Engineering Overview of the University of New Hampshire's Open Ocean Aquaculture Project

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Abstract- Aquaculture products are projected to play an important role in filling the global demand for seafood in the world marketplace. In the US, stiff resistance to near shore aquaculture sites (where most farms are located) will drive the industry to more exposed locations. In an effort to better understand open ocean aquaculture challenges, the University of New Hampshire (UNH) has been investigating the biological, engineering, environmental and economical issues. This overview focuses on the engineering approach utilized by UNH to determine aquaculture system loads, motions and operational logistics by utilizing a variety of tools including numerical and physical models and field experimentation. Numerical modeling is performed with Aqua-FE, a finite element analysis (FEA) program developed to study aquaculture type systems, MSC.MARC/Mentat, a FEA structural modeling program, and FLUENT, a computational dynamics program. Scaled physical model tests are performed in the UNH wave/ tow tank.

In addition, an extensive field program experiments with the use of biofouled net panels, telemetry and control systems, feed buoys, scaled cages and various environmental monitoring equipment. Biofouled net panels were tested to determine the blockage effect due to the biological growth. Feed buoys, with telemetry and control options, have been deployed and tested. A new 20 ton capacity feed buoy has been designed and is currently under construction. A scale, experimental, submersible net pen has been designed, built and deployed to determine the feasibility of various components. Environmental measurements are collected with a surface buoy and the data is transmitted to shore. The resulting information from these experiments can help move the near shore aquaculture industry to more exposed locations.

I. INTRODUCTION

Aquaculture is expected to play an increasing role in the global supply of seafood in the coming years. Wild harvest through traditional fisheries has plateaued at 100 metric million tones (mmt) per year and is expected to remain stagnate. FAO reported that world fish production will increase from 129 mmt in 1999/2001 to 159 mmt in 2010 and 172 mmt by 2015. Out of the expected increase of 43 mmt by 2015, 73% would need to come from aquaculture [1].

In the United States, marine finfish farming is predominantly situated in Maine and Washington and consists of salmon cultured in surface cages. These sites are typically located near shore, in protected areas such as harbors, bays, and inlets. Growing fish in protected waters does have advantages, such as prime working conditions (flat seas), close site proximately to infrastructure/markets, and lower mooring system loading (when compared to exposed sites). However, expansion of aquaculture industries to these locations is often met with stiff resistance from recreational users, local fishermen, the shipping industry and environmentalists. This competition for space coupled with the strong demand for aquaculture products will drive the industry to more exposed or open ocean sites.

Growing fish in exposed waters does have its advantages. Moving away from contested areas will not only reduce user conflict issues, but open large areas of available real estate to choose optimal sites. Anecdotal evidence from Canada suggests that fish grow faster and have better feed conversion rates (FCR's) in exposed locations compared to fish grown in protected areas. In addition, exposed sites typically have a higher water quality, less variations in temperature and less coastal pollution. As a result, these environmental factors improve fish health and reduce the risk of disease.

Growing fish in more exposed conditions, however, does brings new challenges to the industry. The cages, mooring systems, and auxiliary equipment need to withstand a high energy environment with a full range of loading conditions such as strong winds, currents and waves. Typically, this results in higher costs when compared to gear located at protected sites. In addition, traveling to and from the site, daily or even weekly, may be cost prohibitive. Therefore a "control station" at the farm site may be needed. This station, operated from shore, must be outfitted with the necessary equipment to control feeding, record video, monitor system components and send other necessary information back to shore.

Traditionally, near shore aquaculture in protected sites was performed by small businesses. Improving gear and/or operational techniques was performed on a trial and error basis. When moving to exposed locations, however, this approach would become extremely unsafe and expensive. From an engineering perspective, it is important to have information regarding the systems loads, motions, and operational limits prior to deployment of equipment in exposed areas to establish more secure systems to reduce

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farmed fish escapement, liability risks and determine if existing equipment can be used in offshore locations. To accomplish this, a sound engineering approach is used at the University of New Hampshire (UNH) that includes computer models, physical model testing, and an extensive field program.

II. Offshore Aquaculture

For the past seven years, the University of New Hampshire (UNH) has operated an open ocean aquaculture site in 52 meters of water approximately 10 km from the New Hampshire coast in the Gulf of Maine. The site is permitted to perform research related to the operational, engineering, biological and environmental aspects of open ocean aquaculture (OOA). The overall goal of the project is to stimulate the further development of commercial aquaculture in high energy, low temperature environments, with the engineering focus on developing tools for analysis, designing, computer modeling, physical model testing and full scale evaluation of fish cages and their associated mooring systems. The engineering component supports this collective goal by pursuing the investigation of commercial scale fish cage systems, feed buoy development including design and control/telemetry, improved numerical modeling techniques, cage net drag due to biofouling, and exterior-interior cage flow regimes.

To initially support the research, two independent 600 m^3 Sea Station™ fish cages (SS600) were analyzed and deployed at the site in 1999 using separate, robust mooring systems [2], [3], [4]. For over six years, these systems were the focus of an intense engineering and operational analysis program. From the engineering perspective, studies were conducted to investigate the dynamics so that numerical and physical modeling techniques could be developed to cost-effectively engineer and specify equipment suitable for deployment [5], [6], [7], [8], [9].

More recently, an effort was made to expand bio-mass capacity at the site; the two small systems were replaced with a larger four grid mooring, shown in Fig. 1, enabling the deployment of additional containment structures [10]. The new mooring system also allows auxiliary equipment, such as feeding platforms [11], [12], to be installed at the site.

The computer modeling effort has emphasis on improving finite element code for modeling the dynamics of the fish cage in more complex wave and environmental loading. Physical modeling focuses on drag and wave force assessment by using scale models in a wave/tow tank. Using the computer and physical models, evaluations of the response of systems to sea conditions can be performed.

In addition, a major effort over the past five years has been the development of automated feeding systems. An initial prototype was deployed in late 2001, followed by a larger model in 2003. Net Systems has teamed with UNH in an Small Business Innovation Research (SBIR) grant to develop a 20-ton capacity feed buoy that is capable of feeding multiple cages. Refining these systems and improving remote operation of the offshore farm will be the focus of the engineering efforts over the next couple of years.

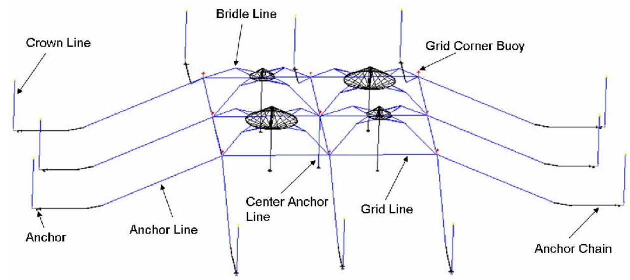

Figure 1. A schematic of the UNH OOA grid deployed in the Gulf of Maine. The grid sits approximately 18 meters below the surface.

III. Computer Modeling

Computer models are extremely useful in analyzing aquaculture structures. The models can be easily modified to account for different designs and a range of loading conditions can be applied. Three computer systems are currently used at UNH to study aquaculture systems. Two are used to study system motions, loads and stresses: (1) a numerical model called Aqua-FE, and (2) a standard finite element analysis (FEA) program called MSC.MARC/Mentat. The Aqua-FE model can simulate wave, currents and storm events on large complex systems where motion and mooring loads can be determined. The FEA program MARC/Mentat is utilized for solid modeling of cage rims (or other critical components) to determine stresses and/or failure modes. A third computation fluid dynamic (CFD) package, FLUENT, is being used to investigate the flow of water around and through fish cages.

A. Aqua-FE

The numerical modeling is performed in a program developed at UNH called Aqua-FE. This finite element analysis program, most recently described in [6], incorporates truss, buoy and stiffener elements to model various parts of net pen and mooring systems. The model uses a nonlinear Lagrangian formulation to accommodate for large displacements of structural elements. The Newmark integration scheme is utilized to solve the nonlinear equations of motion. Wave and current loading on truss elements were incorporated into the model using a Morrison equation formulation [13] modified to include relative motion between the structural element and the surrounding fluid. The program calculates both the normal and tangential drag coefficients, at each time step, as a function of Reynolds number described by [14].

Recently, the Aqua-FE code was modified to allow for a horizontal change in water velocity. The original code applied the same water velocity conditions (due to current) to every submerged element in the model, regardless of wake effects or blockage that may be occurring due to objects such as net or cage components. It is important to note that the water particle velocity, due to waves, affected each element differently depending upon the elements location within the model, applied wave characteristics, depth, etc. This approach has worked well to date, due to the relatively small size farms and limited reduction of current velocities studied. However, this will not work for larger systems with multiple containment net pens (such as salmon farms) that have a varying current distribution throughout the site.

The program was modified to allow for up to 25 different horizontal profiles to be applied to various parts of the model. This would allow for a variety of profile application techniques to be investigated, and if needed, a large current reduction in a complex system. The code was modified to produce a specifically generated file which contains all the wave (height, length, phase) and current (velocity, depth) information for each profile. The program then assigns the proper profile to the associated element for processing. This repeats for each element at each time step. Modifying the code in this manner allows for the most versatile use of the model without compromising the efficiency of the program.

Aqua-FE has been used to study a variety of different aquaculture systems and has compared well with physical model testing and *in-situ* experiments for different cage types and mooring configurations [6], [15], [16]. A direct result of the UNH Open Ocean Aquaculture's numerical modeling efforts and expertise in the field was the awarding of a Saltonstall-Kennedy Grant (# NA03NMF4270183) in 2003 entitled "Engineering Design and Analysis for More Secure Salmon Net Pen Systems." The objective of the project is to work with Heritage Salmon at their twenty-cage site in Broad Cove near Eastport, ME to evaluate the structural integrity of their deployed system for offshore application. The approach specifically targets the site area to establish more secure cages to reduce farmed fish escapement. In addition to this objective, the work investigates the feasibility of expanding salmon farming operations into more exposed areas in an effort to reduce environmental and multi-use issues.

The farm at the Broad Cove site consists of twenty, 100-meter circumference high-density polyethylene (HDPE) surface gravity cages. The farm's southwest corner was outfitted with instrumentation consisting of load cells and wave and current measurement devices. The monitoring data sets are being used to characterize the site, provide environmental forcing and validation data for computer simulations. A computer model of the 20-cage grid system has been built using Aqua-FE (Fig. 2). The results of the computer modeling simulations are being used to evaluate reliability of the existing fish farm site, to predict cage/mooring performance in more exposed environments, and to design secure fish cage/mooring systems. These models will provide quantified data sets that can be used to identify potential failure locations. Design changes can then be implemented to reduce damage and farmed fish escapement. More information regarding this study can be found in a companion paper [17].

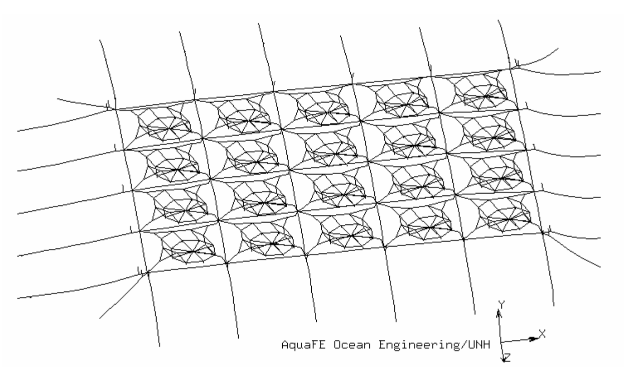

Figure 2. A numerical model of the Broad Cove site under analysis using the UNH developed program, Aqua-FE.

B. Solid Modeling

MSC.MARC/Mentat is a standard finite element analysis program that is used by UNH to analyze the structural integrity of aquaculture components. Since a majority of components used in aquaculture are constructed of high density polyethylene, a finite element methodology has been developed to determine the structural capabilities of HDPE pipe. The approach uses shell elements and employs the localized failure criterion to predict critical loading conditions. Since HDPE is a viscoelastic material, the modulus of elasticity needs to be determined as a function of loading rate. Values for the modulus of elasticity were determined by performing a series of tensile tests using standard "dogbone" samples of HDPE. To investigate the effectiveness of the approach, experiments were performed in the laboratory by testing rings of HDPE pipe to localized failure (kinking) and the results compared well with numerical model simulations. The combined technique was used for the complex geometry of a net pen flotation structure using the experimentally determined material properties.

This approach is useful because the stresses in the system can be determined, as well as the failure mode (an example is shown in Fig. 3). This methodology was utilized in studying standard high density polyethylene near-shore salmon cages to investigate the use of existing equipment in more exposed locations.

C. Computational Fluid Dynamics

A third software package is currently being used to investigate water flow around net pens. To improve farming of finfish in sea cages, it is important to know the flow environment around and inside the cage. For the engineering design of the cages, velocity shadowing is important due to the fact that the forces acting on the cage are highly dependent on

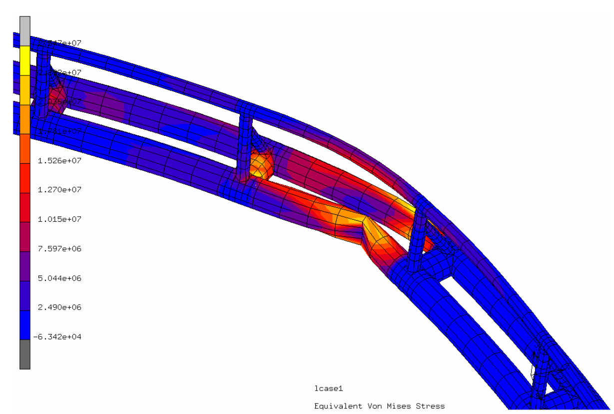

Figure 3. A structural analysis of a typical gravity type cage rim buckling under load.

current. On the environmental side, the flow environment around and inside the cages is an important factor for flushing rate, feeding, and dispersion of effluents from the cages.

One way to get more insight into this problem is to make calculations of the flow. The problem is not trivial to solve, since the main part of a fish farming cage usually is made out of net with many small meshes. Nontrivial fluid dynamic problems are usually solved using some kind of computational fluid dynamics software. One of the widely used CFD software packages is FLUENT from Fluent Inc.

When creating a model of a fish farming cage, the number of elements in the net is too large to be modeled as solid bars, and the net has to be represented in some other way. Using a thin sheet of porous material, in FLUENT, to represent the net of the cage is a promising way to deal with this problem. Although this study is still in its beginning, tow tests and physical models have been utilized to validate preliminary model results. More information regarding this study can be found in a companion paper [18].

IV. PHYSICAL MODELING

Physical model testing is also utilized to better understand aquaculture system response. Physical model tests on aquaculture equipment generally consist of scaled models of fish cages, mooring systems and feed buoys. The tests are conducted in the 37.5 m long by 3.66 m wide by 2.44 m deep wave/tow tank facility at UNH. Physical model testing focuses on drag and wave force assessment and not only verifies the numerical model, but allows for a better visual understanding of the system in its environment. Relative motion between components is also more easily seen than that of numerical model output files.

Load cells are utilized to measure mooring system loads or cage drag. System motion is measured by using UNH's optical positioning instrumentation and evaluation (OPIE) measurement system [19]. The OPIE system uses a digital camera, computer and processing software to track the motion of black dots placed on white background. The data exported by OPIE is then further analyzed to obtain the values of interest.

Physical model testing has been performed to investigate cage systems, feed buoy response, and multiple mooring configurations [3], [15],[20]. Recent physical model tests have been performed to investigate a prototype 20 ton feed buoy (further discussed in the field program section). A Froude scaled, physical model was constructed for wave tank testing after the major design features were finalized, shown in Fig. 4.

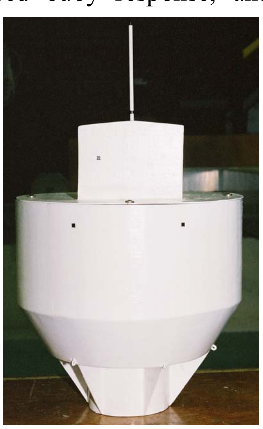

Figure 4. Completed 1:20.7 20-ton buoy scale model.

The buoy underwent a series of free-release and wave tests investigating the heave (vertical motion) and pitch (angular motion) under two different loading conditions: load and light. The load case corresponds to a buoy with full feed and fuel, while the light case includes only the permanent structures on the buoy. More information about the feed buoy construction, interior components and results of various hydrodynamic tests can be seen in a companion paper [21].

V. FIELD PROGRAM

In addition to numerical and physical model testing, UNH operates an field program which includes measurement and subsequent telemetry of environmental and operational information, experimental feeding technology, mooring tension measurements, and prototype fish cage evaluation. The UNH Open Ocean Aquaculture site contains a submerged four cage grid mooring system [10]. The mooring provides a platform for scientific and engineering experiments to take place in an environment that can produce up to 9 meter waves in extreme events. This site allows systems to be deployed, monitored, debugged (if applicable), and operationally tested. The resulting information is then utilized in the next generation of equipment and/or passed along to state, federal or commercial entities interested in the technology. UNH has worked with numerous individuals, companies and organizations involved with open ocean aquaculture, such as Net Systems, Ocean Farm Technologies, JPS Industries and the American Soybean Association.

A. Grid LC measurements

The four-grid mooring system designed and deployed by UNH has been the foundation of all OOA site work over the last three years. As previously mentioned, it acts as a false bottom so that buoys and cages can be attached to a well known position without having to deploy new moorings or anchors in relatively unknown locations. The grid also allows for diver access to cage and buoy hardware for inspection and attachment that would otherwise be inaccessible. While this grid mooring has worked well, many values have not been measured regarding the actual deployed geometry and load distribution. To better understand the deployed grid and its sensitivity to anchor locations, load cells are being incorporated into the northeast corner of the grid.

Three load cells have been deployed in the eastern anchor line, and the northern and eastern grid lines. These instruments are being used to verify the deployed grid tensions and anticipate changes in the line loads due to changes in geometry (when coupled with results from the numerical model).

A second *in-situ* line measurement device has also been developed and used. A portable line tension measurement device has been designed, calibrated and tested. This instrument is submersible and designed to measure the submerged grid tension of any line within the system to "spot check" tensions (without inserting an in-line load cell). Further information regarding this device and preliminary grid tension results can be found in a companion paper [22].

B. *Drag on Biofouled Net Panels*

Since wave and current drag acting on cage netting usually represents the majority of environmental forcing, measurements were made to assess the increase in drag on netting due to biofouling [23]. Drag force was obtained by towing net panels, perpendicular to the incident flow, in experiments conducted in a tow tank and in the field. The net panels were fabricated from netting stretched within a one-meter-square pipe frame. They were towed at various speeds, and drag force was measured using a bridle-pulley arrangement terminating in a load cell. The frame without netting was also drag tested so that net-only results could be obtained by subtracting out the frame contribution. Measurements of drag force and velocity were processed to yield drag coefficients. Clean nets were drag tested in the UNH 36.5 m long tow tank. Nets were then exposed to biofouling during the summer at the OOA site. After recovery, the nets were immediately drag tested at sea to minimize disturbing the fouling communities. Increases in net-only drag coefficient varied from 6% to 240% of the clean net values. The maximum biofouled net drag coefficient was 0.60 based on net outline area. Biofouled drag coefficients generally increased with solidity (projected area of blockage divided by outline area) and volume of growth. There was, however, considerable scatter attributed in part to different mixes of species present.

C. *Telemetry*

It is crucial to have proper telemetry and feeding capabilities for aquaculture sites in exposed locations. Since personnel may not be present at the farm full-time, being able to know up-to-date environmental conditions, current feeding strategies, and system diagnostics from a shore based center is critical. To obtain this information, two types of buoys are utilized at the UNH OOA site: environmental monitoring buoys and semi-autonomous feed buoys.

An environmental monitoring buoy, shown in Fig. 5, measures current profiles, waves (significant wave height and dominate wave period), salinity, temperature, dissolved oxygen and other relevant environmental factors [24], [25], [26]. The buoy then collects, processes, and sends the information back to a communication center located on the UNH campus. This allows personnel to know the conditions at the site and plan necessary operations regarding feeding, maintenance, etc. This buoy also fulfills part of the environmental monitoring requests by the Environmental Protection Agency and the State of New Hampshire.

Figure 5. Deployed environmental monitoring buoy at UNH OOA site.

D. *20 Ton Capacity Feed buoy*

The second set of buoys used are semi-autonomous feeding structures. Two previous feed buoys have been deployed at the site, with remote feeding and system check capabilities [11], [12]. A new 20-ton capacity feed buoy has been designed by UNH in cooperation with Net Systems. The new prototype buoy incorporates knowledge and experience gained by UNH in operating previous feeding buoys. The buoy has undergone intensive numerical and physical model testing and is currently under construction. A external view of the buoy is shown in Fig. 6.

The feed buoy is capable of feeding four different types of cages with different types of feed. The system is equipped with sensors and telemetry equipment, allowing for remote operation. Feeding patterns, system diagnostics, and other important information will be controlled from a shore based center.

The buoy has a full scale diameter of 22.5 ft, height of 28.2 ft and has a total loaded weight of 84 tons. Major components include the steel shell, framing and decks, concrete ballast, four feed silos, internal feed transfer augers, external feed transfer mixing chamber and pumps, generator, and a control system.

The system will be outfitted with equipment allowing shore based monitoring of fuel levels, battery condition, generator operation, feed levels, and valve positions. Modifications to feeding, such as increasing dosages or complete system shut-down can be operated from the world wide web. In addition, the motion of the buoy will be measured to compare with the physical and numerical model test results. Further information regarding feed buoy construction, testing, feed buoy telemetry

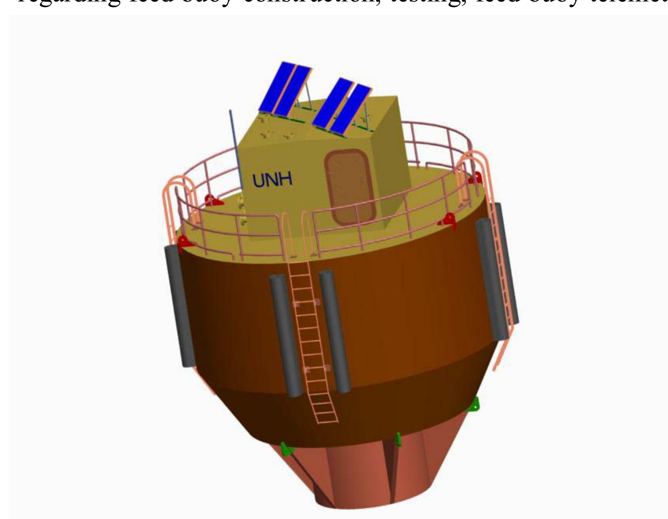

Figure 6. External view of completed 20-ton buoy design.

and control can be found in [21], [27], [28].

E. SBIR Cage

The UNH OOA field program also includes testing of prototype fish cages. JPS Industries, a NH manufacturing company, worked with UNH to obtain a Small Business Innovation Research (SBIR) grant to work on an experimental cage design. This investigation was based in part on experience gained evaluating other commercially available cage systems. Over various phases of this study, a low-cost, submersible fish cage for open ocean aquaculture was investigated. Hydrostatic tests, numerical, physical, and structural modeling were performed on the conceptual, gravity-type design.

This cage concept (Fig. 7) is a modified version of a traditional gravity cage. However, the cage structure has been modified to ease the transportability, construction, and maintenance of the system. It consists of 12 sections of dual HDPE pipes secured with metal fittings. These fittings cap each end of the plastic pipe sections and are bolted together to create a rigid cage structure. They also support the handrail stanchions, triangular stays (supporting the lower rim and ballast) and provide net attachment locations. A bottom ring supports the lower half of the net chamber and is constructed in a similar manner. A bridle, airlift and ballast chain (or deadweight anchor depending upon bottom conditions) hangs below the bottom rim of the cage.

Two variable buoyancy/ballast configurations (to raise and lower the cage) are currently being investigated. The first will be located within one section of the upper rim pipes. This configuration was tested in the Phase I portion of the SBIR program with a scale model cage. Although the current cage design geometry of the cage is now different, the concept is similar and tested well. The second system is an airlift attached below the lower rim.

The airlift was designed to allow surface filling (even with the tank at depth) and to provide precise control of vertical position. Filling the tank in “stages” will allow the system to offset precise weights. By understanding the geometry of the tank, the distance between each valve, and the ballast weight characteristics, the cage system can rise in set increments. Controlling the depth of the cage is important when dealing with fish with swim bladders, which cannot compensate for a rapid depth change. A 1:1.623 scale cage (having a diameter of 50 ft) was constructed and deployed in June of 2006. System testing to determine the optimal ballasting configuration and insure the cage system’s stability in the water column is scheduled for July/August 2006.

Figure 7. JPS Industries SBIR scale cage after assembly.

VI. UNH Open Ocean Aquaculture Outlook

Over the next year, the UNH OOA project is slated to receive, deploy and test the new 20 ton capacity feed buoy. The telemetry and control of the system will be optimized, reducing the need for personnel at the site. In addition, the scale SBIR cage will be tested and working with JPS Industries, a full scale net pen designed. Further experiments and modeling of flow through and around fish cages are planned as well as investigating small scale, high density aquaculture systems. The data gathered from these computer simulations, physical model testing and full scale experiments will provide valuable information for the next generation of aquaculture equipment.

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