to stick to. The aluminum, on the other hand, was cleaned and chemically etched prior to painting. Both components were primed and then painted using a two-part marine epoxy paint. The buoy's area below the estimated waterline was painted with a red anti-fouling paint to inhibit marine algal growth. The photo in Figure 48 shows the steel buoy section with its yellow top coat and red anti-fouling layer. Following its painting in August, the buoy was transported to the UNH JACOE building in Durham, NH. The buoy spent two months in the exterior covered storage area of JACOE, where installation of most mechanical and electrical feed buoy components took place.

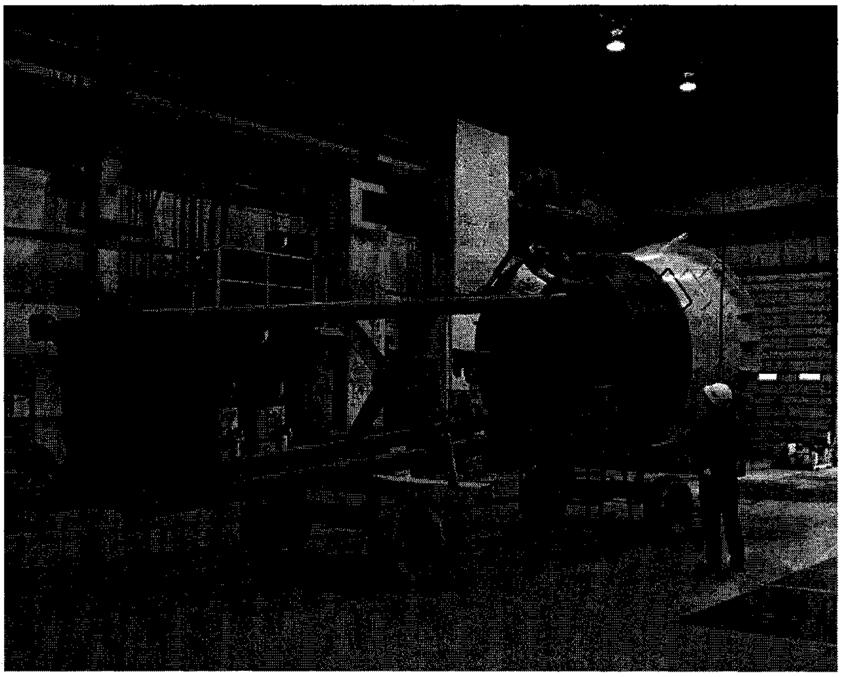


Figure 48: Completing painting at the Aulson Company

10.2 Installation of Internal Components

Due to its bulky size and weight, the one-ton feed buoy was positioned outside the JACOE building in the exterior storage area shown in Figure 49. The purpose of having the feed buoy at UNH was to size, plumb and outfit all essential internal components. This work included installing the shutoff valves, bilge pumps and most of the equipment mentioned in section 8.1. A combined plywood and fiberglass grate deck was cut and installed. This false deck was used to free up precious floor space inside the buoy, but also kept people from stepping on and possibly damaging critical valves or fittings below the buoy's waterline. Main seawater intake valves, two centrifugal pumps, the bilge pumps, and battery bank were all mounted below the deck floor of the buoy.

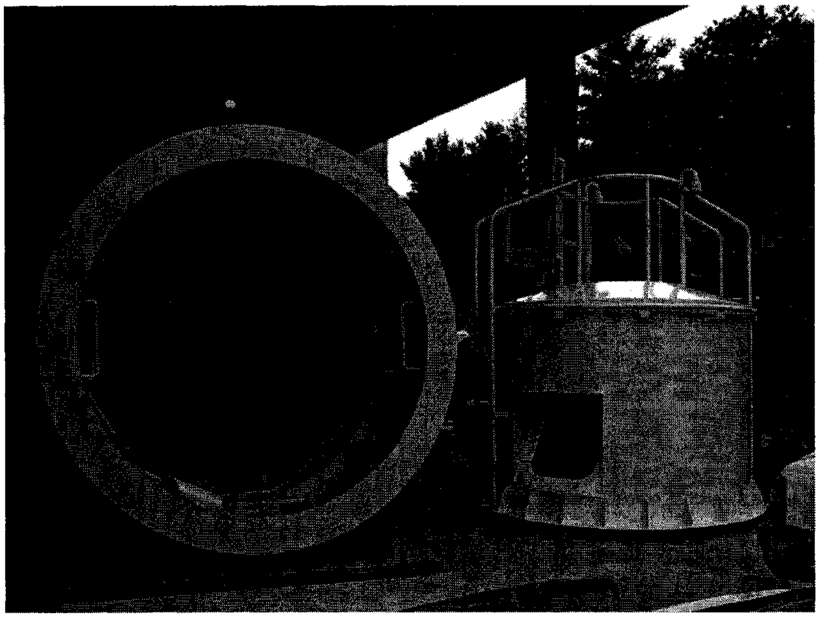


Figure 49: Interior view of steel section (left) and aluminum upper (right) at UNH JACOE

Bumpers around the exterior of the buoy were necessary to prevent damage to the buoy or a support vessel. COTS docking bumpers were priced out, but due to their expense, a less expensive alternate was sought. Fourteen old truck tires, acquired from the UNH mechanic's garage, were used instead. Holes were drilled through the tread of the tire and they were suspended with chain from gussets around the flange and support plates on the buoy's base. The fourteen tires provided protection at a gunwale height around the entire buoy. These tire bumpers can be seen in Figure 50.

After being outfitted at UNH JACOE, the one-ton feed buoy was transported on November 5, 2003 to the New Hampshire Port Authority near the Sarah Long Route 1 Bypass Bridge, a twenty-three kilometer journey. Due to the buoy's large diameter, a special "low boy" flatbed trailer, shown in Figure 50 (left), was necessary to meet state roadway height limits. Once at the Port Authority barge dock underneath the Sarah Long Bridge, the lower steel buoy section was lifted upright, so that the lead ballast bricks could be loaded. The photo in Figure 50 (right) shows the buoy upright, while ballast is being loaded. Slightly over two tons of lead bricks were arranged evenly in four compartment bays in the ballast container. A flat steel plate covered the ballast container so that it could not become dislodged or shift out of balance during transport to or while at the aquaculture site. Once fully loaded, the steel lower buoy section was lowered into the water on the corner of the barge dock. The buoy was tied off to the pier allowing for tidal height changes. The diesel generator, pressure cylinder and other bulky or heavy components were lowered into the buoy using the pierside crane.

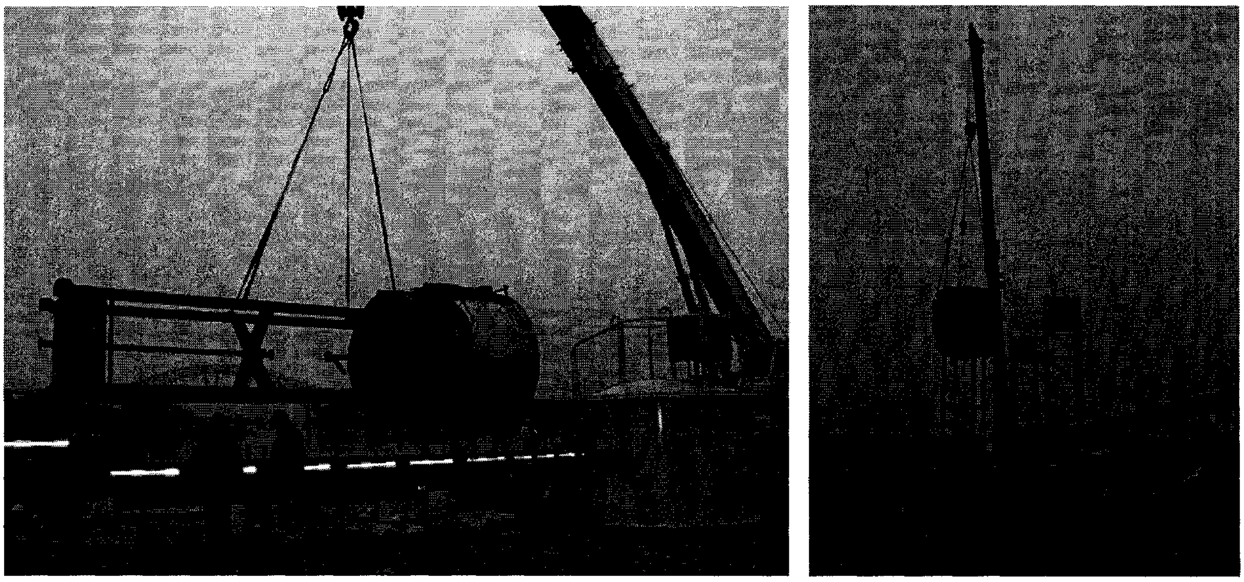


Figure 50: Transport to NH Port Authority (left) and erecting buoy upright to the load ballast weight (right)

When the items inside the buoy were secured, a 0.64 centimeter thick, sixty-durometer rubber gasket was laid out and permanently glued using 3M 5200 Marine Adhesive. This gasket provided cushion and isolation between the two dissimilar metals. The buoy's aluminum upper section was then placed on top of the floating steel section as shown in Figure 51. A pilot hole was located in the flange to ensure its correct orientation and spike wrenches were used to line up the bolt holes. Forty-eight 3/8-inch stainless bolts fastened the two buoy sections together.

The one-ton feed buoy was at the NH Port Authority for one month, while other finishing touches and installations were performed. Other work consisted of piping the generator's cooling and exhaust systems, installing the feeding system equipment, and all electronics and sensors on the buoy. The final part to be installed was the mixing chamber, since its size had to be precisely measured when all other components were installed. The buoy's diesel tank was filled by a Hanscom delivery truck with approximately 650 liters of diesel fuel. The month at the NH Port Authority was used to test all mechanical and electrical components onshore before the buoy was towed to the harsh environment of the OOA site. First-time trials and testing included, for example: making sure the generator ran, its coolant fluid remained sufficiently cool and the battery charging worked correctly. Once this was accomplished, other systems, which relied on the generator for power, could also be tested. This included equipment like the rotary airlock and seawater pumps. Most systems worked when piped or wired correctly, but the true test was the system's operation with the buoy's own control system. Figure 37 is an example of some of the onboard electrical equipment that was tested at this time.

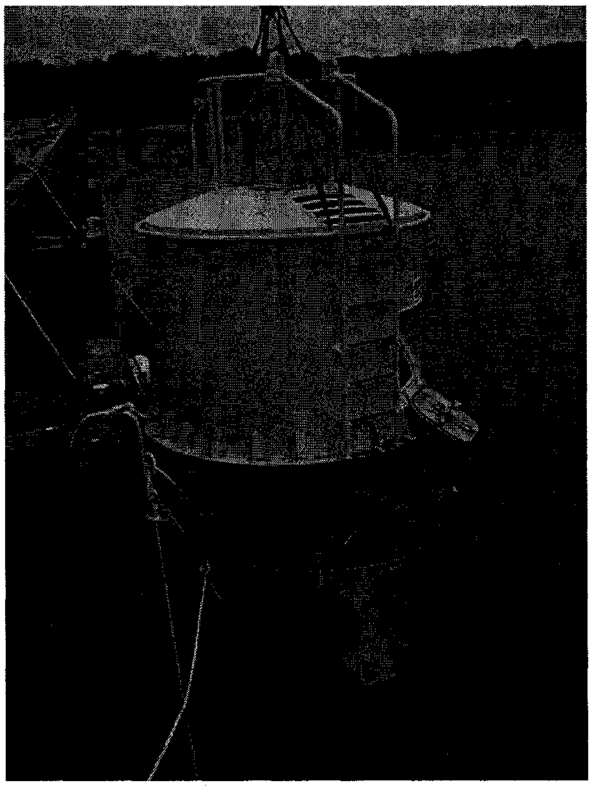


Figure 51: Joining together upper and lower buoy sections

10.3 Deployment

The one-ton feed buoy was towed from the NH Port Authority to the aquaculture site over a two-day period starting on December 9th, 2003. Figure 52 shows the towing arrangement used by the R/V *Gulf Challenger*. Split over two days, the entire tow took approximately six hours, because the tow boat maintained a speed over ground of three knots or less to prevent any possible damage. The buoy was attached to a UNH boat mooring overnight at the Fort Constitution Coast Guard Station. An early start the next day was necessary to finish towing the feed buoy to the OOA site and get it securely connected to the feed buoy mooring.

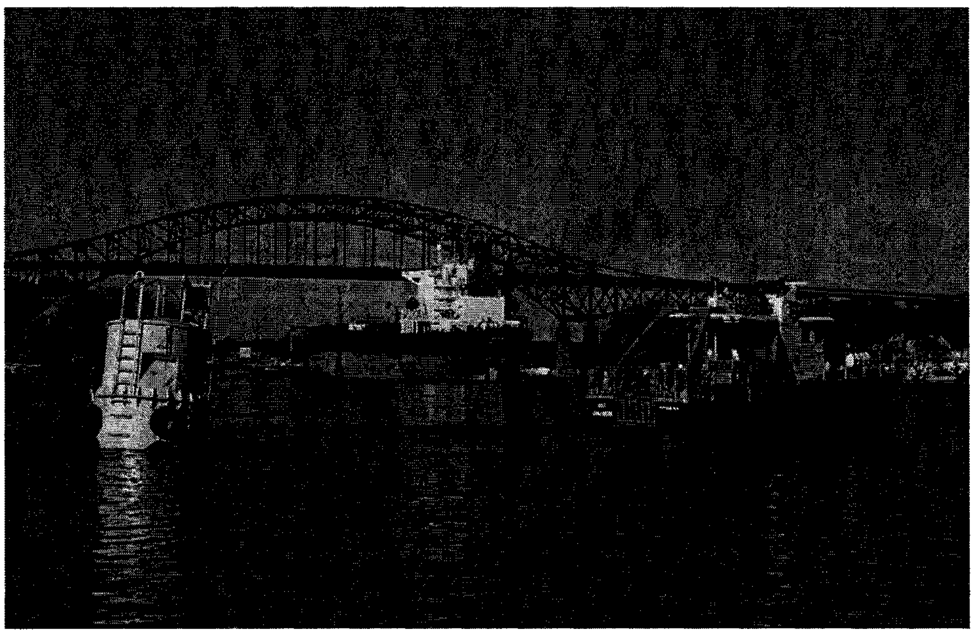


Figure 52: Towing the one-ton feed buoy from NH Port Authority

Once at the OOA cage site, the feed buoy's slack mooring lines without their center weights were connected to the appropriate diagonal grid corners. The center southwest corner was the first to be connected followed by the northeast corner. Once both lines were attached to the cage mooring, the mid-span mooring weights were connected to the center of each mooring line as shown in Figure 53. The Gulf Challenger hauled up the center connection of each mooring line and shackled the concrete restoring weight. The weights were then lowered until the tension of the haul line was slack, meaning the restoring weight had all been transferred to the buoy mooring. This procedure was repeated for the northeast corner. When completed, the one-ton feed buoy was moored on its own two-point mooring as shown in Figure 42.

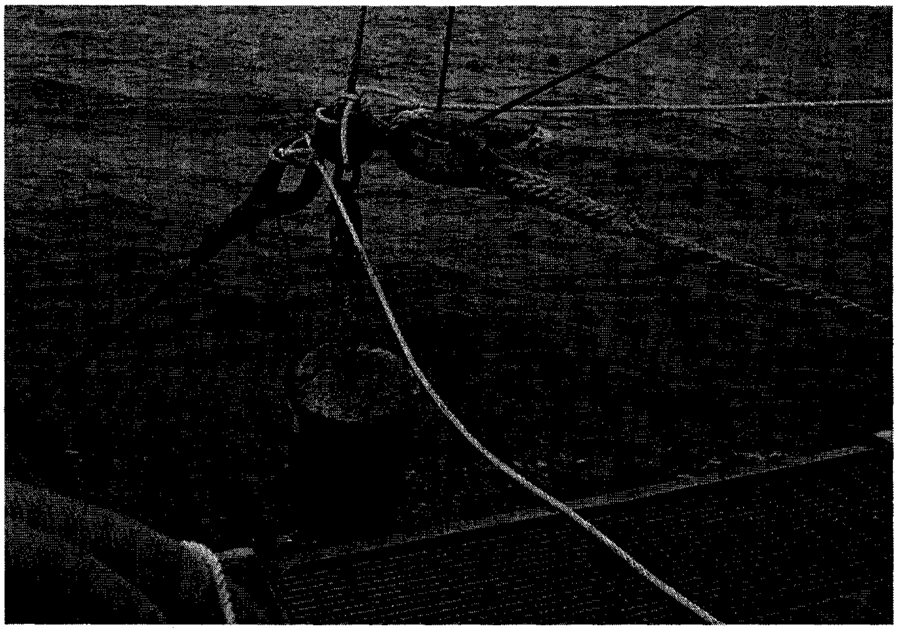


Figure 53: Mid-span concrete mooring weight

The next task of the buoy's deployment was to attach the flexible PVC feed hose from the feed buoy to the cod fish cage approximately one hundred meters away. The feed hose was coupled to the feed buoy's southwest mooring line by tying them together with nylon rope. The feed hose was unrolled in one-hundred-foot sections, flooded with seawater for the hose to submerge and then carried off by SCUBA divers. The divers lashed the feed hose to the southwest mooring line using short sections of nylon rope. In the center where the concrete restoring weight was located, a sufficient amount of slack was given to the feed hose to allow for the rise and fall of the mooring lines without tensioning the inelastic feed hose. The feed hose was not meant to restrain the buoy at all. After the feed buoy mooring, the feed hose was laid out and tied along a bridle line to the rim of the fish cage. Three one-hundred-foot hose sections were needed to reach the fish cage. At the end of the feed hose, a flanged end was installed and then bolted to the fish cage's rim using the connector shown in Figure 38. The rim connection sustained the weight of the hose and relieved any tension from the fish cage, especially its nylon netting. After the rim connection, rigid PVC pipe replaced the flexible hose to the top of the cage, where the feed pellets were dispensed. The rigid pipe was lashed to one of the cage's upper spoke lines, shown in Figure 3. A PVC elbow at the top of the cage diverted the feed through the net and into the cage. Although it was not ideal for the feed pellets to climb from the cage rim to the top of the cage, sufficient flow from the feed buoy's two seawater pumps prevented feed pellets from settling and potentially clogging the feed hose. The rim connection and PVC pipe on the fish cage had been set up days ahead of the feed buoy deployment in order to save time for the buoy.

Unlike the quarter-ton feed buoy, the one-ton feed buoy deployment was accomplished in two days, including the tow from the NH Port Authority. This was possible because the feed buoy had been prepped for operation while at the Port Authority and did not require much setup in the field. The marine weather had also cooperated with the feed buoy deployment, which was an advantage. Following the buoy's deployment to the OOA site, field trials for the one-ton feed buoy began.

CHAPTER 11 - ONE-TON FEED BUOY

FIELD PERFORMANCE

11.1 Field Trials

Figure 54 shows both UNH OOA feed buoys deployed at the aquaculture site in early February 2004. Similar to the quarter-ton buoy, the one-ton feed buoy experienced a few initial start-up problems; however for this buoy all the problems resolved around remotely starting and operating the diesel generator. Problems with the generator included: improper grounding to the starter, an insufficient supply of fuel to the generator, seawater in the diesel tank, weakened starting batteries and possibly gelled diesel fuel due to the cold temperatures.

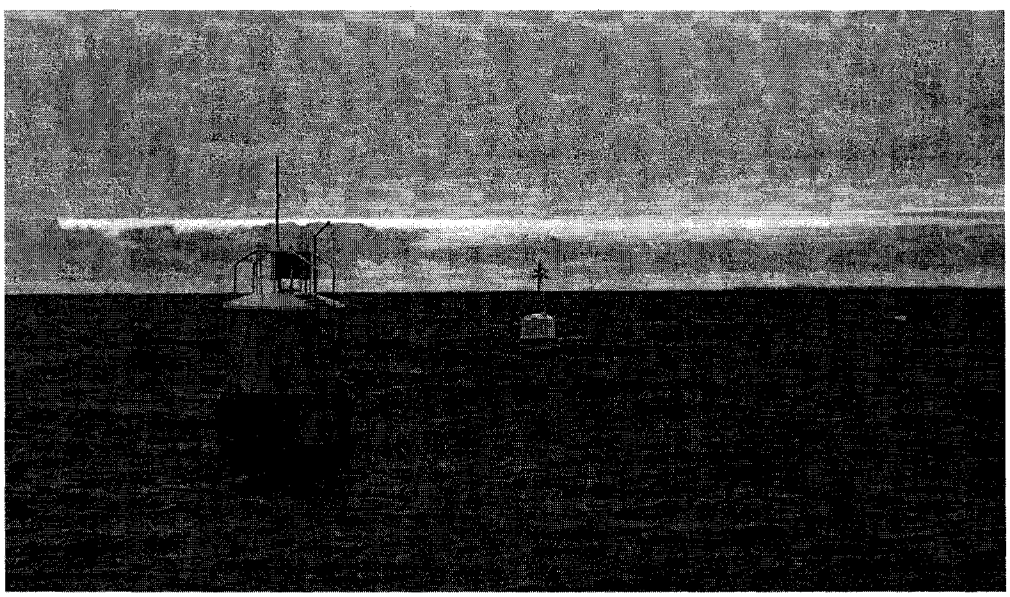


Figure 54: One-ton feed buoy (in foreground) and quarter-ton feed buoy at the UNH OOA site

During the first few weeks of deployment, the buoy's generator would only start intermittently. This problem was pinpointed to a misleading grounding connection on the engine's starter motor. Once corrected, the generator was plagued by other problems. Insufficient supply of diesel fuel to the generator was caused by a weak fuel pump on the generator. This pump lacked the suction to draw diesel fuel from the tank, particularly as the tank's fuel level became lower. Compounding this, the colder weather caused the diesel fuel to gel or become thicker, despite the anti-gelling solution that had been added to the tank. To correct this, an inline 12-volt fuel booster pump was installed. The booster pump was positioned closer to the diesel tank and would begin pumping prior to starting the generator to ensure that fuel was being supplied. As a result of working through the generator's starting problems, the batteries had been drained sufficiently that they would no longer retain a decent charge. These batteries were replaced with new batteries. The final problem addressed in the field was that seawater had gotten inside the diesel tank spoiling the remaining fuel. Though the generator had its own water separator and two additional fuel filters/water separators had been added, a sufficient amount of seawater had entered the tank that the filters and separators would quickly become clogged. Seawater had entered the fuel tank through the fill pipe, which had a lockable cover that was not completely watertight. This cover was added to prevent someone from tampering with or stealing diesel fuel from the buoy. When waves were one-meter or larger, lapping up the side of the buoy, water passed through the cap/cover into the tank. This issue was fixed by replacing the cover with a non-locking threaded pipe cap. The remaining diesel in the tank was pumped out and replaced with new diesel fuel. Note: the diesel tank was drained multiple times to try to remove water that had gotten inside. An additional larger water separator was added, and a normal maintenance practice was started to drain the separator's collection container. After correcting all of these problems, which took a few weeks because of the season and weather, the buoy was operational and supplying the cod fish with feed. During the time that the feed buoy was unable to operate, feed pellets had to be pumped down from the surface to the fish.

Like the smaller feed buoy, the one-ton feed buoy experienced accumulating freezing spray during the winter months. Fortunately, the two side access hatches were placed four feet off the waterline and the increased weight from the ice was negligible. Although this was a better design, it was also the height where much of the freezing spray accumulated, which made opening the hatches and accessing the buoy difficult. Figure 55 shows an OOA diver breaking away accumulated ice so that he could enter the buoy.

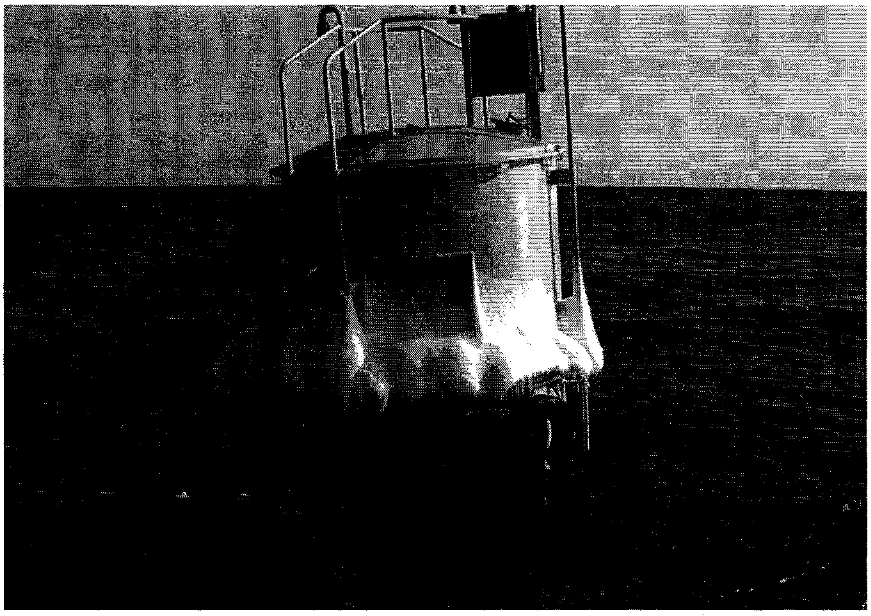


Figure 55: OOA project member breaks away freezing spray ice

Again after the start-up problems in the field were corrected, the one-ton feed buoy performed its designed function feeding the cod fish twice a day with larger volumes than previously available. As the cod fish grew and the waters became warmer in the summer, the volume of feed increased significantly, such that heaving bags of feed on top of the buoy became very laborious. In late spring 2004, the cyclone decelerator unit was delivered and installed on the feed buoy allowing feed to be transferred via a flexible hose from the support vessel to the buoy. The feed access hatch on top of the feed buoy was unhinged and removed. The cyclone decelerator clamped in the hatch's place. The decelerator worked by transferring feed pellets into the top of the unit via high-velocity air. Air speed in the decelerator then dropped, allowing the feed pellets to fall down a hopper funnel into the storage hopper inside the feed buoy.

Additionally, the performance of the onboard electrical system exceeded many expectations. The system's flexibility and physical interior space allowed for several additions to the buoy, including adding an acoustic fish tracking system with its own battery charger and underwater fish cage lighting. Additional power outlets were installed to supply this new equipment. The purpose of the underwater lights, built by JT Electric of the Faeroe Islands, was to stimulate muscle growth and prevent fish sexual maturation by simulating extended periods of daylight during the short winter days. The two 120-VAC metal halide lights were mounted inside the fish cage and ran for six hours a day over two periods. This was deemed a big step towards developing a commercially viable aquaculture system, since fish cage lighting was being utilized at most major aquaculture operations.

The one-ton feed buoy proved to be an asset to the UNH OOA project, because it provided larger amounts of feed twice a day to the caged cod without the need to travel offshore to the site. This regular feeding proved beneficial to the growth of the fish. According to Howell (2005), the cod fish grew reasonably well, because of the regular feedings from the feed buoy and the underwater lights in the cage.

11.2 Modified Mooring

In late July 2004, after the author's involvement with the project, the one-ton feed buoy was relocated from the empty fish cage bay to closer to the cod fish cage, which the buoy was supplying with feed. This was done to free up space in the cage mooring for an additional fish cage. The deployed mooring, shown in Figure 56, consisted of a single open-ended elastic WHOI tether-hose and two concrete center weights. The feed hose was again non-supporting and only used to carry feed to the fish cage. The elastic WHOI tether-hose was a spare from the original feed buoy (Rice et al., 2003). Because of the tether-hose's short length, the remaining length to the feed buoy was created using Polysteel® rope. This configuration was analyzed using FEA techniques prior to its deployment and was deemed adequate for both the feed buoy and the fish cage mooring.

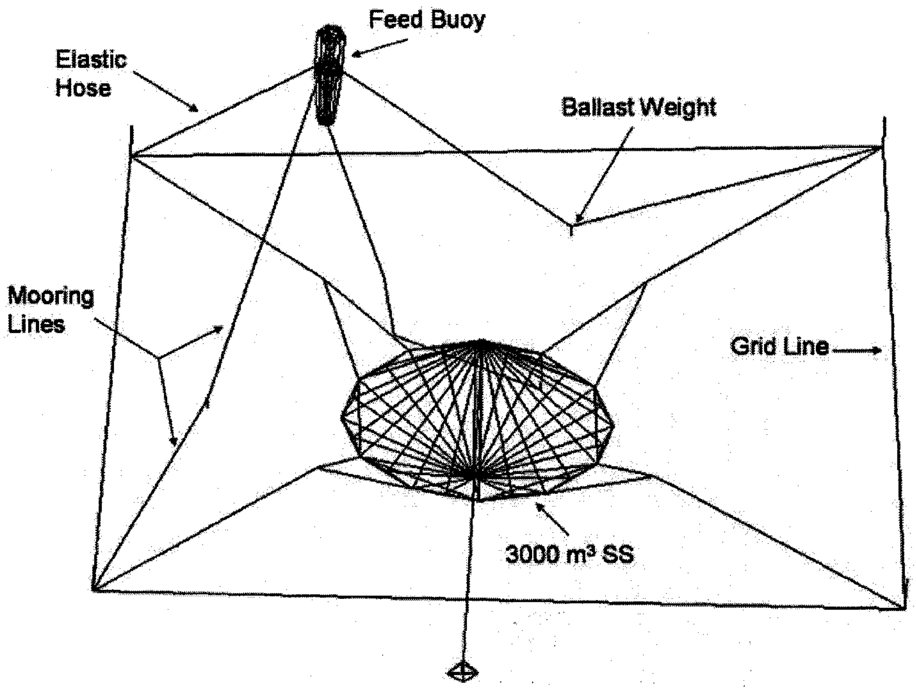


Figure 56: Three-point one-ton feed buoy mooring

11.3 Winter Storm

On December 27, 2004 after being deployed for just over one year, a significant Nor'easter storm struck New England and ultimately caused the one-ton feed buoy to sink. The feed buoy's last data transmission was received at 3:06 am local time on December 27, 2004. At this time, the buoy's 'wake-up' signal was alarming, suggesting that the switch inside the buoy was being shorted by water. Figure 57 displays the month of December 2004 National Data Buoy Center (NDBC) significant wave height data for the following NDBC buoys: Portland, Boston, Stellwagen, Western Maine Shelf and Casco Bay. Figure 58 shows the locations of these buoys.

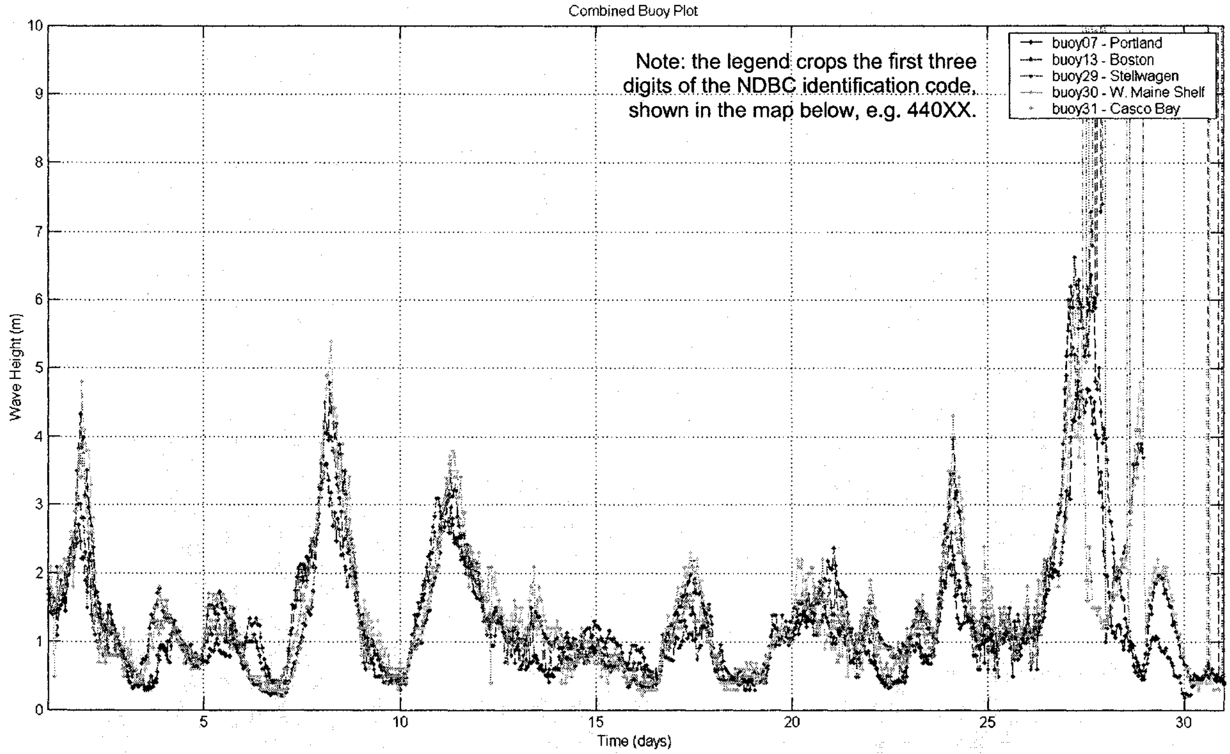
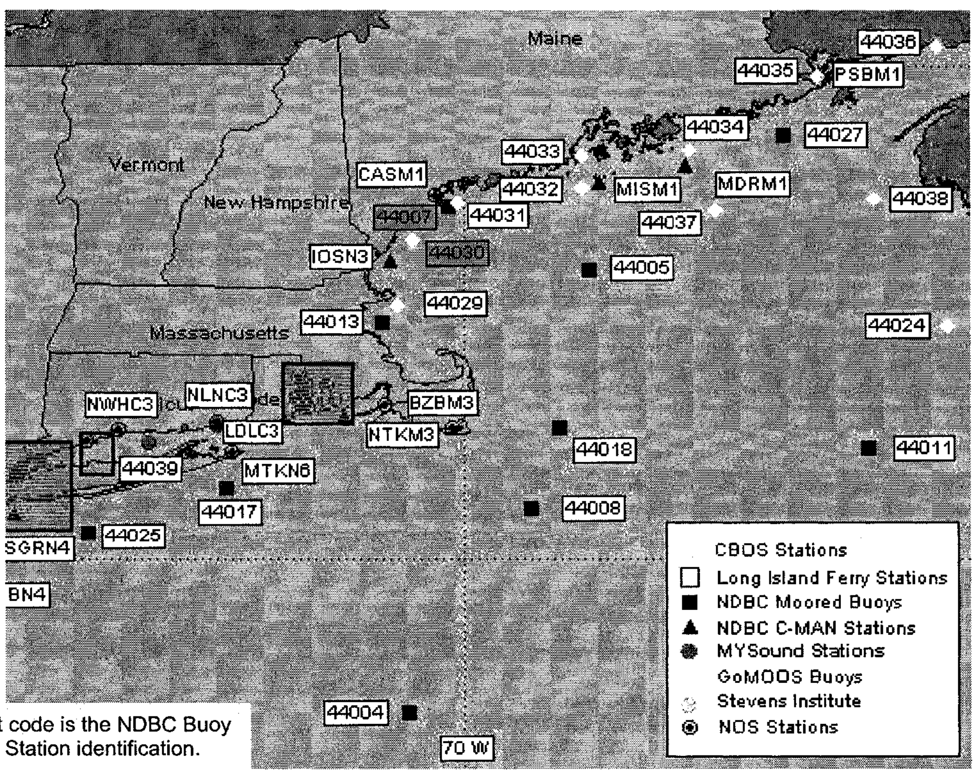


Figure 57: NDBC wave height data for the month of December 2004



Note: 5-digit code is the NDBC Buoy and C-MAN Station identification.

Figure 58: NDBC station locations

The NDBC Boston buoy recorded the peak of the storm at 2:04 AM with a 4.81-meter significant wave height and a dominant period of 7.39 seconds. NDBC Portland had a peak at 12:11 AM with a height of 6.62 meters and 8.11 second period.

Six months later in July 2005, the US Coast Guard recovered the one-ton feed buoy from the ocean seafloor as a training exercise. The feed buoy was off-loaded at the Portsmouth Naval Shipyard's (PNS) Coast Guard pier, where any recoverable equipment or parts were salvaged. The remaining metal was scrapped by PNS. The buoy's aluminum top structure appeared to have imploded as it was severely dented. This suggests that the buoy sank faster than air inside could escape. Upon investigation of the buoy's interior, the most probable scenario for the cause of the buoy sinking is that a weld broke at the base of the feed hopper. This steel plate, which suspended the weight of the entire feed assembly, can be seen in Figure 33. The plate would have been a difficult spot to weld due to tight clearances between the plate and the hopper's framing. Also, the builder likely did not know the weight this plate needed to support, so it was built undersized than it should have been. In large seas, the pitching motion of the buoy may have caused this weld to break, which caused the feed assembly to fall and likely dislodged or broke a watertight connection below the buoy's waterline. The two bilge pumps were unable to keep up with the incoming seawater, thus the buoy sank. It is expected that the feed buoy may have pitched excessively in the storm, since the period of the storm waves closely matched the feed buoy's pitch natural period. It is also suspected that the new feed buoy mooring, deployed six months earlier, was much stiffer than the two previous feed buoy mooring designs and did not allow a full range of motion of the wave's excursion. The stiffness of the mooring was reported by two OOA projects members, who commented that the new mooring produced a tight buoy watch circle.

CHAPTER 12 - CONCLUSIONS

12.1 Quarter-ton Capacity Feed Buoy

As the aquaculture industry moves away from sensitive near-shore farm sites, the development of new feeding systems that are both suitable and reliable for operation in the open ocean will be critical to the success of the offshore aquaculture industry. For the UNH OOA Demonstration project, the development of the quarter-ton capacity feed buoy was the first attempt to build a prototype offshore surface feeding buoy system. Despite its relatively small feed capacity, this feed buoy and its feeding system proved to be a considerable improvement and benefit to feeding submerged finfish aquaculture cages. Since this feeding system could be controlled remotely, it eased the pressure to go to offshore when the marine weather was bad or schedules were busy. The basis for the quarter-ton feed buoy system will likely aid in the development of future, larger open ocean aquaculture feed systems.

Both the quarter-ton feed buoy and its mooring operated for many years without a major failure. FEA modeling, as well as physical model tank testing, proved the buoy's compliant mooring system design for normal use and identified tether weakness during extreme storms. The mooring positioned the feed buoy relatively close to the cage for feeding purposes, yet it also had the ability to absorb large excursions due to large waves, tides and currents. And the addition of the buoy's flotation collar made it virtually unsinkable as was shown during the accumulation of freezing spray and ice. Three suggestions to improve upon the quarter-ton feed buoy design include: 1) strengthening the elastic mooring tethers to prevent overstretching, 2) using miniature waterproof load cells in physical model testing to better estimate mooring loads and 3) to increase the height above the waterline of the side access hatch.

The feed buoy's internal systems also performed exceptionally well both mechanically and electrically. Feed dispensing and conveying equipment operated as was intended with relatively minimal necessary maintenance. Periodic maintenance included cleaning pre-filters on the bilge pumps and occasionally unclogging feed dispensing cups, which may have become blocked with moist feed, an inherent condition of the marine environment. The addition of the centrifugal pump used to force feed pellets and water through the hose was the major improvement over the earlier arrangement that made the feeding system work. The control system provided power and managed all operations of the feed equipment. Radio telemetry allowed data to be sent reliably to shore and commands were received back to the buoy. This flexible system could easily be reprogrammed to allow for immediate changes. The feed buoy was subject to intermittent electrical problems, though they were relatively minor issues for the harsh marine environment where the buoy was located and considering its damaged hatch.

On the initial deployment of the quarter-ton feed buoy, it was observed that the caged haddock had become accustomed to the daily feed cycles and distribution. The haddock would swarm around the feed hose outlet as soon as they heard the buoy's seawater pump turn on. Lessons learned at the quarter-ton feed buoy scale were incorporated into the larger one-ton capacity feed buoy. Since the one-ton feed buoy could not supply multiple fish cages, the quarter-ton feed buoy would continue to be used by UNH OOA, until it could be replaced by a larger feeding system which could feed multiple cages. Until that time comes, the quarter-ton feed buoy will continue to be a 'workhorse' system for the OOA project able to supply feed to finfish in submerged aquaculture cages.

12.2 One-ton Capacity Feed Buoy

Experience with the previous quarter-ton feed buoy served as the basis for design, construction and outfitting of the larger one-ton feed buoy. Prior knowledge and understanding of the buoys' systems made building the second feed buoy quicker and easier than the quarter-ton feed buoy. However, despite their similarities, the one-ton feed buoy had a new level of complexity due to its physical size and weight. This impacted the ease of lifting, handling and transporting the buoy structure. Besides its size, the one-ton feed buoy had other new challenges, mostly related to remotely starting and controlling its onboard diesel generator. As the UNH OOA Demonstration Project expanded, its feeding systems had to also expand to accommodate the increased number of caged and hungry fish. The one-ton feed buoy was successful, as designed, in feeding a single SS3000 fish cage, which at the time contained thirty-five thousand cod fish. Though the buoy's hopper held over one-ton of fish feed pellets, it was well known that this capacity would be quite undersized as the cod became adults and began to eat more. This was particularly true during the summer months when ocean water is warmer and the fish have a greater appetite. A basic calculation of what adult cod fish would eat, assuming their population remained roughly the same, determined that the one-ton capacity feed hopper would need to be filled every other day. Until the time came when a single large feeding system could replace these smaller systems, the one-ton capacity feed buoy would be operated at the OOA site. In the series of offshore feed buoy development, the one-ton feed buoy was one iteration closer to a commercial-sized, near-shore feeding system.

Numerical FEA and physical modeling both proved the WHOI hose mooring design; however due to its price, these mooring hoses were never implemented. The physical modeling effort was successful in determining the buoy design's seakeeping characteristics and wave responses. This new buoy model contributed to the database of various buoy designs and their experimental wave responses. This knowledge of buoy shape factors will be useful for future feed buoy designs.

Mechanical systems of the one-ton feed buoy, including many pumps, valves and other components, performed exceptionally well. Seawater pumps were sufficient in their ability to convey feed pellets through an over one-hundred meter long hose without clogging. Ideally the feed hose should not have been this long, but it was a good test of the system. The buoy's electrical system was a large success due to the design and implementation of these systems by Stanley Boduch and the programming knowledge of Jim Irish. This team developed and constructed every aspect of the electrical system from the MCU to the high power control relays and then communicated instructions on how each component had to be controlled. The control system was much more complex than expected, due to the amount of logic programming that was necessary to make the system autonomous.

The one-ton feed buoy had a significant amount of unused internal space, which led to criticism that the buoy could contain a larger feed hopper and hence a greater capacity of feed. The location of the two side access hatches produced this space. Issues with the quarter-ton feed buoy's hatch being centimeters off the waterline forced the design of the one-ton buoy to install the side hatches roughly 1.4 meters above the water's surface. As shown in Table 3, with a total feed capacity of 1100 kg and an overall buoy mass of 7530 kg, the ratio of feed payload to overall buoy mass is 14.6 percent. The quarter-ton buoy, on the other hand, had a feed payload to buoy mass ratio of 12.3 percent. It is doubtful that the payload to overall mass ratio can be improved upon, using the feed-hopper-at-the-top configuration that was required in the one-ton design. Space inside the one-ton feed buoy allowed a person to stand without feeling unnecessarily cramped, and it allowed for additional fish monitoring equipment and other equipment to be installed.

The one-ton feed buoy was designed, model tested, constructed and deployed in a time period of around ten months. This short amount of time was due to the pressure on the OOA project to feed the already purchased and caged cod fish. The arrival of the cultured fish came prior to there being an available infrastructure to feed them. With OOA engineers and staff available at the moment, the one-ton feed buoy was built in short time. The feed buoy was deployed to the OOA site without a proper hazard or risk analysis being performed on the buoy's structural, mechanical or electrical systems. Ultimately these reasons would have likely contributed to the loss of the feed buoy. It should also be noted that had the one-ton feed buoy been provided with positive buoyancy in the form of either foam or watertight compartments, it (like the quarter-ton buoy) would have at least floated and been repairable to operate once again. Finally, a suggestion for future buoy deployments is to not install them during the winter months when New England weather is at its worst. This makes inevitable first-time installation issues and problem troubleshooting more difficult than if the marine weather was not a factor.

The objective of the two automated feed buoys was to design and build reliable research prototype open ocean feeding systems that could supply fish feed pellets to submerged offshore fish cages. Such systems would ultimately save the aquaculture operation both time and money over other methods such as feeding by hand or from a support vessel. Despite the one-ton buoy's larger feed storage capacity, this buoy was considered small for what is needed for a commercial scale venture. Based generally off the experiences of these feed buoys, a large twenty-ton capacity feed buoy is being developed and built in conjunction with OceanSpar LLC and a NOAA Small Business Innovative Research (SBIR) grant. The twenty-ton capacity feed buoy will be launched and deployed to the UNH OOA Demonstration Project site in the summer of 2007.

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APPENDICES

Appendix A – Quarter-ton Feed Buoy - Reserve Flotation Collar

Built to UNH specifications in September 2002 by Gilman Corporation, Gilman, CT.

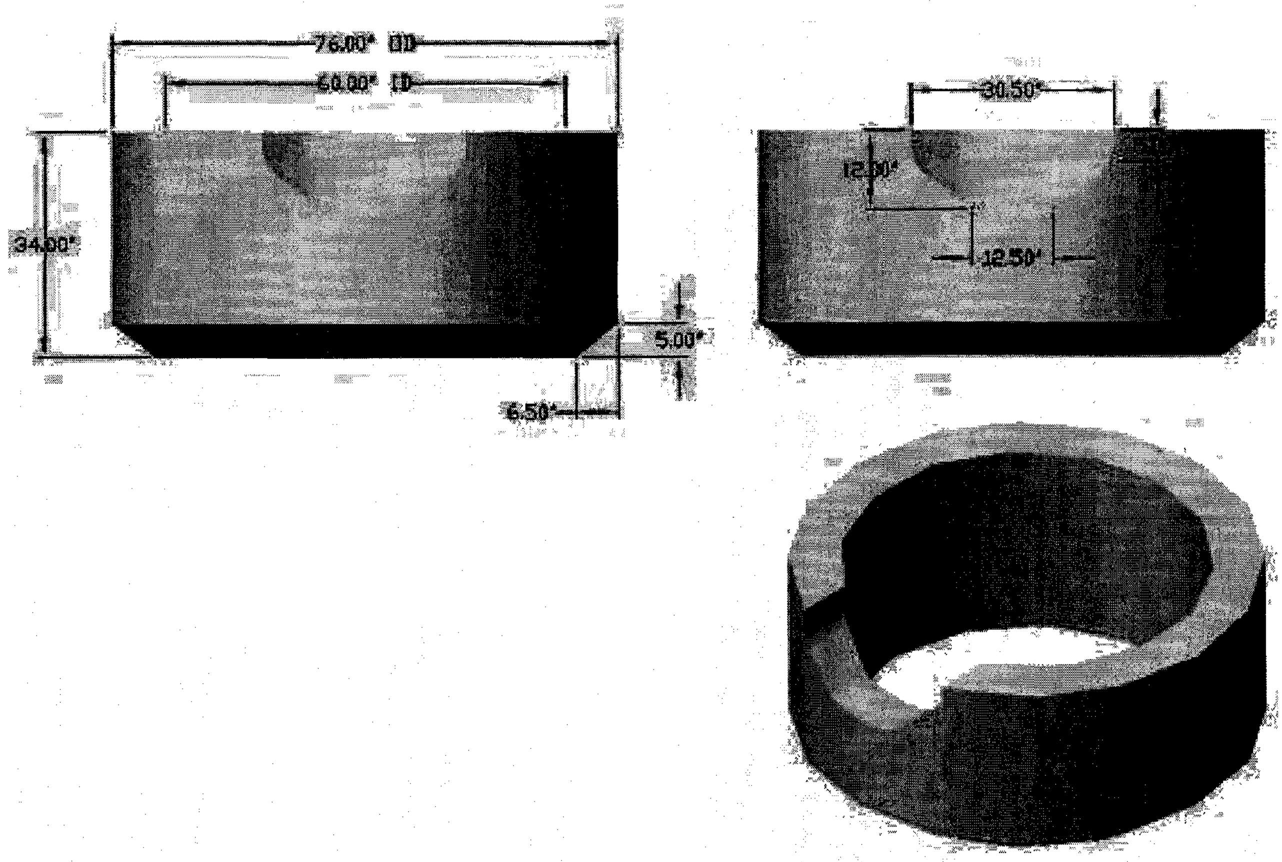


Figure A1: Supplemental flotation collar for the quarter-ton feed

Appendix B – Quarter-ton Feed Buoy - MathCAD-Calculated Hydrostatics

Hydrostatics

Fullerton 02/03

Updated Feed Buoy Equilibrium Calculations

Center of Gravity Calculations

$$y_{cg} \cdot W = \sum_i y_i \cdot \Delta W$$

	Weight (to the nearest pound)	Center of Gravity (all referenced from the buoy's base)	Source measurement
buoy's bottom shell	$W_{bot} := 1027 \cdot lb$	$y_{bot} := 92.5 \cdot in$	measured/MASSPROP
buoy's top shell	$W_{top} := 227 \cdot lb$	$y_{top} := 183.3 \cdot in$	measured/MASSPROP
ballast weight	$W_{ballast} := 1603 \cdot lb$	$y_{ballast} := 8.50 \cdot in$	measured/MASSPROP
floatation collar	$W_{float} := 165 \cdot lb$	$y_{float} := 129.7 \cdot in$	MASSPROP
feed (incl. hopper)	$W_{feed} := 530 \cdot lb$	$y_{feed} := 189.5 \cdot in$	measured / approx.
batteries	$W_{batt} := 280 \cdot lb$	$y_{batt} := 118.0 \cdot in$	measured / approx.
electronics	$W_{elec} := 135 \cdot lb$	$y_{elec} := 136.0 \cdot in$	measured / approx.
wind generator	$W_{wind} := 44 \cdot lb$	$y_{wind} := 273.0 \cdot in$	measured / approx.
solar generator	$W_{solar} := 35 \cdot lb$	$y_{solar} := 202.0 \cdot in$	measured / approx.
fittings, fasteners, etc.	$W_{misc} := 25 \cdot lb$	$y_{misc} := 118.0 \cdot in$	measured / approx.

Subtotals

weight of shell $\quad W_{shell} := W_{bot} + W_{top} + W_{ballast} + W_{float} \qquad W_{shell} = 3022\,lb$

weight of components $\quad W_{comp} := W_{feed} + W_{batt} + W_{elec} + W_{wind} + W_{solar} + W_{misc}$

$W_{comp} = 1049\,lb$

Appendix B cont'd

Total

total buoy weight $W_{total} := W_{shell} + W_{comp}$ $W_{total} = 4071\,\text{lb}$

Center of Gravity

CG of buoy's internal components

$$y_{comp} := \frac{y_{feed} \cdot W_{feed} + y_{batt} \cdot W_{batt} + y_{elec} \cdot W_{elec} + y_{wind} \cdot W_{wind} + y_{solar} \cdot W_{solar} + y_{misc} \cdot W_{misc}}{W_{comp}}$$

$y_{comp} = 165.75\,\text{in}$

(from the buoy's base)

CG of buoy's "shell"

$$y_{shell} := \frac{y_{bot} \cdot W_{bot} + y_{top} \cdot W_{top} + y_{ballast} \cdot W_{ballast} + y_{float} \cdot W_{float}}{W_{shell}}$$

$y_{shell} = 56.79\,\text{in}$

(from the buoy's base)

overall CG of buoy $y_{cg} := \dfrac{y_{comp} \cdot W_{comp} + y_{shell} \cdot W_{shell}}{W_{total}}$ $y_{cg} = 84.87\,\text{in}$

(from the buoy's base)

Appendix B cont'd

Determining the Waterline Position:

density of seawater $\rho_{sw} := 64.0 \cdot \frac{lb}{ft^3}$

total volume of displaced seawater $V_{displaced} := \frac{W_{total}}{\rho_{sw}}$ $V_{displaced} = 63.61\,ft^3$

Calculating Submerged Volumes (see figure below)

outer diameter of the floatation collar $OD := 76 \cdot in$

density of lead $\rho_{lead} := 711 \cdot \frac{lb}{ft^3}$

volume of ballast $V_{ballast} := \frac{W_{ballast}}{\rho_{lead}}$ $V_{ballast} = 2.25\,ft^3$

volume of spar $V_{spar} := \pi \cdot (12 \cdot in)^2 \cdot 102 \cdot in$ $V_{spar} = 26.7\,ft^3$

cb of spar $y_{spar} := 54.5 \cdot in$ measured / approx.

volume of aluminum pieces $V_{alum} := 2326 \cdot in^3$ $V_{alum} = 1.35\,ft^3$

using MASSPROP of discus portion, ballast bin, etc.

cb of alum. pieces $y_{alum} := 37.3 \cdot in$ measured / approx.

volume of discus $V_{discus} := 8143 \cdot in^3$

cb of discus $y_{discus} := 108.0 \cdot in$ measured / approx.

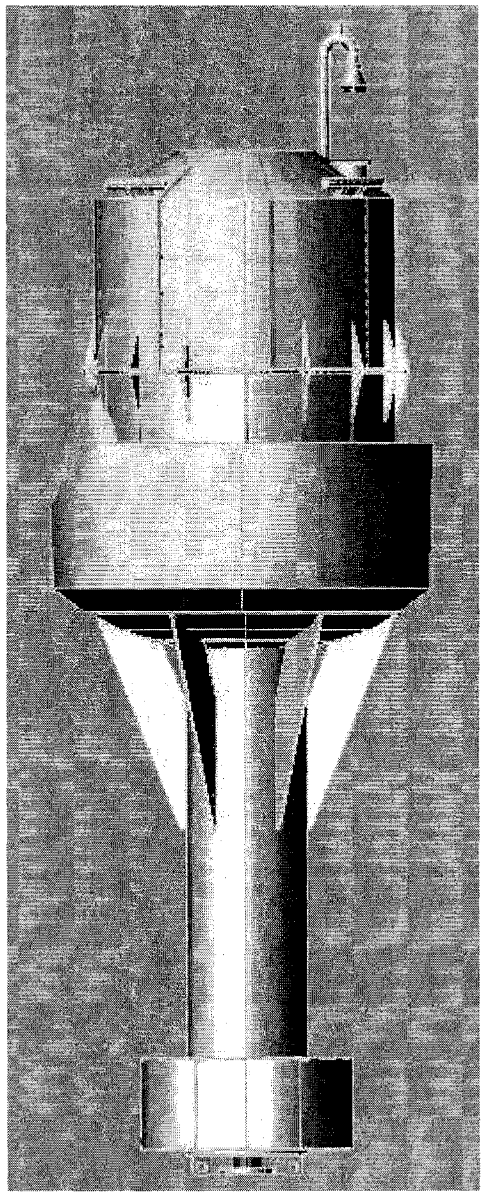
volume of cutout portion of foam

$$V_{cutout} := \left[\pi \cdot \left(\frac{OD}{2}\right)^2 \cdot 5.0 \cdot in\right] - \left[2 \cdot \pi \cdot \left(\frac{OD}{2}\right) \cdot \frac{6.5 \cdot in \cdot 5.0 \cdot in}{2}\right]$$

$V_{cutout} = 10.88\,ft^3$

cb of cutout $y_{cutout} := 112.0 \cdot in + \frac{2 \cdot 5.0 \cdot in}{3}$ $y_{cutout} = 115.33\,in$

Appendix B cont'd



location of waterline

$$y_{wl} := \frac{V_{displaced} - \left(V_{ballast} + V_{spar} + V_{alum} + V_{cutout} + V_{discus}\right)}{\pi \cdot \left(\frac{OD}{2}\right)^2} + 5.0 \cdot in$$

$$y_{wl} = 11.75\,in$$

(from the bottom of the 5' OD cylinder)

Appendix B cont'd

Center of Buoyancy

volume of buoy's OD displaced $V_{OD} := \pi \cdot \left(\frac{OD}{2}\right)^2 \cdot \left(y_{wl} - 5.0 \cdot in\right)$ $V_{OD} = 17.71\,ft^3$

cb of buoy's OD $y_{OD} := 117.0 \cdot in + \frac{\left(y_{wl} - 5.0 \cdot in\right)}{2}$ $y_{OD} = 120.37\,in$

center of buoyancy

$$y_{cb} := \frac{V_{OD} \cdot y_{OD} + V_{cutout} \cdot y_{cutout} + V_{ballast} \cdot y_{ballast} + V_{spar} \cdot y_{spar} + V_{alum} \cdot y_{alum} + V_{discus} \cdot y_{discus}}{V_{displaced}}$$

$y_{cb} = 85.22\,in$
(from the buoy's base)

center of gravity $y_{cg} = 84.87\,in$

distance between cb and cg, (the "righting arm") $y_{bg} := y_{cb} - y_{cg}$ $y_{bg} = 0.35\,in$

Metacentric Height $gm = \frac{I}{V} + bg$ (additive y_{bg} term, since CB is above CG)

moment of inertia $I := \frac{1}{4} \cdot \pi \cdot \left(\frac{OD}{2}\right)^4$ $I = 78.98\,ft^4$

metacentric height $gm := \frac{I}{V_{displaced}} + y_{bg}$ $gm = 15.25\,in$

Appendix B cont'd

Inclination Example - due to a force on the wind generator

upsetting moment = restoring moment

$$F \cdot d = W \cdot gm \cdot \sin(\theta)$$

force of wind (at 50 knots)	$F_{wind} := 50 \cdot lb$	
draft	$d_b := 112 \cdot in + y_{wl}$	
moment arm of wind gen.	$d_{wind} := (d_b + 14 \cdot ft)$	
angle of inclination	$\theta := \mathrm{asin}\left(\frac{F_{wind} \cdot d_{wind}}{W_{total} \cdot gm}\right)$	$\theta = 13.59\,deg$

Inclination Example #2 - due to Glen climbing on the buoy

weight of Glen	$W_{glen} := 200 \cdot lb$	(after eating so many donuts on the ride out!)
distance (bot. to Glen)	$d_{glen} := 18 \cdot ft$	
angle of inclination	$\theta := \mathrm{asin}\left(\frac{W_{glen} \cdot d_{glen}}{W_{total} \cdot gm}\right)$	$\theta = 44.1\,deg$

Buoy's Dynamic Response:

waterplane area	$S := \pi \cdot \left(\frac{OD}{2}\right)^2$	$S = 31.5\,ft^2$
restoring constant	$c := \rho_{sw} \cdot g \cdot S$	$c = 64869 \frac{lb}{sec^2}$
	for waterplane + ballast plate	
added mass	$m_{added} := \left[\frac{8}{3} \cdot \rho_{sw} \cdot \left(\frac{OD}{2}\right)^3\right] + \left[\frac{8}{3} \cdot \rho_{sw} \cdot \left(\frac{41 \cdot in}{2}\right)^3\right]$	$m_{added} = 6270\,lb$
virtual mass	$m_v := W_{total} + m_{added}$	$m_v = 10341\,lb$
undamped natural frequency	$\omega_o := \sqrt{\frac{c}{m_v}}$	$\omega_o = 2.5\,Hz$
umdamped natural period	$T_o := \frac{2 \cdot \pi}{\omega_o}$	$T_o = 2.51\,sec$
damping ratio	$\zeta := 0.88$ (determined from free-release tests of the FB model)	
damped natural frequency	$\omega_d := \omega_o \cdot \sqrt{1 - \zeta^2}$	$\omega_d = 1.19\,Hz$
damped natural period	$T_d := \frac{2 \cdot \pi}{\omega_d}$	$T_d = 5.28\,sec$

Appendix B cont'd

Flooding Example #1 - Can the buoy sink?

diameter inside buoy	$ID := 59.75 \cdot in$	
volume of a battery (Lifeline 12V 105 amp/hr)	$V_{batt} := 807 \cdot in^3$	
volume of elec. cylinder	$V_{cyl} := \pi \cdot (5 \cdot in)^2 \cdot y_{wl}$	
volume of inside buoy below the waterline	$V_{inside} := \pi \cdot \left(\frac{ID}{2}\right)^2 \cdot y_{wl} - \left(4 \cdot V_{batt} + V_{cyl}\right)$	$V_{inside} = 16.66\,ft^3$ $V_{inside} = 124.62\,gal$
equivalent diameter	$D_{eq} := \sqrt{\frac{4 \cdot V_{inside}}{y_{wl} \cdot \pi}}$	$D_{eq} = 55.86\,in$
weight of water inside	$W_{inside} := \rho_{sw} \cdot V_{inside}$	$W_{inside} = 1066.15\,lb$
change in waterline	$\Delta y_{wl} := \frac{W_{inside}}{\pi \cdot \left(\frac{OD}{2}\right)^2 \cdot \rho_{sw}}$	$\Delta y_{wl} = 6.35\,in$

Calculating the volume of reserve buoyancy foam

approx. volume of foam inside	$V_{foam} := 3 \cdot \left(10.5 \cdot 16 \cdot 48 \cdot in^3\right)$	$V_{foam} = 14\,ft^3$ $V_{foam} = 104.73\,gal$
volume of reserve buoyancy from collar	$V_{collar} := \left[\pi \cdot \left(\frac{OD}{2}\right)^2 - \pi \cdot \left(\frac{60 \cdot in}{2}\right)^2\right] \cdot \left(34.0 \cdot in - y_{wl}\right)$	$V_{collar} = 22.01\,ft^3$ $V_{collar} = 164.64\,gal$
volume of reserve buoyancy	$V_{reserve} := V_{foam} + V_{collar}$	$V_{reserve} = 36.01\,ft^3$ $V_{reserve} = 269.37\,gal$

Appendix B cont'd

Flooding Example #2 - Were the central spar to lose its buoyancy

new location of waterline
$$y_{wl} := \frac{V_{displaced} - \left(V_{ballast} + V_{alum} + V_{cutout} + V_{discus}\right)}{\pi \cdot \left(\frac{OD}{2}\right)^2} + 5.0 \cdot in$$

(simply removed V_{spar} term)

$y_{wl} = 21.92\,in$

(from the bottom of the 5' OD cylinder)

new volume of buoy's OD displaced
$$V_{OD} := \pi \cdot \left(\frac{OD}{2}\right)^2 \cdot \left(y_{wl} - 5.0 \cdot in\right)$$
$V_{OD} = 44.42\,ft^3$

new cb of buoy's OD
$$y_{OD} := 117.0 \cdot in + \frac{\left(y_{wl} - 5.0 \cdot in\right)}{2}$$
$y_{OD} = 125.46\,in$

new center of buoyancy

$$y_{cb} := \frac{V_{OD} \cdot y_{OD} + V_{cutout} \cdot y_{cutout} + V_{ballast} \cdot y_{ballast} + V_{alum} \cdot y_{alum} + V_{discus} \cdot y_{discus}}{V_{displaced}}$$

(removed V_{spar} term)

$y_{cb} = 116.42\,in$

(from the buoy's base)

center of gravity (remains the same)
$y_{cg} = 84.87\,in$

new distance from cb to cg, (the "righting arm")
$$y_{bg} := y_{cb} - y_{cg}$$
$y_{bg} = 31.55\,in$

Metacentric Height
$$gm = \frac{I}{V} + bg$$
(additive y_{bg} term, since CB is above CG)

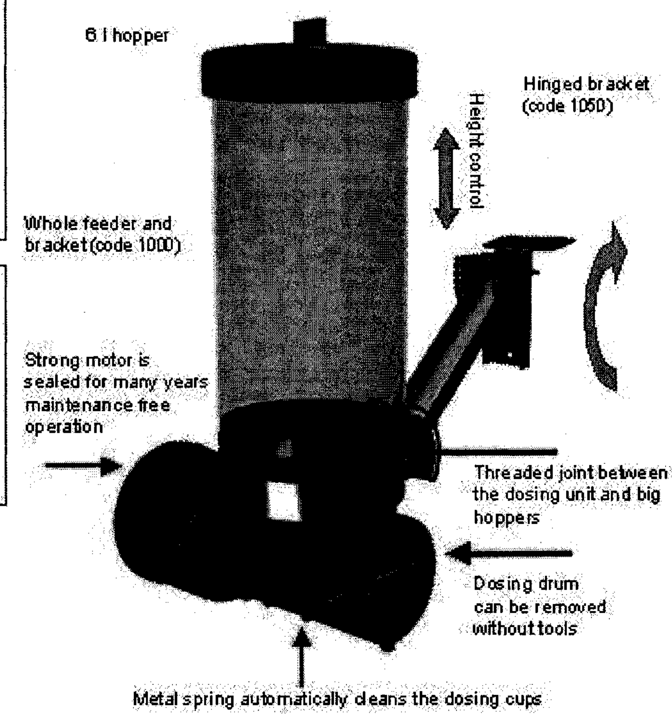
moment of inertia
$$I := \frac{1}{4} \cdot \pi \cdot \left(\frac{OD}{2}\right)^4$$
$I = 78.98\,ft^4$

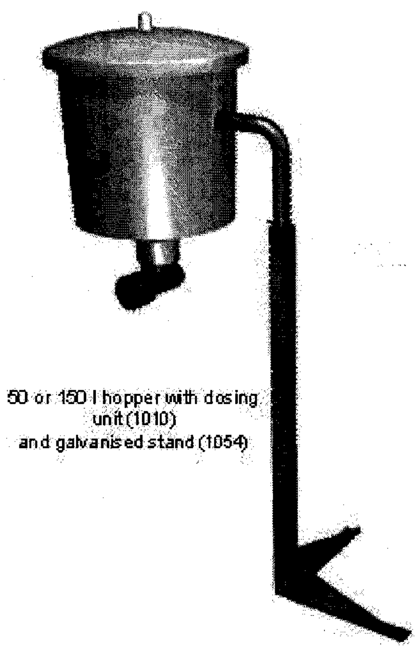
metacentric height
$$gm := \frac{I}{V_{displaced}} + y_{bg}$$
$gm = 46.45\,in$

Appendix C – Quarter-ton Feed Buoy – Arvo-Tec Feed Dispenser

The Arvo-Tec T Drum feeder has a very high accuracy, whilst remaining at a competitive price. The feeder is multifunctional and is suitable for start feeding in hatcheries to on-growing on tanks, ponds and cages.
Economical **Granulate** version available for small feeding applications.

Technical specifications:
- 1, 6 & 10 l transparent and 50, 150 and 350 white hoppers
- Standard motor 24 VAC, 7W, 1 or 2 rpm
- Granule/pellet size 0.3-6 mm
- Minimum dose of 0.3, 1, 5, 20, 45 or 100 g
- Strong, 316 stainless steel bracket
- Accuracy greater than 98 %





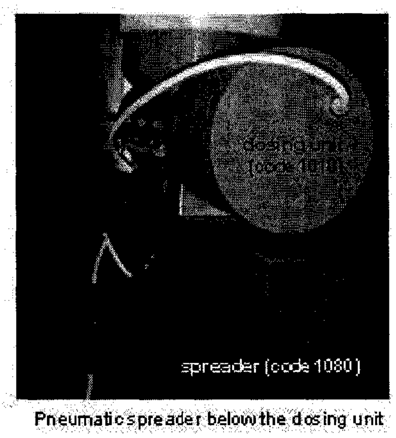


Figure C2: Arvo-Tec Spec Sheet

Figure C3: Interchangeable dispenser cup sizes

Appendix D – Quarter-ton Feed Buoy - Lifeline Battery Specifications

From the Lifeline Battery website (http://www.lifelinebatteries.com/marine.php):

FAQ

Why Choose an AGM Marine Battery?

Absorbed Glass Mat (AGM) batteries include lead plates packed between silica-glass mats, which hold electrolytes in suspension. They have no input current limitations allowing them to recharge more quickly than flooded batteries, which typically accept about 35% of their ampere-hour rating, and Gel cells, that accept about 50%. At higher current loads AGMs also maintain usable system voltages for other high current, short duration loads as opposed to their counterparts, which become more inefficient during high current loads. AGMs also boast a longer lifespan than their counterparts, a deep-cycle flooded battery allows for 350 cycles at a 50 percent discharge level and Gelcells allow for 750 cycles whereas an AGM offers up to 1000 cycles at a 50 percent discharge level.

What is AGM and why do I need it in my Marine Battery?

AGM stands for Advanced Glass Matting and is the material used in high end marine batteries to separate the lead plates. AGM also is useful as its capillary action qualities provide abundant acid contact to the lead plates under extreme vibration, g loads, inverted installations, and more. AGM material simply allows some Marine Batteries to outperform those without due to it's ability to suspend the plates in the sulfuric acid necessary to hold, charge, and discharge marine batteries.

Aren't AGM and GELCELL Marine Batteries both Maintenance Free and tolerant to deep cycling?

AGM Marine Batteries are desirable because they are maintenance free due to the valve-regulated and pressure-sealed design. Like Gel cells they boast high tolerance to occasional deep discharges, excellent shock and vibration resistance, and broad operating temperatures. Here is where the similarities end, AGM Marine batteries have the advantage of being mountable in any orientation without capacity loss which Gel cells do no have.(gel cells will create air pockets and burn out the plates) AGMs also have the lowest internal resistance supporting numerous high demand loads and the fastest recharge times.

DEEP CYCLE MARINE BATTERY APPLICATIONS

Lifeline Battery Part Number	Volts	Overall Dimensions						• Weight lb - kg		Cold Cranking Amps			Rated Cap. Amp. Hrs 20 Hr Rate	Minutes of Discharge		
		Length		Width		Height										
		in	mm	in	mm	in	mm			68° F	32° F	0° F		25 Amps	15 Amps	8 Amps
GPL-24T	12v	11.13	283	6.77	172	9.25	235	56	25.5	800	680	550	80	149	259	524
GPL-27T	12v	12.01	305	6.60	168	9.25	235	65	29.5	845	715	575	100	186	324	655
GPL-31T	12v	12.90	328	6.75	172	9.27	236	69	31.4	880	750	600	105	195	340	688
GPL-4C	6v	10.27	261	7.12	181	10.24	260	66	30	1095	925	750	220	492	856	1692
GPL-4DA	12v	20.76	527	8.70	221	9.44	240	135	61.2	1595	1360	1100	210	390	680	1375
GPL-4DL	12v	20.76	527	8.70	221	9.76	248	135	61.2	1595	1360	1100	210	390	680	1375
GPL-8DA	12v	20.76	527	10.89	277	9.41	239	162	73.6	1975	1675	1350	255	475	825	1670
GPL-8DL	12v	20.76	527	10.89	277	9.73	220	162	73.6	1975	1675	1350	255	475	825	1670
GPL-U1T	12v	7.71	196	5.18	132	6.89	175	24	10.9	325	275	215	33	50	93	185

LIFELINE MARINE BATTERIES FEATURE:

Why do so many marine and RV enthusiasts choose Lifeline Batteries exclusively for their expensive equipment? It probably has to do with one of these reasons;

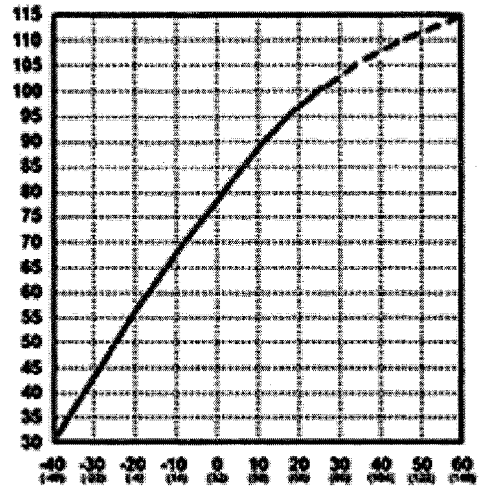
- Aircraft class cell construction:

- Lowers internal resistance for high repeated engine start current.
- Withstands shock and vibration much better than flooded or gelled electrolyte designs.

- Twice as many discharge/charge cycles as the leading gel marine battery (see chart).
- Faster recharge; no current limitations with voltage regulated recharging.
- Much better charge retention than flooded cell types, even at high ambient temperatures.
- Full recharge after 30 days storage in a full discharge condition 77°F (25°C).
- Sealed construction with absorbed electrolyte - no shipment restrictions; submersible without damage; install in any position; no need for watering; no corrosion on terminals.
- Cell safety vent valves - pressure regulated, non-removable.
- Rugged, non-marring polypropylene (copolymer) case/cover.
- Safety - even during severe overcharge the LIFELINE AGM MARINE battery produces less than 2% hydrogen gas (4.1% is required for flammability in air).
- Military approved; Manufactured to DOD military specifications;
- Lifeline Marine batteries are not restricted from shipment by air. Passes DOT 49 CFR Sec.173.159.

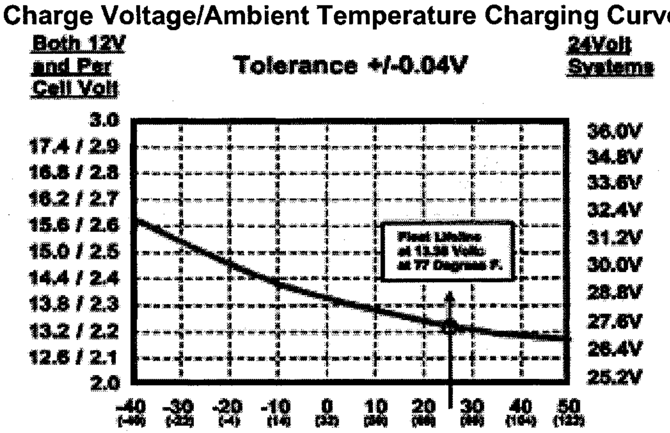
Appendix D (cont'd)

Battery Capacity at Different Temperatures



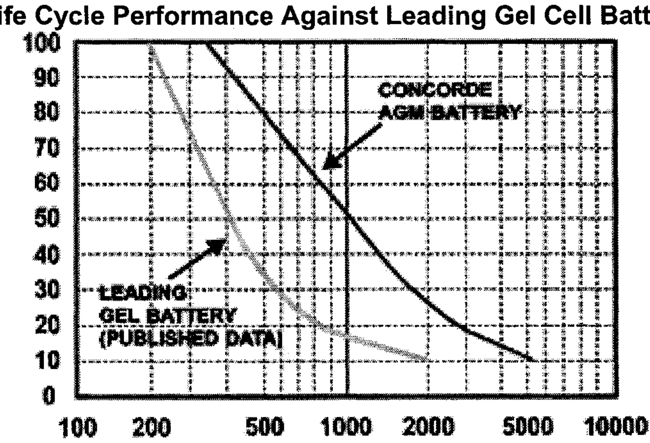
Achieving full capacity at a specified temperature is a function of charging voltage. Refer to the "Lifeline" Charge Voltage/Ambient Temperature Charging Curve to ensure your batteries are being fully charged.

Charge Voltage/Ambient Temperature Charging Curve



NOTE: This graph depicts "Float Voltage". To determine "Bulk" Voltage charging rates add 1.0 Volts to the float voltage setting.

Life Cycle Performance Against Leading Gel Cell Battery



Lifeline Marine and RV batteries consistently perform twice as long as Gel Cell Batteries

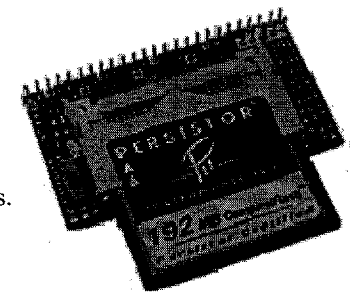
Appendix E – Quarter-ton Feed Buoy - Persistor Instruments CF-1 Specifications

From http://Persistor.com website:

68338 Based Computer Systems

Persistor® CF1

The original CF1 was based on Motorola's MC68CK338, which Motorola discontinued in February 2001. We purchased enough parts to continue to be able to offer the CF1 in limited quantities to our original CF1 customers.



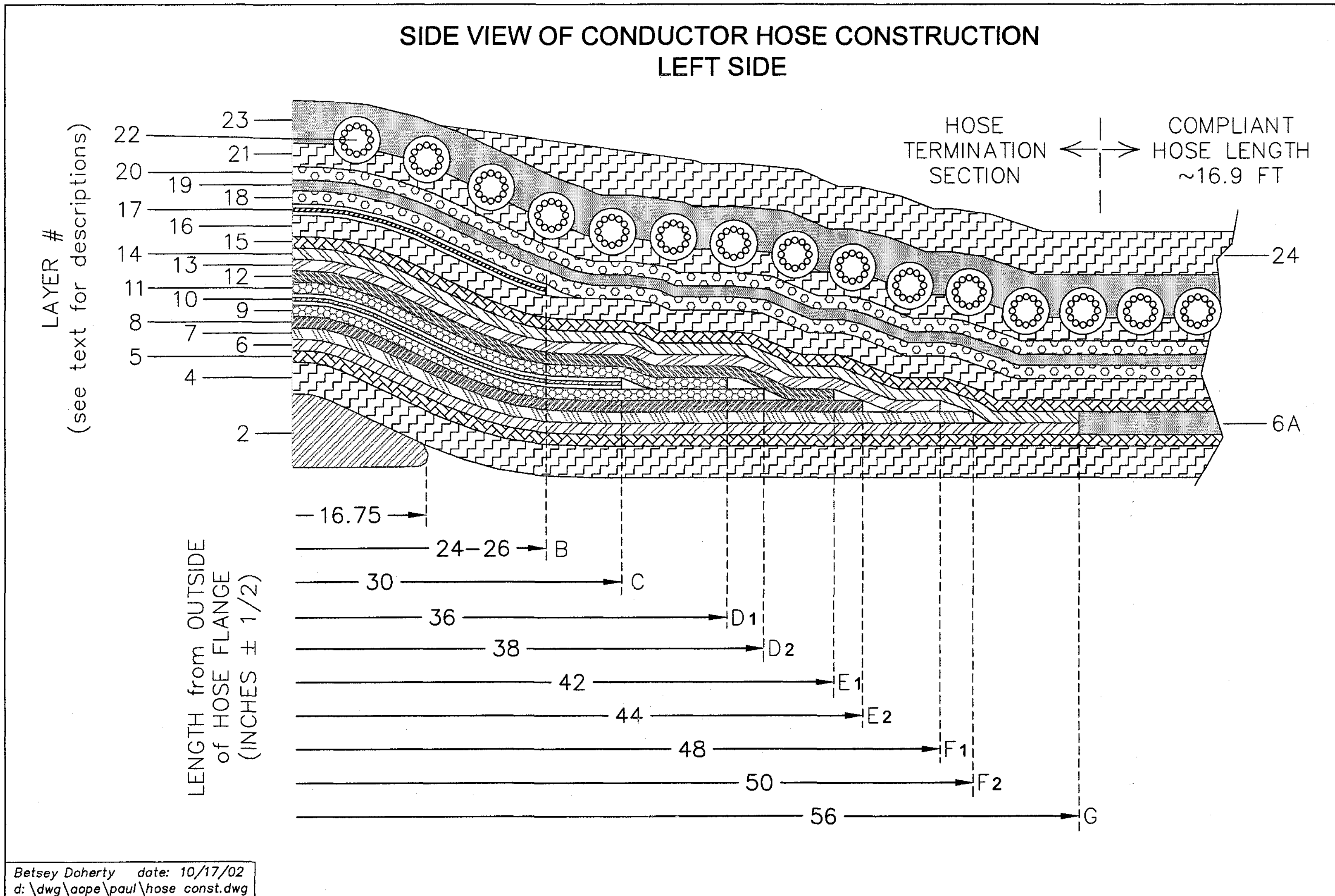
The original CF1 is based on the discontinued Motorola MC68338.

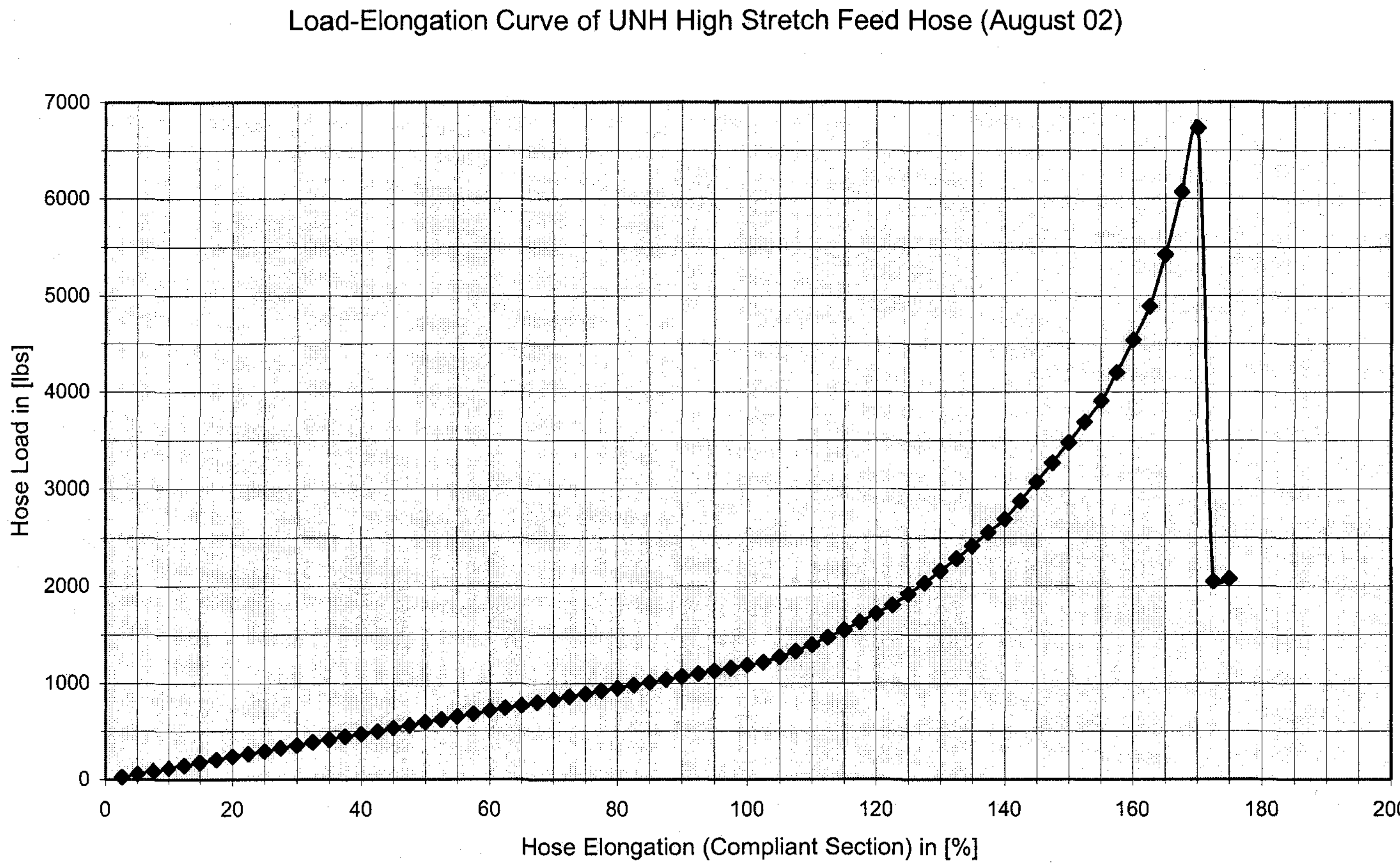
We recommend new customers choose the CF2 for embedded controller and data logging applications. The 68332 based CF2 is a next generation replacement for the CF1, with as much functional and form duplication as was humanly possible.

If you have the CF1 designed into an application, please contact us with your anticipated needs as we continue to manage the end of life for the CF1 product.

Persistor Part Numbers

- **PERCF1C** Single Board Computer
  - Motorola 68338 based Single Board Computer
  - 16MHz operation allows 2.5MIPS
  - 3.3 Volt operating voltage
  - Built in power regulator accepts 3.6 to 20 volt input
  - Low Current Capability:
    - <10uA Suspend
    - <250uA Nap (No Compact Flash Card)
    - 5mA to 50mA Run
  - Header accepts Type I (up to 512 MB) CompactFlash memory cards
  - 1MB Flash 512KB SRAM , 8KB Virtual EEPROM
  - Real Time Clock , RS-232 , 18 Digital I/O
  - -40C to +80C Full Industrial Temperature Range


SIDE VIEW OF CONDUCTOR HOSE CONSTRUCTION
LEFT SIDE
LAYER #
(see text for descriptions)
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
2
HOSE TERMINATION SECTION
COMPLIANT HOSE LENGTH ~16.9 FT
24
6A
LENGTH from OUTSIDE of HOSE FLANGE (INCHES ± 1/2)
16.75
24-26 B
30 C
36 D1
38 D2
42 E1
44 E2
48 F1
50 F2
56 G
Betsey Doherty date: 10/17/02
d: \dwg\aope\paul\hose const.dwg



8-27-02/wp

Notes:

(1) This is a calculated behavior for the compliant (center) section of the feed hose. The curve coincides with the measured long-term load elongation behavior of the actual hose.

(2) The rubber hose wall supports the applied tension entirely up to a load of 1200 lbs (105 % stretch).

(3) Beyond 1200 lbs tension the reinforcing nylon cords are sharing the applied load with the rubber. At 1800 lbs (122% stretch) the cords are tensioned to 10 % of their breaking strength, at 2300 lbs (133 % stretch) to 20 %, and at 3100 lbs (145% stretch) to 30 percent, the maximum working load recommended.

(4) At 4200 lbs tension and 158 % stretch the cords are loaded to half of their strength, and around 6700 lbs and 170 % elongation the cords will break, leaving the rubber to stretch further, with the tension dropping to 2,000 lbs.

(5) *The calculated behavior is determined with for the fluid filled and sealed hose. If the hose ends are not sealed, the hose is expected the* stretch more under a given tension, since it can contract without the resistance of the water fill.

(6) With an assumed overall length of 26 ft and 18 ft compliant center length the hose assembly will stretch an additional 18.5 ft at 1200 lbs, 22 ft at 1800 lbs, and 16 ft at maximum work load. Al 30.6 ft stretch will break the hose.

Appendix G – Quarter-ton Feed Buoy – WHOI Report on Feed Hose Construction

High Stretch Feed Hose with Embedded Conductors

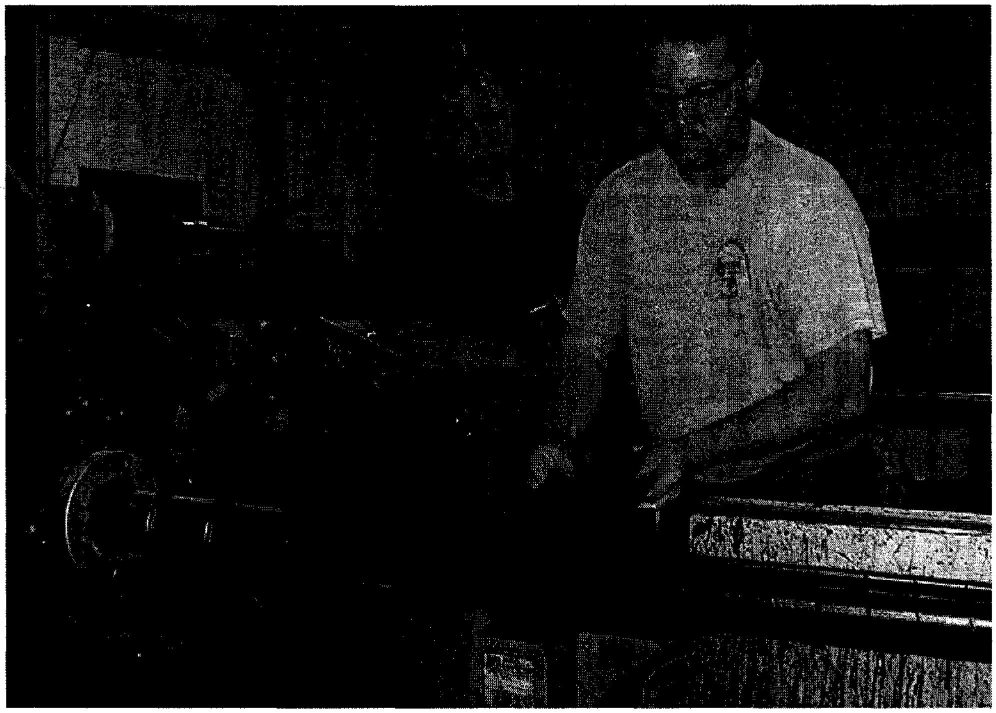


Figure 11. Feed Hose manufacturing, applying rubber inner liner layer over steel mandrel

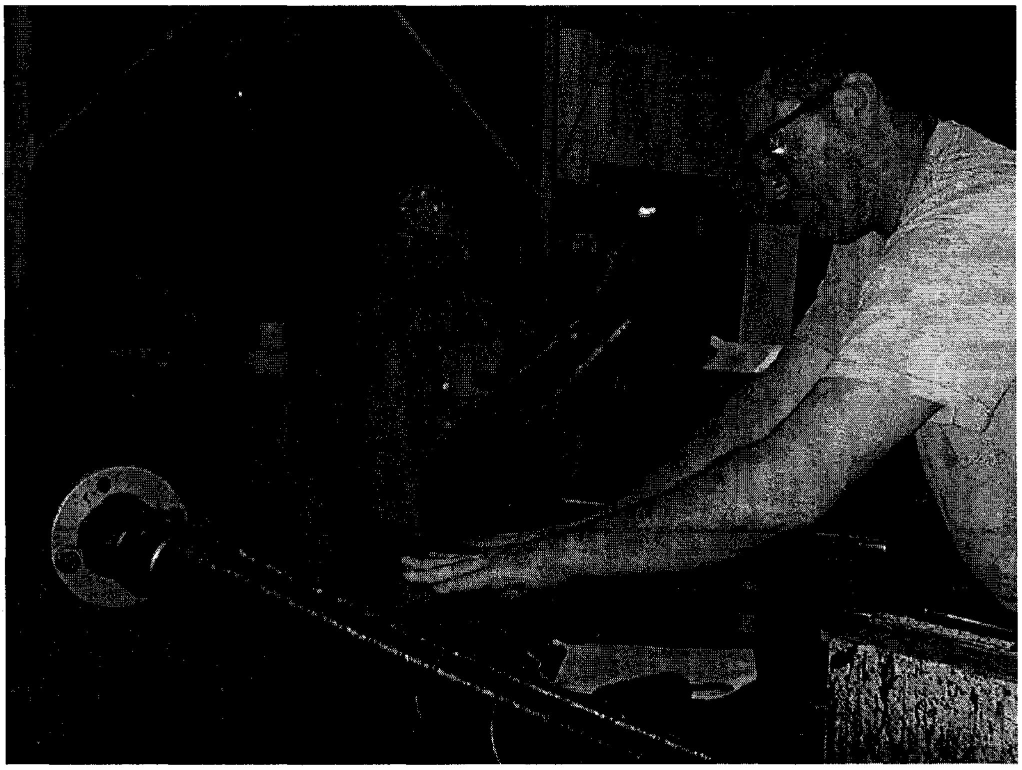


Figure 12. Feed Hose Manufacturing, applying rubber coated reinforcement layer.

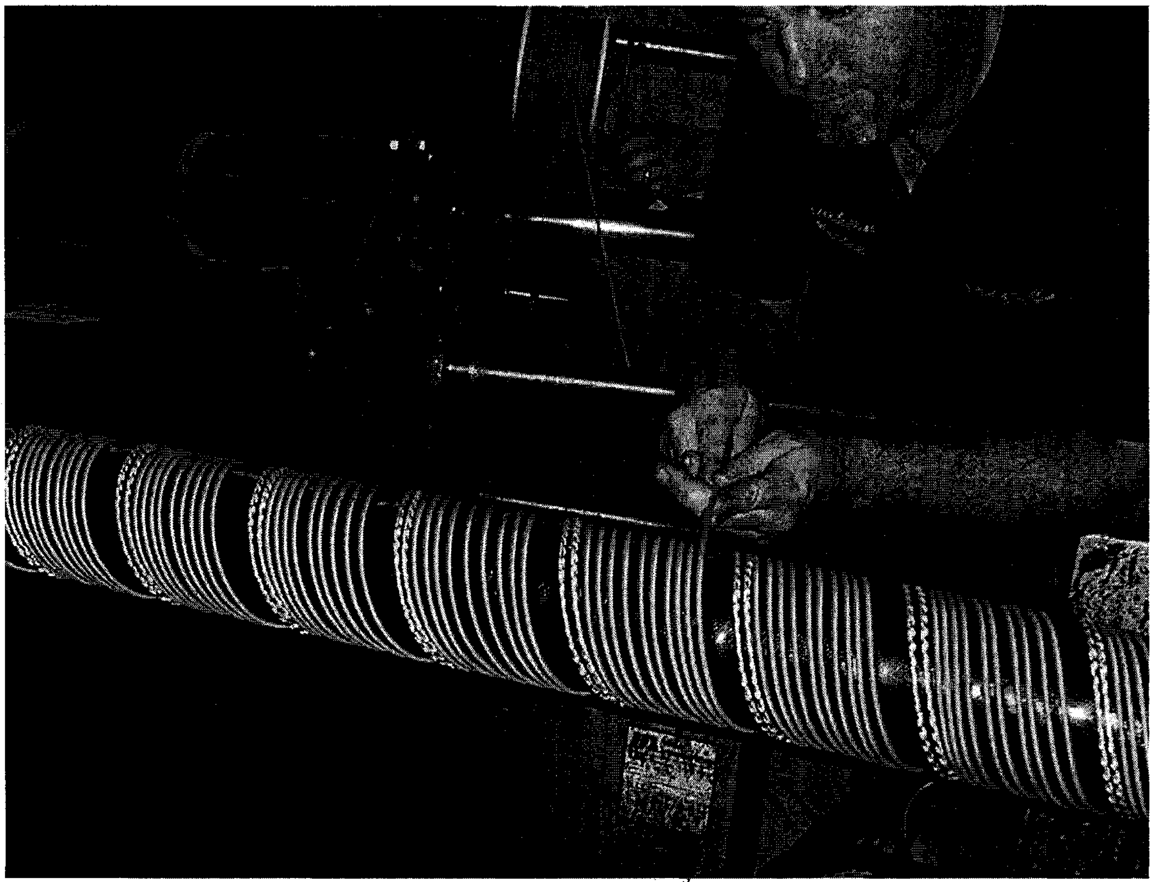


Figure 13. Feed Hose Manufacturing, spiraling 12th conductor wire around hose body

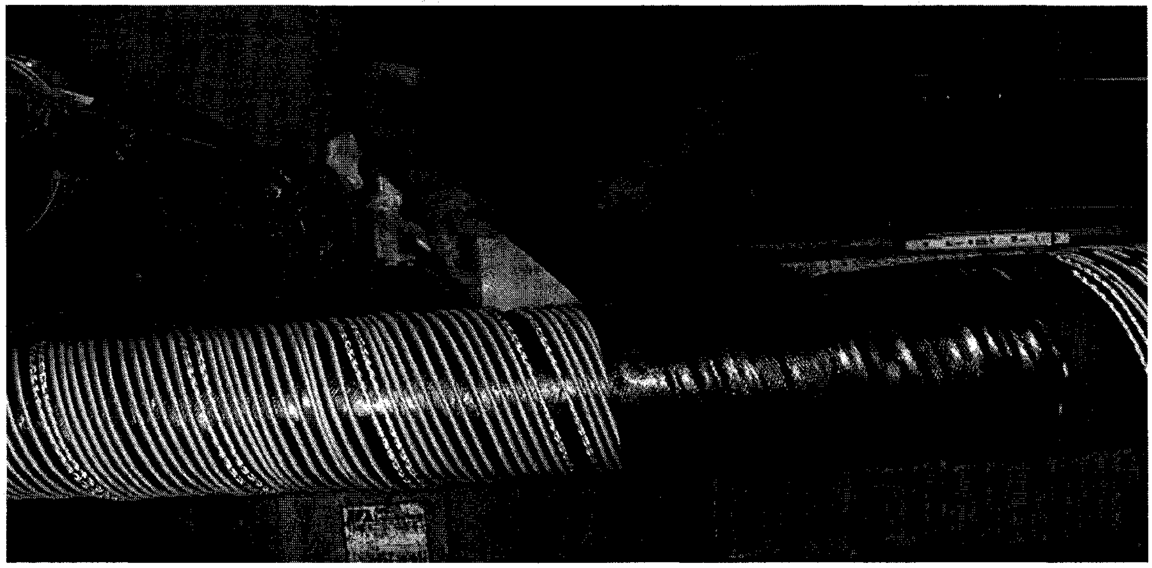


Figure 14. Feed Hose Manufacturing, applying the first layer of rubber jacketing over conductor and reinforcement layers. A ½ inch thick outer jacket was built up to protect the conductors from damage. The completed hose is wrapped with nylon curing weave and vulcanized (steam treated at over 300^0 F) to give it a tire-like toughness. The conductors on the far right, located next to the coupling section of the hose, were left uncovered and grouped to form the electrical pigtails.

The completed hose was furnished with electrical connector pigtails at WHOI, see Figure 15. Special care was taken to assure their survival at sea.

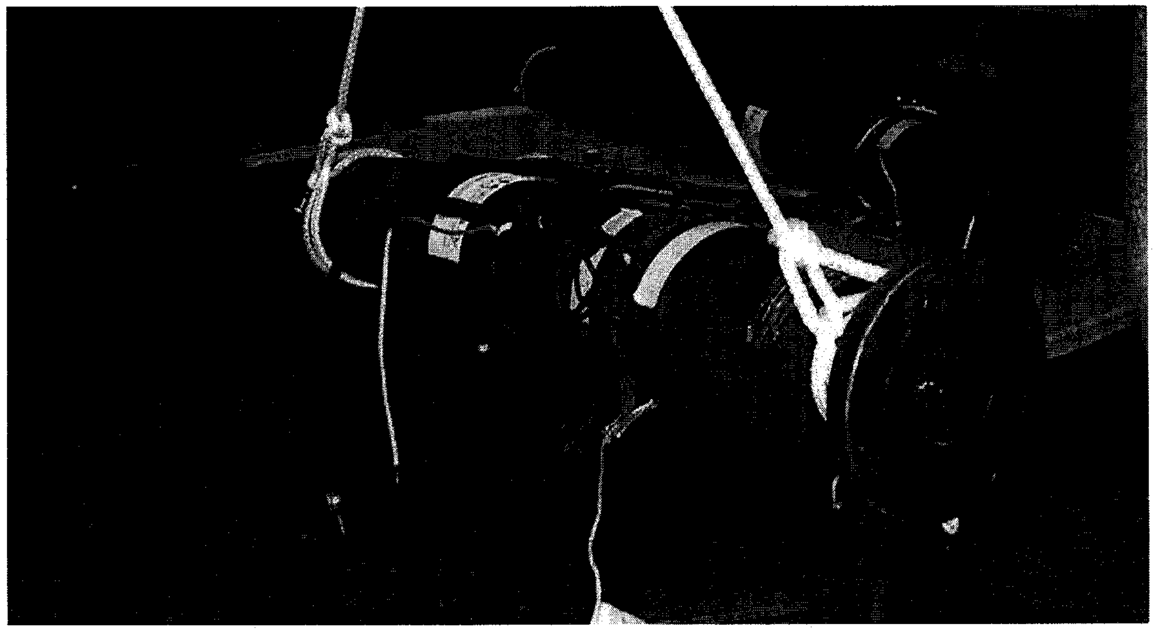


Figure 15. Feed Hose is being furnished with Electrical Connector Pigtails at WHOI. Image shows connected electrical pigtails with plug-in connector before covering breakout area solidly with rubber and sealing tape.

The hose was pull tested and load cycled to 2,500 lbs maximum (for safety reasons), see Figure 16. Conductance was monitored on one wire during the test, and all wires were checked before and after the test, there was no change in nine conductors monitored.

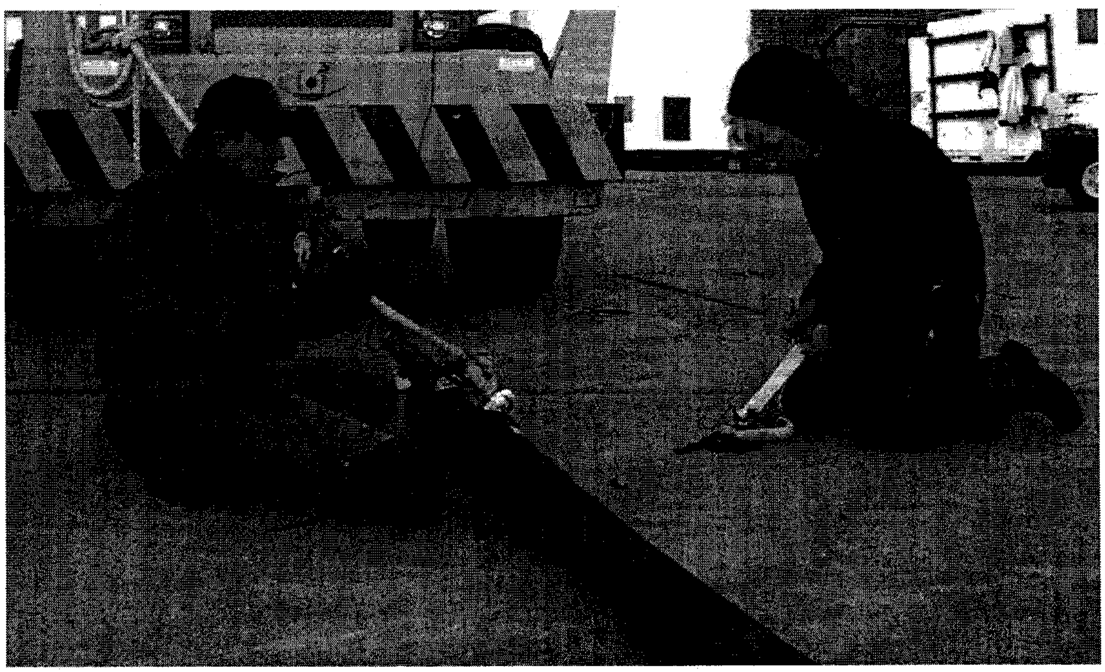


Figure 16. Pull and Load Cycling Test of Feed Hose with Monitoring of Conductance

Appendix H – Quarter-ton Feed Buoy - Mooring Specifications

Fullerton 10/02

Site Specifications Worksheet for the Feed buoy Mooring

General OOA Site Values:

Water depth = 170' (52.0m) (@MLW)

Typical tidal elevation change = 10.0ft (3.0m)

Max. design wave height = 29.5ft (9.0m)

Max. design current = 3.3 ft/s (1.0 m/s) (@ surface)

FeedBuoy:

Draft = 11.0ft (3.4m) (draft = the depth to hose/mooring attachments)

Weight = 4500lb (~2050 kg) (fully loaded with 500lb fish feed)

Fish Cage (South): (same as North cage)

Submerged depth = 31.0ft (9.5m) (@MLW)

Grid Corners: (NE and SE for FeedBuoy mooring)

Length grid to grid = 213' (65.0m)

Ave. Depth = 60' (18.3m) (@MLW)

Feed Hose:

Length (unstretched) = 26.0' (7.9m)

Length of stretchable portion = 18.0' (5.5m)

Spring constant (linear portion) = 65.4 lb/ft (97.3 kg/m)

Mooring: (* number of elastics and their lengths are due to change)

Number of mooring legs = 2 (NE and SE grid corners)

*Number of elastics per leg = 4

*Length of elastics (unstretched) = 36.0' (11.0m)

Max. length elastic working strength = 250%

Spring constant individual elastics (linear portion) = 2.7 lb/ft (4.0 kg/m)

Length of braided rope = 65.6ft (20.0m)

Appendix I - One-ton Feed Buoy - MathCAD Hydrostatics

Fullerton 01/04

"As-Deployed" Hydrostatics for the One-Ton-Capacity Feed Buoy

Abbreviations and Subscript Notations:

L = length

W = weight

V = volume

ρ = density

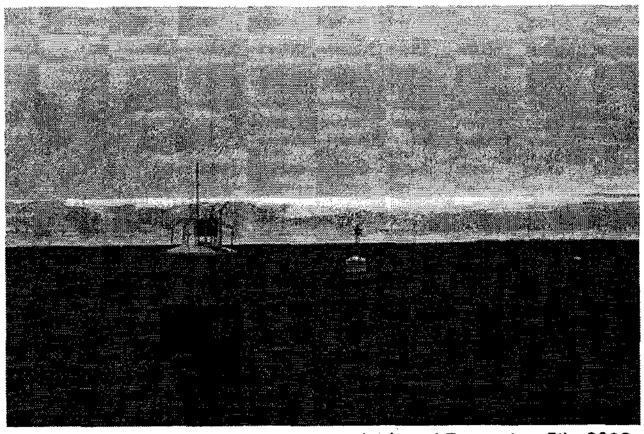
D = diameter

OD = outer_diameter

y = distance(cg, cb)

cg = center_of_gravity

cb = center_of_buoyancy



deployed December 5th, 2003

Densities:

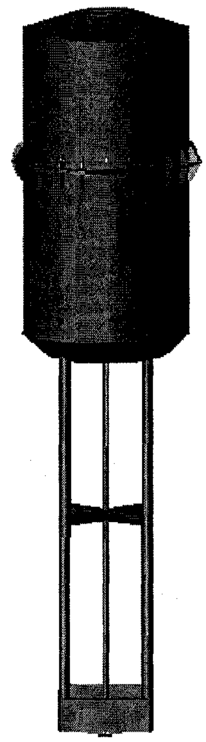
seawater	$\rho_{sw} := 64.0 \cdot \frac{lb}{ft^3}$
freshwater	$\rho_{fw} := 62.4 \cdot \frac{lb}{ft^3}$
aluminum 6061	$\rho_{al} := 169 \cdot \frac{lb}{ft^3}$
steel	$\rho_{steel} := 491 \cdot \frac{lb}{ft^3}$
lead	$\rho_{lead} := 711 \cdot \frac{lb}{ft^3}$
diesel	$\rho_{fuel} := 7.96 \cdot \frac{lb}{gal}$

Appendix I cont'd

Center of Gravity Calculations

$$y_{cg} \cdot W = \sum_i y_i \cdot \Delta W$$

W = weight
y = center of gravity



Weights and center of gravities are either:
-known/measured
-estimated
-approximated through AutoCAD *MASSPROP* function*

* *MASSPROP* is an AutoCAD function, which calculates geometric mass properties of the selected drawn objects. As long as objects are drawn accurately with proper dimensions and thicknesses, the MASSPROP results (volumes and center of gravities) are accurate.

Part Description	Defining or Calculating		Results
Buoy's External Shell:			
buoy's bottom shell (steel)	$V_{bot} := 23392 \cdot in^3$	(MASSPROP)	
	$W_{bot} := \rho_{steel} \cdot V_{bot}$		$W_{bot} = 6647\,lb$
	$y_{bot} := 216.3 \cdot in$	(MASSPROP)	Note: CG's of all components are taken about the feed hose flange.
length of pipe legs	$L_{pipes} \equiv 17 \cdot ft$		
ballast weight	$W_{ballast} \equiv 4500 \cdot lb$	(known)	
	$y_{ballast} := 9 \cdot in$	(estimate)	
height from the feed hose flange to the inside floor (a second reference)	$h_{floor} := L_{pipes} + 6 \cdot in + h_{cone} + 12 \cdot in$		$h_{floor} = 19.5\,ft$

Appendix I cont'd

tire bumper weight

$W_{tires} := 14\cdot(30\cdot lb)$ (estimate) $W_{tires} = 420\,lb$

$y_{tires} := 23.5\cdot ft$

buoy's top shell
(aluminum)

$W_{hatches} := 2\cdot(52\cdot lb) + 49\cdot lb$ (known)

$V_{top} := 10022\cdot in^3$ (MASSPROP)

$W_{top} := \rho_{al}\cdot V_{top} + W_{hatches}$ $W_{top} = 1133\,lb$

$y_{top} := 370.9\cdot in$ (MASSPROP)

Buoy's Internal Components

feed

$W_{feed} := 2000\cdot lb$

$y_{feed} := h_{floor} + 132.0\cdot in$ (MASSPROP)

feed hopper
(500 gal., poly. tank w/ center lid)

$W_{hopper} := 255lb$ (known)

$y_{hopper} := h_{floor} + 132.0\cdot in$ (MASSPROP)

feed mechanisms
(rotary feeder/airlock, knife valve, pumps, and mixing chamber, etc.)

$W_{airlock} := 185\cdot lb$ (known)

$y_{airlock} := h_{floor} + 75\cdot in$ (measured)

$W_{knife} := 15\cdot lb$ (known)

$y_{knife} := h_{floor} + 82\cdot in$ (measured)

$W_{pumps} := 55\cdot lb$ (known)

$y_{pumps} := h_{floor} - 10\cdot in$ (measured)

$W_{mixing} := 35\cdot lb$ (estimate)

$y_{mixing} := h_{floor} + 52\cdot in$ (estimate)

Appendix I cont'd

$$W_{mech} := W_{airlock} + W_{knife} + W_{pumps} + W_{mixing}$$

$$W_{mech} = 290\,lb$$

$$y_{mech} := \frac{y_{airlock} \cdot W_{airlock} + y_{knife} \cdot W_{knife} + y_{pumps} \cdot W_{pumps} + y_{mixing} \cdot W_{mixing}}{W_{mech}}$$

$$y_{mech} - h_{floor} = 4.71\,ft$$

electronics
(pressure cylinder, circuit box, wiring, lights, stop switches, etc.)

$W_{cyl} := 85 \cdot lb$ (measured)

$y_{cyl} := h_{floor} + 10 \cdot in$ (estimate)

$W_{box} := 4 \cdot (25 \cdot lb)$ (estimate)

$y_{box} := h_{floor} + 42 \cdot in$ (estimate)

$W_{misc2} := 20 \cdot lb$ (estimate)

$y_{misc2} := h_{floor} + 26 \cdot in$ (estimate)

$$W_{elec} := W_{cyl} + W_{box} + W_{misc2} \qquad W_{elec} = 205\,lb$$

$$y_{elec} := \frac{y_{cyl} \cdot W_{cyl} + y_{box} \cdot W_{box} + y_{misc2} \cdot W_{misc2}}{W_{elec}}$$

$$y_{elec} - h_{floor} = 2.26\,ft$$

fittings, fasteners, hoses, filters, etc.

$W_{misc} := 25 \cdot lb$ (estimate)

$y_{misc} := h_{floor} + 14 \cdot in$ (estimate)

Power Components

generator
(5kW Northern Lights)

$W_{gen} := 350 \cdot lb$ (known)

$y_{gen} := h_{floor} + 10.0 \cdot in$ (estimate)

Appendix I cont'd

diesel fuel

$W_{fuel} := \rho_{fuel} \cdot (200 \cdot gal)$ $\qquad W_{fuel} = 1592\,lb$

$y_{fuel} := h_{floor} + 18.0 \cdot in$ (measured)

batteries
(two 12V AGM 105amp/hr)
(one 12V MF starting battery)

$W_{batteries} := 2 \cdot (71 \cdot lb) + 37 \cdot lb$ (known/measured) $\qquad W_{batteries} = 179\,lb$

$y_{batteries} := h_{floor} - 10 \cdot in$ (estimate)

solar panels

$W_{solar} := 30 \cdot lb$ (estimate)

$y_{solar} := h_{floor} + 17 \cdot ft$ (estimate)

Subtotal of Weights

weight of buoy structure

$W_{shell} := W_{bot} + W_{top} + W_{tires} + W_{ballast}$ $\qquad W_{shell} = 12700\,lb$

weight of feed components

$W_{comp} := W_{hopper} + W_{feed} + W_{mech} + W_{elec} + W_{misc}$

$W_{comp} = 2775\,lb$

weight of power components

$W_{power} := W_{gen} + W_{fuel} + W_{batteries} + W_{solar}$

$W_{power} = 2151\,lb$

Check of Weights The crane operator at the Port Authority said the aluminum buoy section weighed ~1700 lb and the steel section 7200 lb.

Summing of the components weighed results:

$$W_{top} + W_{airlock} + W_{knife} + W_{hopper} + W_{solar} + W_{misc2} = 1638\,lb$$

$$W_{bot} + W_{tires} + W_{pumps} + W_{misc} = 7147\,lb$$

Appendix I cont'd

Condition#1 - fully-loaded

Total Weight:

max. buoy weight $W_{total} := W_{shell} + W_{comp} + W_{power}$ $W_{total} = 17626\,lb$

$W_{total} = 8.81\,ton$

Center of Gravity Calculations

CG of buoy's "shell"

$$y_{shell} := \frac{y_{bot} \cdot W_{bot} + y_{top} \cdot W_{top} + y_{tires} \cdot W_{tires} + y_{ballast} \cdot W_{ballast}}{W_{shell}}$$

$y_{shell} = 13.23\,ft$

(from the feed hose flange)

CG of buoy's feed components

$$y_{comp} := \frac{y_{feed} \cdot W_{feed} + y_{hopper} \cdot W_{hopper} + y_{mech} \cdot W_{mech} + y_{elec} \cdot W_{elec} + y_{misc} \cdot W_{misc}}{W_{comp}}$$

$y_{comp} = 29.11\,ft$

(from the feed hose flange)

CG of buoy's power components

$$y_{power} := \frac{y_{gen} \cdot W_{gen} + y_{fuel} \cdot W_{fuel} + y_{batteries} \cdot W_{batteries} + y_{solar} \cdot W_{solar}}{W_{power}}$$

$y_{power} = 20.91\,ft$

(from the feed hose flange)

overall CG of buoy

$$y_{cg} := \frac{y_{shell} \cdot W_{shell} + y_{comp} \cdot W_{comp} + y_{power} \cdot W_{power}}{W_{total}}$$

$y_{cg} = 16.67\,ft$

(from the feed hose flange)

Appendix I cont'd

Condition#2 - no comsumables (ie. feed or fuel)

Total Weight:

$$W_{empty} := W_{total} - (W_{feed} + W_{fuel})$$

$W_{empty} = 14034\,lb$

$W_{empty} = 7.02\,ton$

Center of Gravity Calculations

CG of buoy's feed components

$$W_{comp\_empty} := W_{comp} - W_{feed}$$

$$y_{comp\_empty} := \frac{y_{hopper} \cdot W_{hopper} + y_{mech} \cdot W_{mech} + y_{elec} \cdot W_{elec} + y_{misc} \cdot W_{misc}}{W_{comp\_empty}}$$

$y_{comp\_empty} = 25.52\,ft$

(from the feed hose flange)

CG of buoy's power components

$$W_{power\_empty} := W_{power} - W_{fuel}$$

$$y_{power\_empty} := \frac{y_{gen} \cdot W_{gen} + y_{batteries} \cdot W_{batteries} + y_{solar} \cdot W_{solar}}{W_{power\_empty}}$$

$y_{power\_empty} = 20.67\,ft$

(from the feed hose flange)

overall CG of "empty" buoy

$$y_{cg\_empty} := \frac{y_{shell} \cdot W_{shell} + y_{comp\_empty} \cdot W_{comp\_empty} + y_{power\_empty} \cdot W_{power\_empty}}{W_{empty}}$$

$y_{cg\_empty} = 14.21\,ft$

(from the feed hose flange)

Appendix I cont'd

Calculating weight per inch submerged

outer diameter of buoy $OD := 96 \cdot in$

weight of water per inch submerged $R := \pi \cdot \left(\frac{OD}{2}\right)^2 \cdot \rho_{sw}$ $R = 268.08 \frac{lb}{in}$

change in waterline with and without feed $\frac{W_{feed}}{R} = 7.46 in$

change in waterline with and without diesel fuel $\frac{W_{fuel}}{R} = 5.94 in$

total waterline change due to consumables $\frac{W_{feed}}{R} + \frac{W_{fuel}}{R} = 13.4 in$

Total Displacement

total volume of displaced seawater $V_{displaced} := \frac{W_{total}}{\rho_{sw}}$ $V_{displaced} = 275.4 ft^3$

$V_{displaced} = 2060 gal$

with no Consumables $V_{displaced\_empty} := \frac{W_{empty}}{\rho_{sw}}$ $V_{displaced\_empty} = 219.28 ft^3$

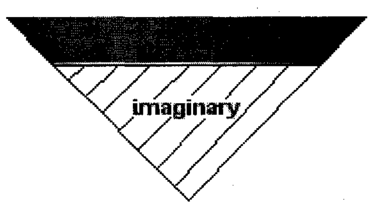
$V_{displaced\_empty} = 1640 gal$

Calculating Submerged Volumes

Bottom Cone of Buoy

angle of bottom cone $\theta_{cone} \equiv 45 \cdot deg$

change in radius of cone $\Delta r_{cone} \equiv 12 \cdot in$



Calculating the volume of cone minus imaginary cone

overall height of bot. cone $h_{cone} \equiv \Delta r_{cone} \cdot \tan(\theta_{cone})$ $h_{cone} = 12 in$

Appendix I cont'd

volume of imaginary cone $V_{imag\_cone} := \frac{1}{3}\cdot\pi\cdot\left(\frac{OD}{2} - \Delta r_{cone}\right)^2\cdot\left(\frac{OD}{2}\cdot\tan(\theta_{cone}) - \Delta r_{cone}\cdot\tan(\theta_{cone})\right)$

$V_{imag\_cone} = 28.27\,ft^3$

volume of bottom cone $V_{cone} := \left[\frac{1}{3}\cdot\pi\cdot\left(\frac{OD}{2}\right)^2\cdot\frac{OD}{2}\cdot\tan(\theta_{cone})\right] - (V_{imag\_cone})$

$V_{cone} = 38.75\,ft^3$

cb of bottom cone $y_{cone} := L_{pipes} + 53\%\cdot h_{cone}$ (MASSPROP)

<u>Support Pipe Legs</u>

# of ballast legs
(weights incl. above in shell) $N := 4$

outer diameter of pipes $OD_{pipes} := 6.625\cdot in$

sub. volume of supports $V_{pipes} := N\cdot\left[\pi\cdot\left(\frac{OD_{pipes}}{2}\right)^2\cdot(L_{pipes} - h_{cone})\right]$ $V_{pipes} = 15.32\,ft^3$

cb of support pipes $y_{pipes} := \frac{L_{pipes}}{2}$

<u>Ballast Weight</u>

volume of ballast $V_{ballast} := \frac{W_{ballast}}{\rho_{lead}}$ $V_{ballast} = 6.33\,ft^3$

<u>other submerged volumes</u>
(plate steel, mooring tabs, gussets, etc.)

volume of misc. pieces $V_{misc} := 5500\cdot in^3$ (estimate / MASSPROP) $V_{misc} = 3.18\,ft^3$

cb of misc. pieces $y_{misc} := \frac{L_{pipes}}{4}$

volume of fully submerged objects $V_{submerged} := V_{ballast} + V_{pipes} + V_{cone} + V_{misc}$

$V_{submerged} = 63.58\,ft^3$

Appendix I cont'd

$V_{submerged} = 63.58\,ft^3$ compared to the total volume of water displaced: $V_{displaced} = 275.4\,ft^3$

Determining the Waterline:

location of waterline $h_{wl} := \dfrac{V_{displaced} - V_{submerged}}{\pi \cdot \left(\dfrac{OD}{2}\right)^2}$ $h_{wl} = 50.57\,in$

(from the base of the 8' cylinder)

$y_{wl} := L_{pipes} + h_{cone} + h_{wl}$ $y_{wl} = 22.21\,ft$

(from the feed hose flange)

total draft $d := y_{wl}$

without Consumables
(ie. feed and fuel)

$h_{wl\_empty} := \dfrac{V_{displaced\_empty} - V_{submerged}}{\pi \cdot \left(\dfrac{OD}{2}\right)^2}$

$h_{wl\_empty} = 37.17\,in$

(from the base of the 8' cylinder)

$y_{wl\_empty} := L_{pipes} + h_{cone} + h_{wl\_empty}$ $y_{wl\_empty} = 21.1\,ft$

(from the feed hose flange)

Center of Buoyancy Calculations

volume of buoy's OD displaced $V_{OD} := \pi \cdot \left(\dfrac{OD}{2}\right)^2 \cdot h_{wl}$ $V_{OD} = 211.82\,ft^3$

cb of buoy's OD $y_{OD} := \left(y_{wl} - h_{wl}\right) + \dfrac{h_{wl}}{2}$ $y_{OD} = 241.28\,in$

Appendix I cont'd

center of buoyancy

$$y_{cb} := \frac{V_{OD} \cdot y_{OD} + V_{ballast} \cdot y_{ballast} + V_{pipes} \cdot y_{pipes} + V_{cone} \cdot y_{cone} + V_{misc} \cdot y_{misc}}{V_{displaced}}$$

$y_{cb} = 18.47\,ft$

(from the feed hose flange)

without Consumables
(ie. feed and fuel)

$$V_{OD\_empty} := \pi \cdot \left(\frac{OD}{2}\right)^2 \cdot h_{wl\_empty}$$

$V_{OD\_empty} = 155.7\,ft^3$

$$y_{OD\_empty} := h_{floor} + \frac{h_{wl\_empty}}{2}$$

$y_{OD\_empty} = 252.59\,in$

$$y_{cb\_empty} := \frac{V_{OD\_empty} \cdot y_{OD\_empty} + V_{ballast} \cdot y_{ballast} + V_{pipes} \cdot y_{pipes} + V_{cone} \cdot y_{cone} + V_{misc} \cdot y_{misc}}{V_{displaced\_empty}}$$

$y_{cb\_empty} = 18.72\,ft$

(from the feed hose flange)

Hydrostatic Results **with** Consumables

location of waterline

$h_{wl} = 50.57\,in$

(from the base of the 8' cylinder)

overall draft

$d = 22.21\,ft$

center of gravity

$y_{cg} = 16.67\,ft$

(from the feed hose flange)

center of buoyancy

$y_{cb} = 18.47\,ft$

(from the feed hose flange)

distance between cb and cg, (the "righting arm")

$$y_{bg} := y_{cb} - y_{cg}$$

$y_{bg} = 21.6\,in$

$y_{bg} = 1.8\,ft$

Appendix I cont'd

Hydrostatic Results **without** Consumables

location of waterline $h_{wl\_empty} = 37.2\,in$

(from the base of the 8' cylinder)

center of gravity $y_{cg\_empty} = 14.21\,ft$

center of buoyancy $y_{cb\_empty} = 18.72\,ft$

distance between cb and cg, (the "righting arm") $y_{bg\_empty} := y_{cb\_empty} - y_{cg\_empty}$ $y_{bg\_empty} = 54.14\,in$

$y_{bg\_empty} = 4.51\,ft$

Metacentric Height $gm = \frac{I}{V} + bg$ (additive y_{bg} term, since CB is above CG)

moment of inertia $I := \frac{1}{4}\cdot\pi\cdot\left(\frac{OD}{2}\right)^4$ $I = 201.06\,ft^4$

metacentric height $gm := \frac{I}{V_{displaced}} + y_{bg}$ $gm = 2.53\,ft$

$gm = 30.36\,in$

$gm_{empty} := \frac{I}{V_{displaced\_empty}} + y_{bg\_empty}$ $gm_{empty} = 5.43\,ft$

Appendix I cont'd

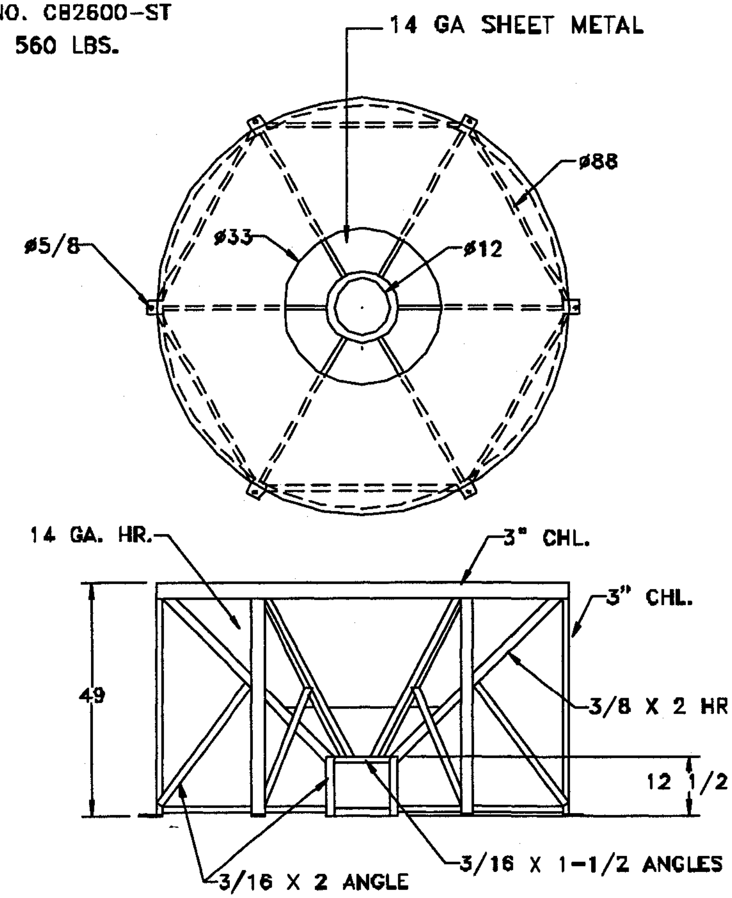
Buoy's Dynamic Response:

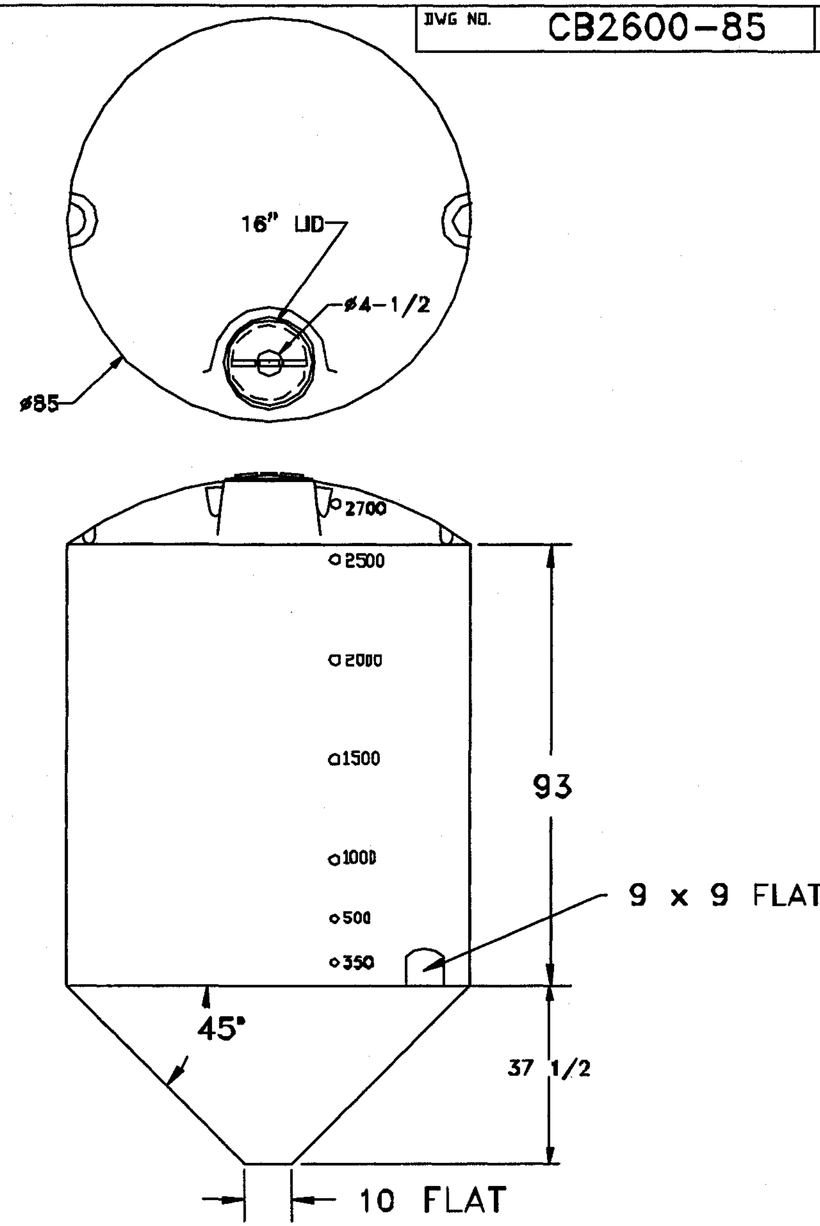
waterplane area	$S := \pi \cdot \left(\frac{OD}{2}\right)^2$	$S = 50.27\,ft^2$
restoring constant	$c := \rho_{sw} \cdot g \cdot S$	$c = 103503 \frac{lb}{sec^2}$
added mass (approximated)	$m_a := \left[\frac{8}{3} \cdot \rho_{sw} \cdot \left(\frac{OD}{2}\right)^3\right] + \left[\frac{8}{3} \cdot \rho_{sw} \cdot \left(\frac{5 \cdot ft}{2}\right)^3\right]$	$m_a = 13589\,lb$
added mass (experimentally)	$m_{added} := 114.6\% \cdot W_{total}$	$m_{added} = 20199\,lb$
virtual mass	$m_v := W_{total} + m_{added}$	$m_v = 37825\,lb$
undamped natural frequency	$\omega_o := \sqrt{\frac{c}{m_v}}$	$\omega_o = 1.65\,Hz$
undamped natural period	$T_o := \frac{2 \cdot \pi}{\omega_o}$	$T_o = 3.8\,sec$
damping ratio	$\zeta := 0.10$ (determined experimentally with scaled model)	
damped natural frequency	$\omega_d := \omega_o \cdot \sqrt{1 - \zeta^2}$	$\omega_d = 1.65\,Hz$
damped natural period	$T_d := \frac{2 \cdot \pi}{\omega_d}$	$T_d = 3.82\,sec$

DWG NO. CB2600-85 | SH | REV

1. SPECIFIC GRAVITY IS 1.75
2. 1 PIECE ROTATIONALLY MOLDED
3. TRANSLUCENT
4. FDA APPROVED RESIN
5. CALIBRATED IN GALLONS
6. THREE YEAR WARRANTY
7. UV STABILIZED
8. MIXER OR PUMP MOUNT ON REQUEST

STAND PART NO. CB2600-ST
STAND WEIGHT 560 LBS.





Appendix K - One-ton Feed Buoy - Ace Roto-Mold Feed Hopper

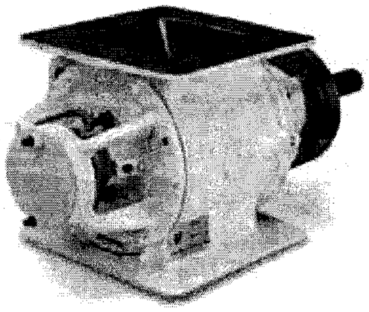
REV	DESCRIPTION	DATE	APVD	DRAWN: DEAN	DATE: 12-9-93	MATERIAL: HIGH DENSITY POLYETHYLENE	ACE ROTO MOLD A DIVISION OF DEN HARTOG INDUSTRIES, INC.
				APPROVED	DATE		PART NO. CB2600-85
SCALE NONE				THIRD ANGLE PROJECTION		PART WEIGHT 500 LBS.	SIZE A — CB2600-85 — REV

UOS DIMENSIONS ARE IN INCHES
GENERAL TOLERANCES
± .5% @ 68° F

PAV-6 C/S-304-SS

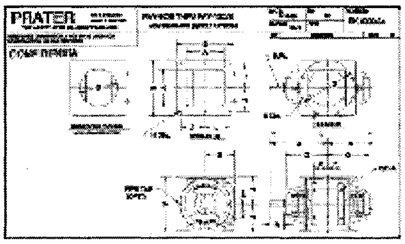
Prater 6" Rotary Airlock - 304 Stainless Steel

- The Basic Valve Consists Of A 304 Stainless Steel Body And End Plates
- Square Inlet And Round Outlet - With Universal Flange
- Flanges Custom Drilled To Customer's Pattern
- End Plates Are Drilled And Tapped For Optional Air Purged Seals
- 8 Blade, 304 Stainless Steel, Open Ended Rotor With Welded Pocket Bottoms
- (2) Sealed Outboard Bearings - Lubricated For Life
- Jack Bolt Holes Are Drilled In End Plates For Quick And Easy Removal
- Operating Temperature Up To 500°F. With Standard Bearings
- (2) Self Adjusting Packing Gland Assemblies
- A Shaft Extension For A Drive On One Side Only



Description

Capacity:	Theoretical: 0.15 cu. ft. (4.3 L) /rev. Practical: 0.12 cu. ft. (3.4 L) /rev.
Bearings:	Type: Ball Bearing Size: 1.0" 25.4 mm Life Rating L-10: > 60,000 hrs Outboard Mounted: Yes
Housing:	Material: 304 Stainless Steel Thickness: 0.38" x 0.31"; 9.5 x 7.9 mm
Flanges:	Square Outline: Drilled Round or Square Inlet Size: 6.0" 152 mm Outlet Size: 6.0" 152 mm Thickness: 0.31" 7.9 mm
Shaft:	Material: 304 Stainless Steel Drive Stub Shaft Dia.: 1.0" 25.4 mm Packing Seal: PTFE
Sound Level:	< 75 db scale A
Rotor:	Type: Fabricated Material: 304 Stainless Steel Number of Blades: 8 Blade Thickness: 0.38" 9.5 mm Design Radial Clearance: 0.004" to 0.006" (At Operating Temp) 0.10 to 0.15 mm
Drive Includes:	0.5 Hp, 60 Hz, 3 Ph, 230/460 V. Motor, Motor Base, Gear Reducer, Chain Drive & OSHA Guard
Approximate Weights and Dimensions:	**Airlock Only** Length: 19.5" 495 mm Width: 10.0" 254 mm Height: 10.0" 254 mm Weight: 90 lbs 41 kg Shipping Weight: 120 lbs 55 kg **With Drive & Standard Guard** Length: 21.1" 536 mm Width: 27.6" 701 mm Height: 16.8" 427 mm Weight: 180 lbs 82 kg Shipping Weight: 210 lbs 96 kg



Click For Drawing Detail.

DWG PDF
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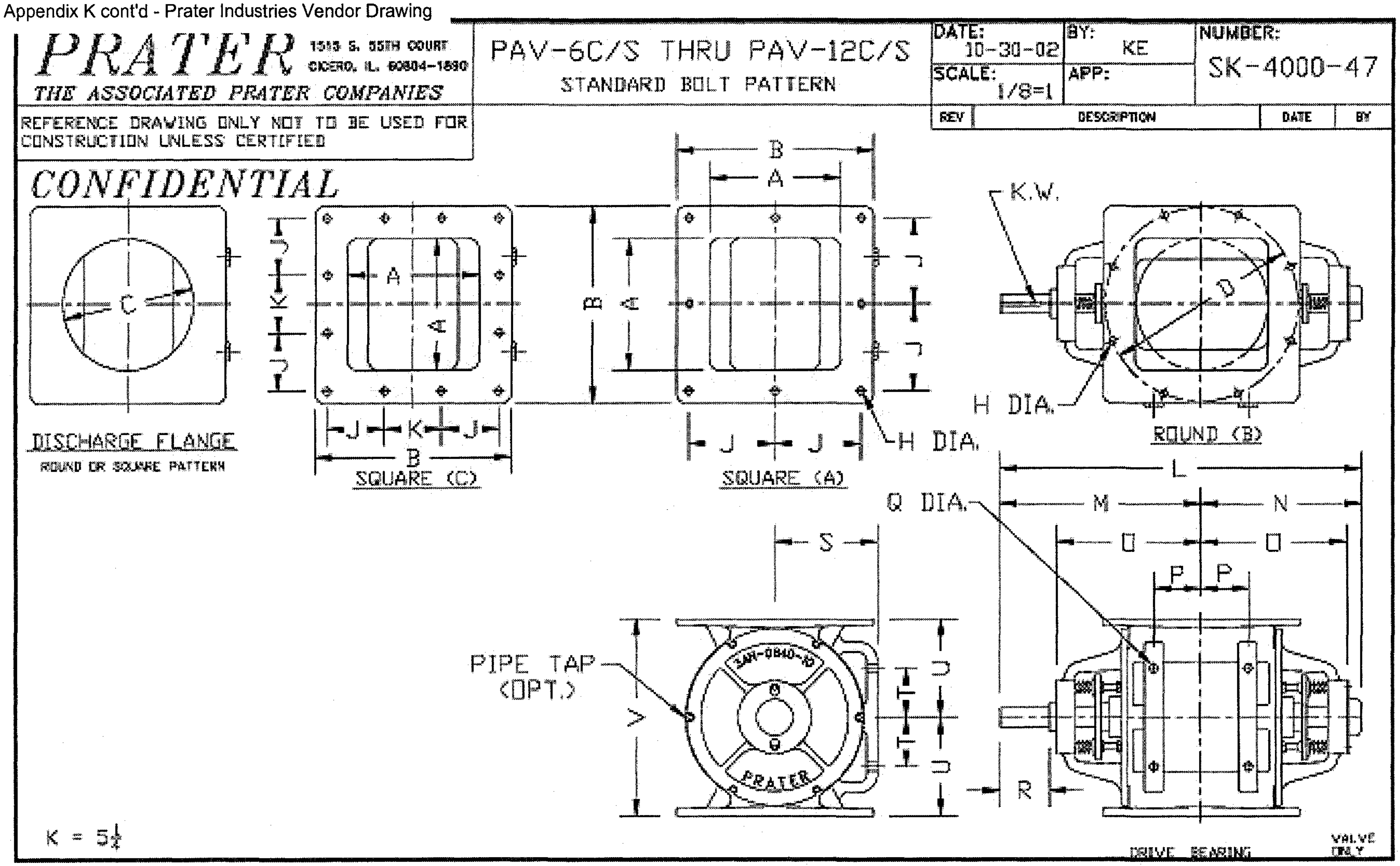
Available Options

- Air Purge Seals
- Food Grade Seals
- Food Grade White Epoxy Paint
- Shear Pins
- High Temp. Bearings And Seals For Operation To 1000°F.
- Wear And Corrosion Resistant Coatings
- Inlet Baffle
- Discharge Adapter
- L-Slot Wear Bars
- Vented Pockets
- Reduced Size Pockets
- Neoprene Flange Gaskets

For full details and a complete list of options, contact your Prater Representative.



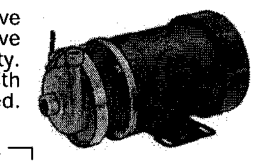
MODEL	A	B	C DIA.	D DIA.	H	HOLE QTY.	J	L	M	N	O	P	Q	R	S	T	U	V	KEY WAY	SHAFT DIA.	SHAFT DIA.	FLANGE THK.	WEIGHT LB.
PAV-6 C/S	6	10	6	9 1/2	7/16	8	4 5/16	19 3/8	10 11/16	8 11/16	7 13/16	2 1/4	1/2	2 1/2	5 1/4	2 1/2	5	10	1/4X 1/8	1	1	5/16	90
PAV-8 C/S	8	12	8	11 3/4	7/16	8	5 1/4	21 15/16	12 1/4	9 11/16	8 13/16	2 7/8	1/2	3	6 1/4	3	6	12	1/4X 1/8	1 3/16	1 3/16	7/16	110
PAV-10 C/S	10	15	10	14 1/4	7/16	8	6	25 3/16	14 1/8	11 1/16	10 1/8	3 1/4	1/2	3 1/2	7 3/4	4	7 1/2	15	3/8X 3/16	1 7/16	1 7/16	1/2	165
PAV-12 C/S	12	18	12	17	7/16	12	5 1/8	29 15/16	16 11/16	13 1/4	12	3 1/2	7/8	3 3/8	9 1/4	5	9 1/16	18 1/8	3/8X 3/16	1 3/4	1 15/16	5/8	373

Centrifugal Transfer Pumps

For information about centrifugal transfer pumps, see page 281.

Additional Information: For additional information about the compatibility of 32 common chemicals for the pumps on this page, go to our web site, www.mcmaster.com, and search for the number specified in the presentations below (for example, **4320KAC**), or fax us at 630-782-3800 and request the number specified.

Type 316 Stainless Steel Centrifugal Pumps



Extremely resistant to corrosion, these pumps handle water as well as many acids, caustics, and chemicals. Pumps have an aluminum motor mount and a Type 316 stainless steel open impeller, except 4320K35, K36, K37, K38, and K39 have a closed impeller. Motors are totally enclosed fan-cooled (TEFC) and generate 3450 rpm. Rated for continuous duty. Pumps must be hardwired. Max. temp. is 300° F. Fluids must be compatible with wetted parts (materials in contact with solution). Wetted parts are carbon, ceramic, Type 316 stainless steel, and Viton. Motors are UL listed and CSA certified.
Additional Information: ***4320KAC (See top of page for details)***

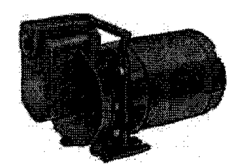
	PUMP PERFORMANCE								Full	Connections, NPT female			
	gpm @ ft. of head				Shutoff,				Load				
hp	20 ft.	30 ft.	40 ft.	50 ft.	ft.	VAC	Hz	ph.	Amps	Intake	Discharge		Each
1/3	29	23	10	—	44	115/230	60	1	4.6/2.3	3/4"	1/2"	**4320K32**	$404.86
1/2	36	30	22	10	54	115/230	60	1	8/4	3/4"	1/2"	**4320K33**	412.95
3/4	38	33	27	18	59	115/230	60	1	8.6/4.3	3/4"	1/2"	**4320K34**	421.05
3/4	65	53	38	20	61	115/230	60	1	8.6/4.3	1 1/4"	3/4"	**4320K35**	583.00
1	83	63	35	15	59	115/230	60	1	10.4/5.2	1 1/2"	1 1/4"	**4320K36**	631.58
1	50	15	—	—	34	230/460	50/60	3	3.2/1.6	1 1/2"	1 1/4"	**4320K61**	615.38
1 1/2	98	83	60	30	69	230/460	50/60	3	4.2/2.1	1 1/2"	1 1/4"	**4320K37**	631.58
1 1/2	80	58	20	—	49	230/460	60	3	4.2/2.1	1 1/2"	1 1/4"	**4320K65**	615.38
2	115	90	54	10	52	230/460	60	3	5.6/2.8	2"	1 1/2"	**4320K63**	728.74
2	—	—	115	90	82	230/460	50/60	3	5.6/2.8	2"	1 1/2"	**4320K38**	696.35
3	—	—	135	115	88	230/460	50/60	3	8/4	2"	1 1/2"	**4320K39**	696.35
3	—	—	125	95	79	230/460	60	3	8/4	2"	1 1/2"	**4320K64**	728.74

Cast Type 316 Stainless Steel Centrifugal Pumps

Because they are cast, the Type 316 stainless steel housings have thicker, stronger walls than machined housings for enhanced durability. Plus, they resist corrosion. Discharge adjusts to four different positions. Impellers are semi-open and Type 316 stainless steel. Motors are totally enclosed fan-cooled (TEFC) and generate 3450 rpm. Rated for continuous duty. Pumps must be hardwired. Max. temp. is 200° F. Fluids must be compatible with wetted parts (materials in contact with solution). Wetted parts are carbon/ceramic, 18-8 and Type 316 stainless steel, and Viton. Motors are UL listed and CSA certified.
Additional Information: ***8124KAC (See top of page for details)***

	PUMP PERFORMANCE								Full	Connections, NPT female			
	gpm @ ft. of head					Shutoff,	VAC @		Load				
hp	10 ft.	20 ft.	30 ft.	50 ft.	70 ft.	ft.	60 Hz	ph.	Amps	Intake	Discharge		Each
1/3	29	24	17	—	—	45	115/230	1	7/4	3/4"	1/2"	**8124K31**	$360.44
1/2	42	35	25	—	—	45	115/230	1	9/5	1"	3/4"	**8124K32**	404.73
3/4	47	40	31	—	—	48	115/230	1	9/5	1"	3/4"	**8124K33**	424.58
1	69	60	48	—	—	48	115/230	1	12/6	1 1/4"	1"	**8124K34**	450.55
1 1/2	71	62	52	7	—	52	115/230	1	18/9	1 1/4"	1"	**8124K35**	462.76
1 1/2	71	62	52	7	—	52	230/460	3	5/3	1 1/4"	1"	**8124K36**	520.80
2	—	90	85	71	56	110	115/230	1	22/11	1 1/2"	1 1/4"	**8124K37**	702.55
2	—	90	85	71	56	110	230/460	3	6/3	1 1/2"	1 1/4"	**8124K38**	736.91
3	—	103	99	88	72	130	230	1	16	1 1/2"	1 1/4"	**8124K39**	771.27
3	—	103	99	88	72	130	230/460	3	8/4	1 1/2"	1 1/4"	**8124K41**	805.64

Self-Priming Type 316 Stainless Steel Centrifugal Pumps

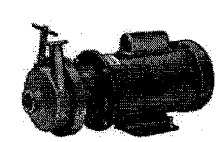


After an initial fill of the pump casing, these pumps are self-priming to 6 ft. Plus, they have the chemical and corrosion resistance of a cast Type 316 stainless steel housing. Pumps have a centerline discharge to prevent stalling and a self-cleaning semi-open Type 316 stainless steel impeller. Motors generate 3450 rpm. Pumps are rated for continuous duty and must be hardwired. Fluids must be compatible with wetted parts (materials in contact with solution). Wetted parts are carbon, ceramic, 18-8 and Type 316 stainless steel, and Viton. Motors are UL listed and CSA certified.
Additional Information: ***99505KAC (See top of page for details)***

	PUMP PERFORMANCE							Full		Connections,		*Open Dripproof*
	gpm @ ft. of head			Shutoff,		VAC @		Load	Max.	NPT female		
hp	5 ft.	20 ft.	50 ft.	ft.	Motor♠	60 Hz	ph.	Amps	Temp.	Intake/Discharge		Each
1/3	36	24	—	44	ODP	115/230	1	8/4	200° F	1"	**99505K51**	$523.09
1/2	45	35	—	48	ODP	115/230	1	10/5	200° F	1"	**99505K53**	550.58
3/4	52	42	10	54	ODP	115/230	1	13/7	200° F	1"	**99505K55**	557.45
3/4	52	42	10	54	TEFC	230/460	3	3/2	200° F	1"	**99505K63**	631.56
1	59	50	24	60	ODP	115/230	1	17/9	200° F	1"	**99505K57**	572.73
1	59	50	24	60	TEFC	230/460	3	4/2	200° F	1"	**99505K65**	637.64
1 1/2	66	57	33	68	ODP	115/230	1	22/11	200° F	1"	**99505K59**	581.89
1 1/2	66	57	33	68	ODP	230/460	3	7/4	200° F	1"	**99505K61**	644.51
1 1/2	66	57	33	68	TEFC	230/460	3	5/3	200° F	1"	**99505K67**	660.55
2	66	58	32	68	TEFC	230/460	3	6/3	200° F	1"	**99505K69**	679.64

♠ ODP=open dripproof; TEFC=totally enclosed fan-cooled.

Sanitary Type 316 Stainless Steel Centrifugal Pumps



For use in food, beverage, and other sanitary applications, pumps meet 3-A sanitary standard requirements for product-contact surfaces. Pumps have a Type 316 stainless steel open impeller. Motors are totally enclosed fan-cooled (TEFC). Intake and discharge connections are 1 1/2" tube OD (tri-clamp style). Pump head rotates 360° for easy discharge-line connection. Rated for continuous duty. Pumps must be hardwired. Fluids must be compatible with wetted parts (materials in contact with solution). Wetted parts are Buna-N, PTFE, and Type 316 stainless steel.
Additional Information: ***49635KAC (See top of page for details)***

	PUMP PERFORMANCE							115/230 VAC, 60 Hz, 1 ph.			230/460 VAC, 60 Hz, 3 ph.		
	gpm @ ft. of head				Shutoff,		Max.	Full Load			Full Load		
hp	10 ft.	20 ft.	30 ft.	40 ft.	ft.	rpm	Temp.	Amps		Each	Amps		Each
1/2	54	37	—	—	25	1725	225° F	7.5/3.9/3.7	**49635K21♣**	$921.11	2.1/2/1	**49635K22▲**	$927.99
1	—	95	56	—	40	3450	225° F	11.8/5.9	**49635K35**	808.89	3.7/3.6/1.8	**49635K34▲**	788.06
1 1/2	—	—	78	36	47	3450	225° F	15/7.5	**49635K37**	861.11	4.2/2.1	**49635K36**	828.36
2	—	—	—	87	62	3450	225° F	9.9	**49635K39★**	890.56	5.2/2.6	**49635K38**	854.10

♣ 115-208/230 VAC. ★ Supplied with 230 VAC only. ▲ 208-230/460 VAC.

McMaster-Carr Supply Company Chemical Compatibility Information Disclaimer

This information was provided to McMaster-Carr by our suppliers to be used only as a general reference guide to aid in the selection of products in which chemical and material compatibility issues are a factor. This guide is not intended as a complete nor conclusive database and McMaster-Carr does not guarantee these ratings since the resistance of a material can be greatly affected by the temperature, consistency, and presence of other chemicals. Ultimately, the consumer must determine the chemical compatibility of an item based on the conditions in which the product is being used.

Key to Ratings

A	*No Effect*—Excellent chemical resistance. No performance degradation.
B	*Moderate Effect*—Some chemical resistance. Some performance degradation. Shortening of product life.
C	*Not Recommended*—Questionable resistance. Do not use.
D	*Information Not Available*—No information available for this item.

Key to Numbers

1	Good from 40° to 200° F
2	Good up to 72° F
3	Rating for Ethylene Glycol

Cast Type 316 Stainless Steel Centrifugal Pumps

	8124K31	8124K32	8124K33	8124K34	8124K35	8124K36	8124K37	8124K38	8124K39	8124K41
Acetone	C	C	C	C	C	C	C	C	C	C
Ammonium Hydroxide	B (1)	B (1)	B (1)	B (1)	B (1)	B (1)	B (1)	B (1)	B (1)	B (1)
Chlorine	B (1)	B (1)	B (1)	B (1)	B (1)	B (1)	B (1)	B (1)	B (1)	B (1)
Diesel Fuel	C	C	C	C	C	C	C	C	C	C
Gasoline	C	C	C	C	C	C	C	C	C	C
Glycol	A (3)	A (3)	A (3)	A (3)	A (3)	A (3)	A (3)	A (3)	A (3)	A (3)
Hydrochloric Acid (20%)	C	C	C	C	C	C	C	C	C	C
Hydrochloric Acid (37%)	C	C	C	C	C	C	C	C	C	C
Hydrochloric Acid (100%)	C	C	C	C	C	C	C	C	C	C
Isopropyl Alcohol	C	C	C	C	C	C	C	C	C	C
Kerosene	C	C	C	C	C	C	C	C	C	C
Lacquer Thinner	C	C	C	C	C	C	C	C	C	C
Methyl Chloride	C	C	C	C	C	C	C	C	C	C
Methyl Ethyl Ketone (MEK)	C	C	C	C	C	C	C	C	C	C
Mineral Spirits	C	C	C	C	C	C	C	C	C	C
Nitric Acid (20%)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)
Nitric Acid (50%)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)
Nitric Acid (concentrated)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)
Oil (Hydraulic)	C	C	C	C	C	C	C	C	C	C
Paint	C	C	C	C	C	C	C	C	C	C
Phosphoric Acid (<40%)	C	C	C	C	C	C	C	C	C	C
Phosphoric Acid (> or = 40%)	C	C	C	C	C	C	C	C	C	C
Seawater	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)
Sodium Hydroxide (20%)	B (1)	B (2)	B (2)	B (2)	B (2)	B (2)	B (2)	B (2)	B (2)	B (2)
Sodium Hydroxide (50%)	B (1)	B (2)	B (2)	B (2)	B (2)	B (2)	B (2)	B (2)	B (2)	B (2)
Sodium Hydroxide (80%)	B (1)	B (2)	B (2)	B (2)	B (2)	B (2)	B (2)	B (2)	B (2)	B (2)
Sodium Hypochlorate	C	C	C	C	C	C	C	C	C	C
Sulfuric Acid (<10%)	B (1)	B (1)	B (1)	B (1)	B (1)	B (1)	B (1)	B (1)	B (1)	B (1)
Sulfuric Acid (10-75%)	C	C	C	C	C	C	C	C	C	C
Sulfuric Acid (75-100%)	C	C	C	C	C	C	C	C	C	C
Water	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)	A (1)
Xylene	C	C	C	C	C	C	C	C	C	C

Appendix M – One-ton Feed Buoy - Northern Lights Diesel Generator

From the Northern Lights' website (http://www.northern-lights.com/):

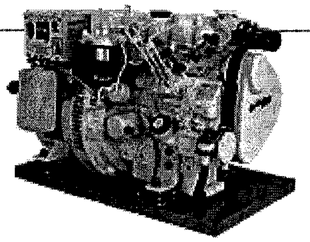
M673D | Northern Lights Marine Generator

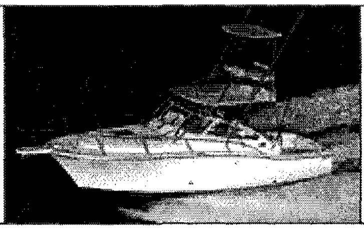
60 Hz / 1800 rpm: **5 kW** | 50 Hz 1500 rpm: **4.5 kW**

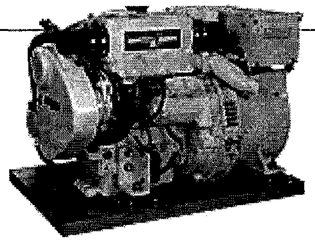
Small marine gensets are asked to run reliably year after year, start ever larger electric motors and provide clean power for electronics. Yet many small 3600 rpm sets are built only to be small and light.

The M673D is different. It runs at 1800 rpm, not 3600. During 2000 hours of operation the M673D will turn 216 million fewer revolutions than a 3600 rpm set. Its pistons will travel 38,522 fewer miles. Its cylinders will withstand 108 million fewer detonations. Which engine do you think will give more years of reliable service?

The M673D has a balanced Lugger three cylinder diesel instead of a rough two banger. Four plateform isolation mounts reduce vibration transmission even more. An air intake silencer/filter, cast valve cover and cast iron, wet exhaust system muffle engine noise. The cast-iron, freshwater colling system and gear driven seawater pump minimize troublesome belts, hoses and gaskets. Your service points are on one common side to streamline maintenance.







For maximum comfort afloat add a sound enclosure. Only 32.5 inches long, it fits your boat and it has powder-coated, aluminum panels with trigger latches to make routine maintenance, well, routine.

The generator end has a broad voltage capability in both 50 and 60 Hz operation. The automatic voltage regulator provides clean power and is powered by a special AC winding for faster response and better motor starting.

A 30 amp AC circuit breaker in the junction box protects your wiring. Safety shutdowns for low oil pressure, high coolant temperature and high exhaust temperature are standard.

The M673D meets current emission standards. You, your moorage neighbors and the environment will all benefit.

1800 rpm reliability, low emissions, quiet operation and strong motor starting. All in one small package that fits your vessel and boating style.

MODEL SPECIFICATIONS:

Cylinders: **3 inline**

Bore: **2.52 (64 mm)**

Stroke: **41.1 cid (0.676 ltr)**

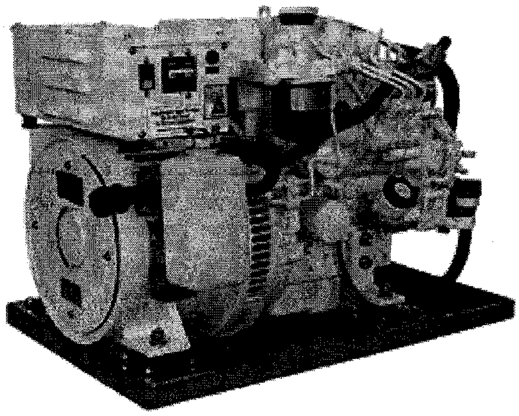
Aspiration: **Natural**

Length: **27.08 in (688 mm)**

Width: **17.08 in (434 mm)**

Height: **19.5 in (494 mm**

Weight: **355 lbs (161 kg)**



NOTE: Information, specifications, materials and dimensions subject to change without notice.

Appendix N – One-ton Feed Buoy - WHOI Mooring Specifications and <u>AquaFE</u> Results

Mooring Specifications:

<u>Mooring hose</u>, (x2):

inner Diameter (ID) = 2.0 in.
outer Diameter (OD) = 3.2 in.
overall unstretched length = 48 ft.
max. stretched length = 106 ft.

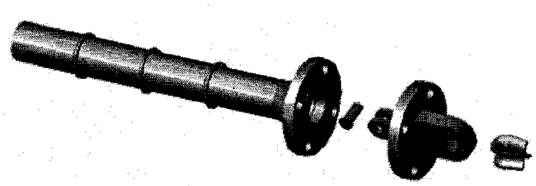
strain-relief end length (x2) = 4.5 ft.
compliant (stretchable) length = 39 ft.
max. working load = 3,300 lbf.
min. breaking load = 7,200 lbf.

internal stop rope length = 106 ft.
Vectran 7/16" 12-strand braid
max. working load = 4,000 lbf.
min. breaking load = 20,000 lbf.

<u>Feed hose</u>, (x1): in two 50 ft. sections

inner Diameter (ID) = 3.0 in.
outer Diameter (OD) = ~4.2 in.
overall unstretched length = 100 ft.
max. stretched length = 180 ft.

strain-relief end length – to feed buoy (x1) = 4.5 ft.
strain-relief end length – midpoint (x2) = 4.5 ft.
strain-relief end length – to cage (x1) = 6.0 ft.
compliant (stretchable) length = 80 ft.
max. working load = 1,800 lbf.
min. breaking load = 6,700 lbf



<u>Mooring rope</u>, (x2):

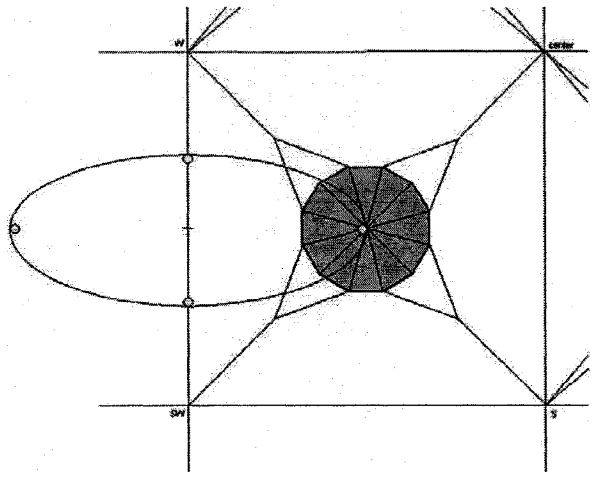
length = 61.7 ft. (~60 ft. with shackles, etc.)
Yalon 1" double braided or 8-plait nylon
max. working load = 6,800 lbf.
min. breaking load = 30,600 lbf.

<u>AquaFE</u> Modeling Results

Storm Condition Parameters
Wave Height = 9 m
Period = 8.8 sec
Current = 1 to ¼ m/s at bottom

Watch Circle in Storm Conditions:
55 ft. North or South
128 ft East or West

Figure N1, below, shows the expected watch circle of the one-ton feed buoy on the WHOI mooring hose mooring.



Appendix N (cont'd) - AquaFE Modeling Results (cont'd)

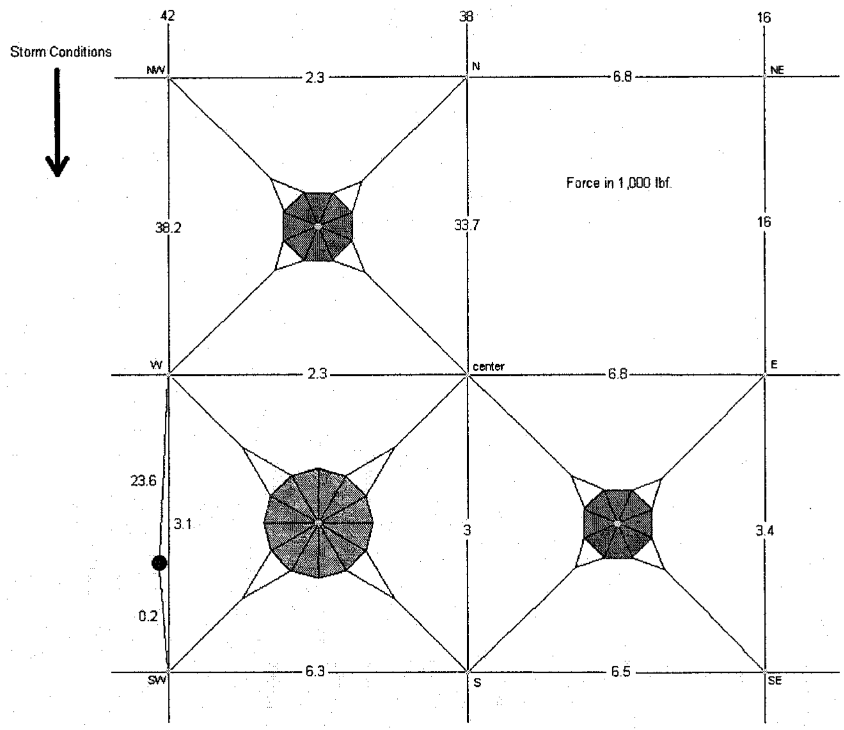


Figure N2: Storm Conditions inline with the FB Mooring

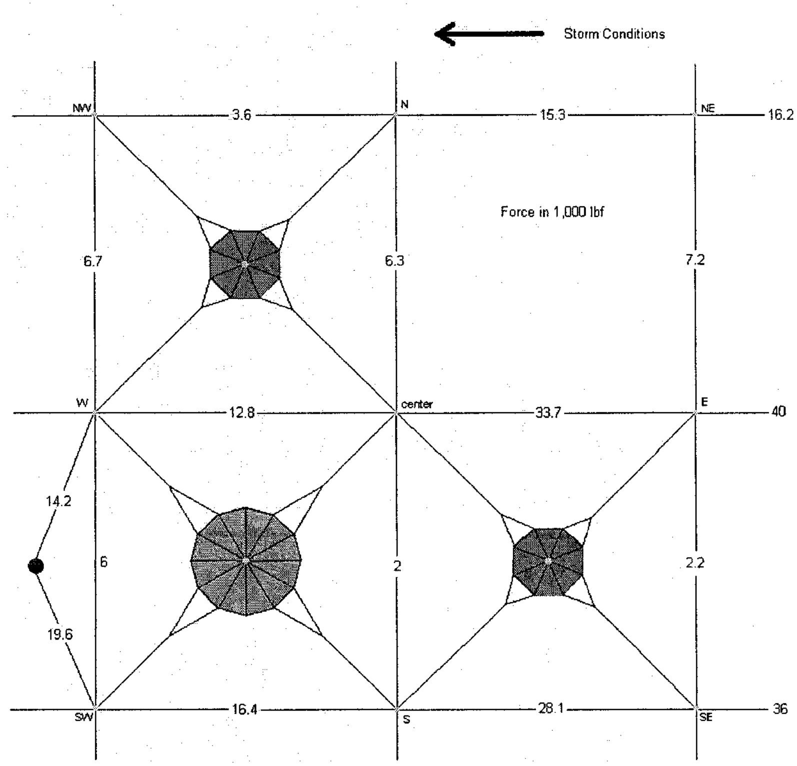


Figure N3: Storm Conditions perpendicular with the FB Mooring

Appendix N (cont'd) - Embedded Feed Hose Conductors

Roughly eighteen (18) 1/8th-inch conductors can fit around a 3-inch ID feed hose

Conductors listed in order of priority

1) Underwater Video Cameras (3-4 cameras)
2) HTI Acoustics Fish Monitoring System (4 hydrophones)
3) Underwater Cage Lights (2 lights)
4) Environmental Data, i.e. SEACAT (2 instruments)

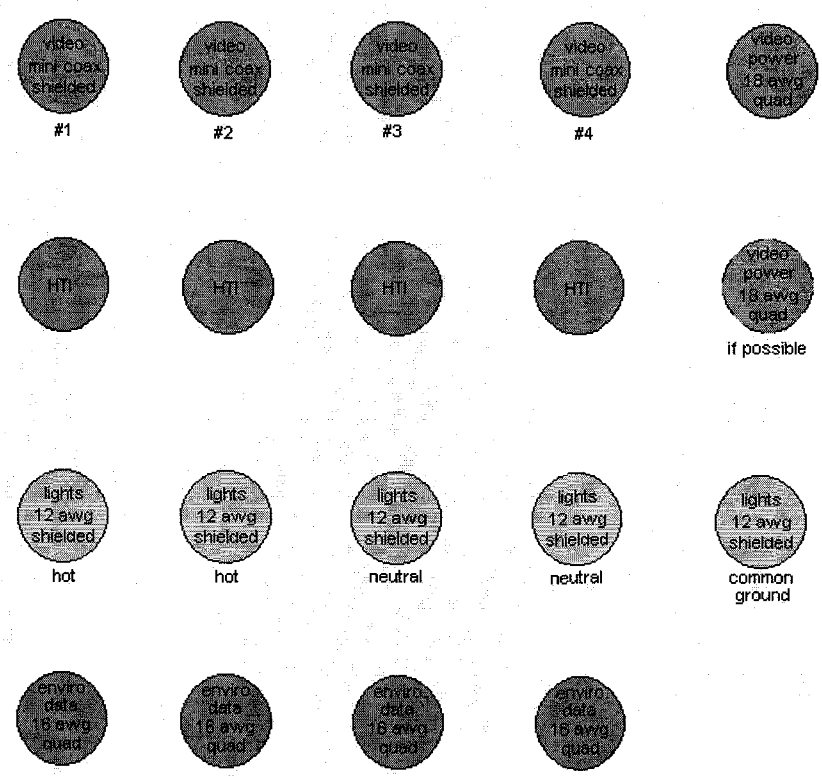


Figure N4: Proposed Feed Hose Conductor Usage

Appendix N (cont'd) – One-ton Feed Buoy–Mooring Hose Flange Design

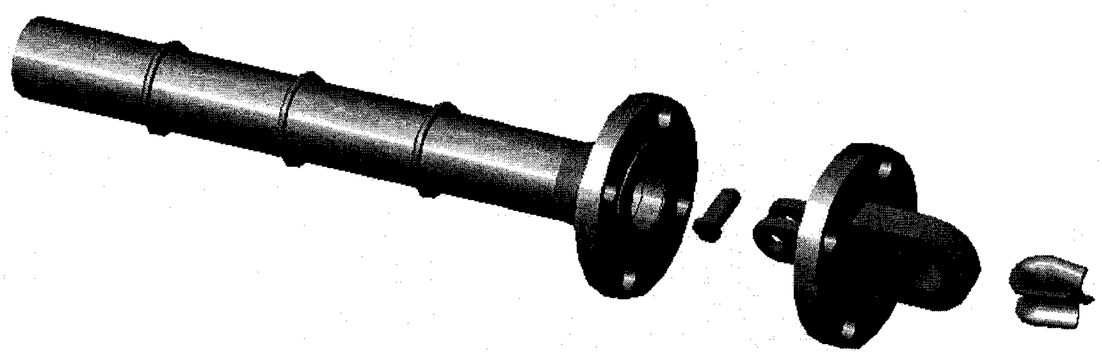


Figure N5: Isometric of Mooring Hose Parts

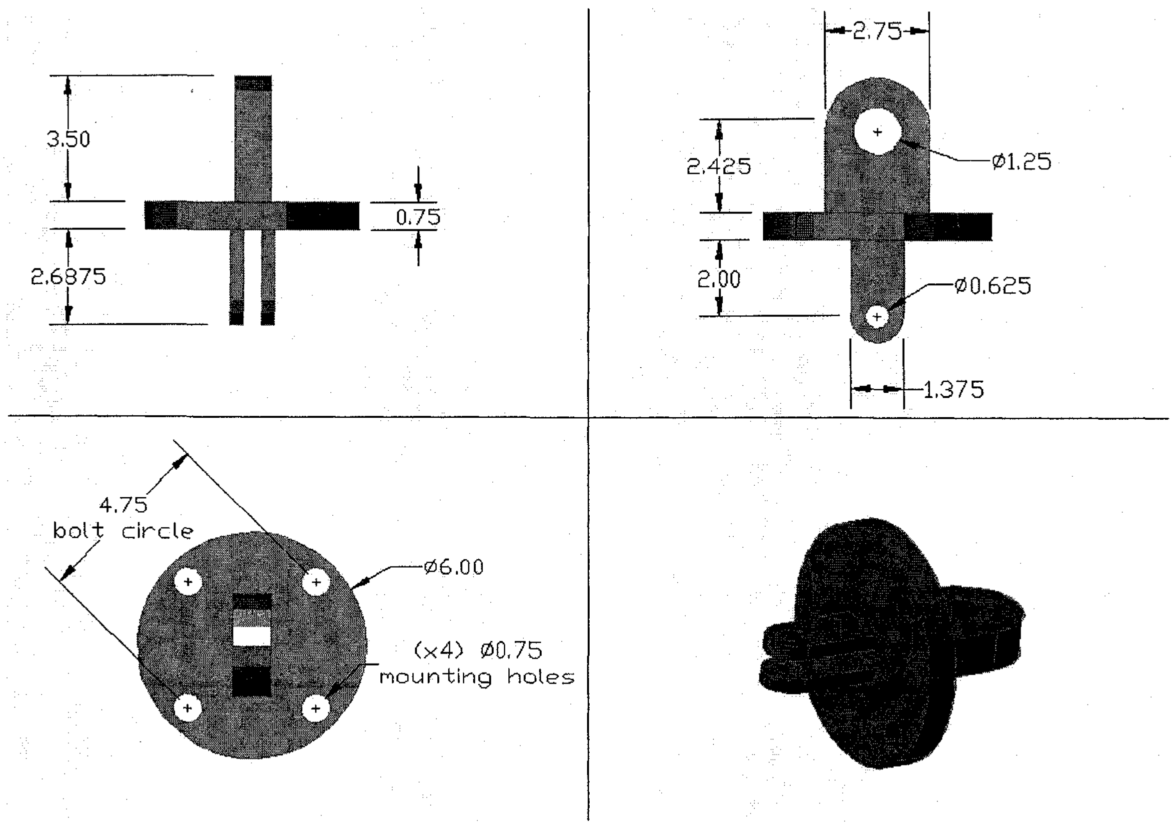


Figure N6: Mooring Hose Cap (Part Number MH-2)

Appendix O – One-ton Feed Buoy - Sample Wave Tank Model Test Plan

Physical Modeling 1-ton Feed Buoy Mooring

Test Plan

FB and SS $3000m^3$ cage scale (1:24)

FB two-point mooring: 3" ID elastic hose mooring

Free-Release Tests:

T_{heave} = 0.72 sec (3.53 sec fs)

T_{pitch} = 1.51 sec (7.40 sec fs)

Regular (single frequency) Waves:

Test #							
T (sec)	2.39	1.91	1.43	1.19	0.80	0.60	0.48
T_{fs} (sec)	11.7	9.4	7.0	5.8	3.9	2.9	2.3
L (m) *(ft)*	8.44 *27.70*	5.64 *18.49*	3.19 *10.47*	2.21 *7.25*	1.00 *3.28*	0.56 *1.84*	0.36 *1.18*
H (cm)	**6.33**	**6.33**	**6.33**	**6.33**	**3.17**	**2.53**	**1.90**
H_{fs} (m)	1.52	1.52	1.52	1.52	0.76	0.61	0.46
C (m/sec)	3.53	2.95	2.23	1.86	1.25	0.93	0.75
f (Hz)	0.42	0.52	0.70	0.84	1.25	1.67	2.08

Note: T = 2.8 sec. → transverse tank wave
T = 2.0 sec. → seiching in back of paddle

OPIE Calibration: FB = 10cm
circle = 9cm

Test Notes:

#1

#2

#3

#4

#5

#6

#7

#8

#9

#10